NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP Report 374

Effect of Highway Standards on Safety

Transportation Research Board
National Research Council

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Report 374

Effect of Highway Standards on Safety

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Subject Areas

Highway and Facility Design
Highway Operations, Capacity and Traffic Control
Safety and Human Performance

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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FOREWORD

By Staff
Transportation Research Board

This report provides a comprehensive overview of current understanding of the relationships between safety and design. It translates all of the data or models related to the safety impacts of design decisions to a similar format. The report also includes eight research plans formulated to address the existing gaps in the state of the practice. The report is useful to designers interested in formally evaluating the safety of a given design, to students and educators studying highway design and safety, and to researchers as a benchmark for the current state of the practice.

This research was initiated on the premise that the safety of a highway is intrinsically based in its design. It is clear that design decisions related to the horizontal and vertical alignment of a highway influence the way vehicles operate on a roadway and consequently the risks associated with the use of the roadway. Less apparent—but equally important to safety—are decisions related to the selection of cross-sectional features and the provisions for the use of ancillary hardware in the roadway environment. Clearly, everyone is interested in providing a safe highway, but the realities of limited resources, environmental concerns, land use constraints, and other factors make design decisions difficult.

NCHRP Project 17-9 started with the premise that it would be possible to develop guidelines for assessing the safety benefits associated with specific design elements and that such guidelines could be integrated into the design process. It was believed that sufficient research had been conducted to understand the effects of geometric and traffic features on safety, but that the results had not been synthesized into a unified document and correlated with current design practices. Such a document would define the relative safety benefits of highway design features and allow highway agencies to select features considering their safety impacts. The project panel, therefore, defined the twofold objectives of this research: (1) to assess the safety effects of highway design standards and (2) to synthesize the findings into documents that will provide guidance in addressing safety needs given limited resources and other constraints. The research was intended to address geometric, cross-sectional, and roadside design elements for all roadway types, environments, and traffic situations.

Bellomo-McGee, Inc. of Vienna, Virginia, was selected to undertake the research, which began in early 1993 with an in-depth literature review and state surveys. The contractor compiled the findings of these efforts in an interim report, which was presented to the project panel in May 1994. After a detailed review of the interim report, the panel met with the contractor in July 1994. The contractor's interim report indicated that while sound research efforts had led to a greatly improved understanding of the effects of design on safety, some relationships were not well defined and significant gaps remained in the knowledge about these effects. For example, many of the studies used as the basis for current practices were studies that included only a limited set of conditions, reflected the biases of particular state practices, and involved small samples. A significant deficiency exists in the understanding of the combined and interactive effects of multiple design features (e.g., the relative safety of curves on a downgrade). Further, the contacts with states indicated that there was wide variation in practices and only limited definition of threshold values for limiting design conditions. The panel agreed with the contractor's conclusions and decided to refocus the objectives of the project. Efforts to validate some of the recent findings were continued as planned, but efforts to develop a guidebook were abandoned. The contractor instead focused on developing a research program to fill the gaps in the current state of the practice.

The panel agrees with the general scope and intent of the eight research plans outlined by the contractor. For each research plan, the revised final report provided a detailed discussion of the objectives, critical factors to consider, data requirements, projected work elements, and anticipated costs to conduct the research. Many of these research plans were estimated to require significant amounts of funding and time.

The focus of this research is two-lane roadways, because these roadways represent the most extensive type of highway in the U.S. network, and many miles of it are in need of improvement. Decisions about the extent of resurfacing effort relative to ancillary improvements frequently need to be made in an environment where conflicting objectives often exist. This project will attempt to gather fundamental data, establish thresholds, and formulate guidelines. The other seven research problem statements generated in the 17-9 effort are being considered as candidates for future research funding.

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ACKNOWLEDGMENTS

The research reported herein was performed by Bellomo-McGee, Inc. Dr. Hugh W. McGee was the principal investigator and Warren Hughes contributed significantly as a senior investigator. Other participants included Kevin Daily, who performed the case study analyses; Guenther Lerch, a consultant during the first phase of the project; and Syed Hussain and Sarath Joshua, former staff members.

This effort required the support of state departments of transportation. In addition to the 37 states that responded to the questionnaire, the researchers acknowledge California, Louisiana, Maryland, Michigan, New York, North Carolina, and Washington, which the principal investigator visited, and Maryland, New York, Washington, and North Carolina, which provided project data for the case study analyses.

EFFECT OF HIGHWAY STANDARDS ON SAFETY

SUMMARY

Ideally, highway safety can be maximized by applying the highest geometric design standards. However, limited resources and constraints due to physical, right-of-way, and environmental features often restrict the highway designer's ability to develop geometric designs that exceed minimum design standards, forcing the designer to make critical design decisions that will affect the safety of the project. Therefore, decision makers and designers need guidance on the relative incremental and combined effects of roadway and roadside design elements on safety so they can make more informed design decisions. Accordingly, the objectives of this research were to assess the safety effects of highway design parameters for roadway cross-section (i.e., shoulder width and lane width), alignment (i.e., vertical curvature, horizontal curvature, and stopping sight distance [SSD] related to alignment), and roadside and to synthesize the findings to provide guidance on safety needs, given limited resources and other constraints. Also, deficiencies in the state of the art were to be identified, and research plans were to be formulated to address these needs.

State Design Practices

To determine current practices in applying design standards for different classes of roads, varying traffic conditions, and other factors, the researchers conducted interviews with officials in 7 states and sent a questionnaire to all 50 states. On the basis of the responses from 37 states, they determined that, while most states claim they use the functional system prescribed by the American Association of State Highway and Transportation Officials (AASHTO) as a basis for design elements, numerous other factors dictate the selection of minimum values for certain design elements. It appears that for 3R (resurfacing, restoration, and rehabilitation) and 4R (addition of reconstruction) projects, states have minimum design criteria that are not based exclusively on functional class and, in many cases, may be lower than AASHTO standards. Although about half of the responding states indicated that they do have an established process for explicitly considering the safety impacts of design decisions, many states believe that by following design standards they are considering safety. None of the respondents indicated that they assess the safety impacts of design decisions as a normal course of design. The consensus is that states are apparently designing to minimum standards in practically all cases.

Many state respondents indicated that, during the design process, they frequently perform trade-off analyses. The most common elements identified, ranked on the basis of the number of times cited, were the following:

- Flatter sideslope versus barrier
- Lane width and/or shoulder width
- Roadside obstacle removal versus barrier/protection provision
- Vertical alignment (i.e., longer sight distance versus higher excavation cost).

In terms of percentage of responses, the state respondents also identified the following as design elements that frequently require design exception reports:

Percent of Responses	Design Element
53%	Shoulder width
33%	Vertical alignment/curvature
31%	Lane width
28%	Horizontal alignment/curvature
19%	SSD (alignment related)
17%	Bridge width
17%	Maximum grade
14%	Clear zone
14%	Sideslope
11%	Lateral clearance
11%	Superelevation
8%	Reduced design speed

These responses provide insights on the specific design elements on which safety guidance is most needed. It appears that trade-off analyses are most often conducted for issues related to roadside, and design exceptions are most often prepared for cross-section and for alignment. The states were also asked to rank a list of items that would be most helpful to designers in considering safety in design. "A step-by-step process with built-in accident/design element relationships for conducting cost/safety trade-off analysis for design elements" was the top choice of 44 percent of the respondents. "A concise listing of minimum (or maximum) values which would define limits for safe design for different types of roads" was identified as the top choice of 31 percent of the respondents.

Assessment of Documented Relationships

An extensive literature review was undertaken to investigate documented relationships between accidents and alignment, cross-section, or roadside design elements. Only a limited number of documented relationships of safety to design elements exist, and none can be considered truly definitive. A majority of documented relationships pertain to a single design element or a limited number of related design elements (e.g., shoulder width and lane width) without considering the effect of other elements. Many of the relationships have focused solely on one type of highway (e.g., two-lane rural road) and, therefore, may not be appropriate for other facility types.

Several studies have presented accident relationships for design elements of horizontal curves. In general, accident rate increases as a function of increasing degree of curvature, although the relationship is affected by other variables, including length of curve, roadside design, superelevation, lane width, shoulder width, and the presence of a spiral transition. Published accident data suggest that the potential for a run-off-road accident is significantly higher on the outside of curves than on tangents and that roadside design is a determinant of horizontal curve safety.

Several promising relationships on pavement width, lane width, and shoulder width have been documented for two-lane rural roads. In general, some empirical evidence and engineering judgment indicate that 12-ft lanes are "safe," 11-ft lanes are safe enough for certain situations, and 10- and even 9-ft lanes can provide a modicum of safety on two-lane roads for specific combinations of low speed and low volume, with only a few wide vehicles. In addition, substantial evidence indicates that increasing shoulder width on two-lane rural roads will result in fewer accidents. For divided highways, a relationship between decreasing accident rate and increasing median width has been established, although the data appear to suggest that unprotected medians (i.e., without median barriers) need to be at least 30 ft wide to have a positive safety benefit.

On the basis of the available literature, it appears that providing clear zones with traversable slopes greatly enhances roadway/roadside safety. The need for a "forgiving" roadside is paramount on the outside of isolated horizontal curves that are greater than 6 degrees. Studies have also documented that sideslopes steeper than 4:1 pose a greater hazard to motorists compared with flatter sideslopes, although one study contends that slopes should be 5:1 or flatter to significantly reduce the hazardousness of the roadside.

The available data and documented studies are not sufficient to allow any definitive conclusions about the relationship of vertical alignment elements to safety. Crest vertical curves with large grade differentials (i.e., greater than 6 percent) pose a higher risk for accidents than crest vertical curves with small grade differentials. Steep (greater than 4 percent) upgrades and downgrades pose a greater hazard, especially when trucks are involved. The accident potential is greater for horizontal curves on or immediately after grades steeper than 3 percent.

Available Accident Prediction Models

A number of accident prediction models have been developed from previous highway safety research studies. While a few are noteworthy and can serve as tools for designers to assess the safety impacts of alternative designs, all currently available models have limitations. To evaluate alternative cross-sections for two-lane rural roads, Zegeer's cross-section model appears to represent the best model (see References *4* and *5*). The model, however, does not consider the effects of horizontal or vertical alignment, the frequency of horizontal curves greater than 3 degrees, the frequency of sight-restricted curves, the percent grade, the frequency of access points, driveways and intersections, and average operating speeds or design speed. Moreover, the model cannot be applied to multilane highways. In addition, the accident prediction model requires the specification of a visually based roadside hazard rating on a scale of 1 to 7, rather than the specification of sideslope and clear zone. While suggested accident reduction factors (ARFs) for increasing roadside recovery distance and for flattening sideslopes have been developed for use with the model, the model is more appropriate for evaluating alternative cross-section improvements to *existing* two-lane roads than for evaluating the safety impacts of *new* two-lane rural roads.

For evaluating the design of individual horizontal curves on two-lane rural roads, Zegeer's horizontal curve model appears to be superior to Glennon's horizontal model as a design evaluation tool that can predict accidents (see References *6*, *15*, and *16*). However, the procedure is limited to evaluating individual horizontal curves and cannot evaluate highway sections with varying alignment (e.g., combinations of curves and tangents). The model does not consider the effect of vertical alignment, the consistency of horizontal alignment for all curves in the section, the frequency of sight-restricted crest vertical curves, or the influence of intersections and driveways. In addition, because the procedure does not consider a roadside hazard rating, the model is limited in its ability to estimate the true safety benefit of adding guardrail to curves with hazardous roadside obstacles or sideslopes, because a guardrail neither flattens the sideslope nor increases the roadside recovery area.

Neuman and Glennon developed a procedure to evaluate the potential safety benefits of increasing SSD for crest curves on two-lane roads that do not meet AASHTO minimum design standards (see References *13* and *15*). However, application of the model to a specific case project indicated reduced safety for some incremental increases in sight distance—a result counterintuitive. The model cannot be used to assess alternative vertical curve designs for curves that are within standards.

The ROADSIDE model can be applied to evaluate alternative designs primarily for roadside hazards having a specific width, length, and lateral offset from the edge of the travel way. The current model is mathematically appealing in that impacts with a specific roadside obstacle can be estimated easily based on an assumed rate of roadside encroachments. However, the model is based on very limited, mid-1960s empirical data for encroachments into freeway medians. In addition, the model does not currently consider the effect of upstream or downstream alignment.

Research Plans

To address these deficiencies, the researchers developed a set of eight plans for future research. These research plans included descriptions of the objectives, research approach, critical factors, data requirements, work elements, and projected costs. Topics that are addressed by the eight proposed research plans include the following:

- Accident relationships for roadside design elements for two-lane and multilane rural highways
- The development of accident prediction models that explicitly consider total accidents by severity and cross-section, alignment, and roadside design parameters for paved, two-lane rural roads with average daily traffic (ADT) of more than 2,000 vehicles per day (vpd)
- The development of accident prediction models that explicitly consider total accidents by severity and cross-section, alignment, and roadside design parameters for paved and unpaved low-volume, two-lane rural roads (i.e., ADT of fewer than 2,000 vpd)
- The development of statistical relationships that express total accidents by severity as a function of alternative cross-sections for urban and rural multilane arterial and collector highways
- The development of accident prediction models that estimate total accidents by severity as a function of horizontal alignment, vertical alignment, and intersections
- The development of statistical relationships that express total accidents by severity as a function of alternative cross-sections for urban and rural interstates and other freeways and expressways
- The identification of specific combinations of geometric features and characteristics that experience increases in accident and/or severity after the resurfacing projects on two-lane rural roads, the quantification of the order-of-magnitude of the expected increase in accidents, and the development of the safety-design element relationship
- The development of the relationships between accidents and geometric design consistency for two-lane rural roads.

These proposed research efforts will fill critical gaps in the state of the practice and support other ongoing research and development efforts. For example, the Federal Highway Administration (FHWA) has embarked on a program to establish an interactive highway safety design model (IHSDM). The IHSDM, which had been advanced only to the conceptual level at the time this report was prepared, will ultimately give the highway designers the tools to perform quantitative safety assessments of designs consistently and logically. The first proposed research plan calls for the development of the IHSDM accident predictive models for basic highway segments. The major product of this proposed plan would be a series of statistical models that relate on-roadway accidents to cross-section, alignment, and traffic parameters for various functional highway classifications.

CHAPTER 1

INTRODUCTION

RESEARCH PROBLEM

Design standards are essential to highway safety. Highway agencies apply design standards based on the anticipated use of the roads in their system. The variables considered include functional classification, volume, traffic mix, terrain, roadside environment, and character of travel. Ideally, applying the highest design standards would be expected to maximize safety. This assumption holds true when one compares the safety record of the Interstate system, which has been built to the highest standards, with other classes of roads.

While construction of new highways is limited, there is a continual need to improve facilities to meet increasing traffic demand and/or resolve safety problems. In most cases, budget limitations and environmental concerns preclude adopting desirable design standards to maximize the level of safety for the user. Instead, agencies must resort to using minimum design standards and, in some cases, may seek a variance for one or more design elements.

To determine what standard should be used for any specific design element, highway agency personnel need a better understanding of the incremental and combined effects of roadway design features on safety. Such an understanding represents a major facet of an effective highway safety management effort.

A considerable amount of research has been conducted to understand the effects of geometric and traffic features on safety. The results of that research need to be synthesized into one document and effectively correlated with current design practice. This effort will develop a hierarchy of the relative safety benefits of highway design features and will enable highway agencies to select design features that are essential to highway safety, as well as allow comparisons between alternative investment policies that will optimize the overall safety of their highway systems, despite limited resources and other constraints.

OBJECTIVE

In recognition of this problem statement and research need, the stated overall objective of this research was to assess the safety effects of highway design standards and to synthesize the findings into a document that would provide guidance in addressing safety needs. More specifically, the requirements were the following:

1. Identify critical variables and parameters in the relationship between design features and highway safety.
2. Determine state highway agency practice for applying design standards and for considering safety during highway improvements.
3. Prepare a synthesis document that relates and assesses the effects of particular features on highway safety under varying conditions.
4. Apply the information to actual projects as case studies.
5. Develop research plans to address deficiencies in relationships between specific design elements and safety.

One of the original requirements was to prepare a user's manual that would concisely present the design element/safety relationships and procedures for using them in the decision process. However, after completing the first phase of this project, which met the first three objectives, it became clear that, despite substantial research, very few definitive and reliable relationships could be recommended in a user's manual. Hence, in the second phase, the project placed more emphasis on identifying research needs while still presenting the best information available.

PROJECT SCOPE

It could be interpreted from the discussion above that all design elements for all portions of all highway types were considered. In executing this project it became clear that such an all-encompassing scope was not feasible, and therefore, some focusing was necessary.

For instance, highways can be stratified into two parts: junction points (i.e., interchanges and intersections), and segments or sections between these junction points. Highways can be stratified also by other features, such as bridges, weaving areas, and sections with truck climbing lanes, but, for the purpose of this project initial stratification into two groups was appropriate. This project, however, did not consider junction points. While some of the included design elements have a role in the design of these features, it was assumed that they have been or are being treated adequately in other studies.

The second factor limiting the scope of this project was the type of highway. As indicated by the study objective, the project was to include all roadway types, which would mean from low-volume, two-lane rural roads to multilane interstate freeways. While the literature review discussion provides information for all roadway types, from discussions with state personnel it appears that guidance is most needed for nonfreeway facilities and, especially, for 3R or 4R projects.

The third limiting factor has to do with the number of design elements that are considered. Highway design is based on standards developed and/or adopted by the FHWA, AASHTO, and individual states and local jurisdictions. A review of the contents

TABLE 1. Selected design elements that influence safety

Category	Design Element
Alignment, Horizontal	Degree of curvature Superelevation
Alignment, Vertical	Grade Critical length of grade Vertical curves— sag and crest
Cross-Section	Number of lanes Lane width Shoulder type Shoulder width Median type Median width
Roadside	Sideslopes Horizontal clearance to obstruction (clear zone) Ditch design Traffic barriers—roadside Median barriers

of one of the primary design standards and guidance manuals, AASHTO's *A Policy on Geometric Design of Highways and Streets* (1990) (*1*) (frequently referred to as the Green Book) clearly indicates that numerous specific elements constitute the design of a facility. An argument can be made that nearly every element discussed in that document affects the level of safety to the user. Even considering that this project is limited to geometric, cross-section, and roadside elements, there are still numerous design elements that affect safety. Table 1 provides a list of design elements for roadway sections that, intuitively at least, are related to safety. The elements have been grouped into three categories: alignment, cross-section, and roadside. These categories of design elements became the focus of the research.

RESEARCH APPROACH

The research started with a comprehensive literature review, a survey of state highway agencies regarding their policy and practices for considering safety in their design, and on-site interviews with personnel from selected states. This information-gathering effort became the foundation for an interim report (*2*), which documented the results and findings to include what was known about relationships of design elements to safety. In the next phase, the "best" relationships were applied to design projects provided by some states to demonstrate their applicability and usefulness. Also, research programs were formulated for the areas in which knowledge was deficient.

REPORT CONTENTS

Chapter 2 discusses the results of a survey of state highway agencies concerning how they consider safety in their design procedures. Chapter 3 summarizes the documented relationships between safety and geometric elements and features. Chapter 4 discusses the critical voids in the knowledge of safety effects of design standards and presents recommended research problem statements. Appendixes A through D provide supporting material as noted throughout the chapters.

CHAPTER 2

RESULTS OF STATE SURVEYS AND VISITS

One of the task requirements was to contact all state highway agencies to determine their practices in applying design standards for different classes of roads, varying traffic conditions, and other factors. Also, information was to be gathered on the processes used by agencies to consider safety in their design procedures and selection of roadway improvements. This information was obtained in two ways: 1) a questionnaire was sent to all 50 states, and 2) on-site interviews were conducted with 7 states: California, Louisiana, New York, Maryland, North Carolina, Michigan, and Washington. The results of that effort are discussed in this chapter.

STATE QUESTIONNAIRE

Appendix A provides the questionnaire that was sent to the 50 states. The responses to each question from each of the 37 states that returned the questionnaire were provided in the interim report (*2*) and need not be repeated here. The following sections discuss the principal findings.

Question 1: How much of the highway design is performed in-house versus by outside consultants?

The percentage of design performed in-house ranges considerably, but most states perform the majority of design themselves. This issue is important to this project only to the extent that whatever guidance or procedure is developed must find its way to engineering design firms as well as in-house staff. For both in-house staff and outside consultants, design standards, policies, and procedures are typically provided in the design manual, which is frequently supplemented by bulletins, directives, procedural memoranda, and the like.

Question 2: What is your state's design classification primarily based upon?

Most states (32 of 37) responded that they have adopted the AASHTO functional classification system as a basis for design elements. While most states claim that they follow the AASHTO functional classification system, a further examination of their design manuals and policy memoranda indicates that other factors dictate the selection of minimum values for certain design elements. For example, Maryland uses a "design designation" that considers functional classification (AASHTO modified), design/posted speed, traffic volume, control of access, intensity of development, and terrain. Another example is New York, where design standards for various geometric elements are based on road class (i.e., Interstate, primary roads, and secondary roads) and other factors, including area type (urban or rural), terrain type, design class (determined by design hourly volume), and design speed. Also, it appears that for 3R and 4R projects, states have minimum design criteria that are not exclusively based on functional classification and, in many cases, may be lower than AASHTO standards. The fact that many states use factors other than roadway classification makes it difficult to compare state design standards for specific elements with AASHTO's.

The design classification system is important to the issue of designing for safety because once a road is placed in a certain category, many of the design standards are predetermined with little variation. The design standards set for a specific class are considered "safe" for that type of road. If the designer meets even the minimum level for a specific design element, then it is presumed that an acceptable level of safety will be achieved.

Question 3: Does your state have an established process for explicitly considering the safety impacts of design decisions?

Slightly more than half of the states (20 of 37) indicated that they do have "an established process for *explicitly* considering the safety impacts of design decisions" [emphasis added here]. Some states believe that by following design standards, either AASHTO's or their own, which presumably already have been developed to meet safety requirements, they are considering safety. They and others responding "yes" cited their normal design review process.

None of the states indicated that it quantitatively assesses the safety impacts of design decisions as a normal course of design. However, some states, notably Alaska, Kansas, Massachusetts, Ohio, New York, and North Carolina, do perform some type of safety assessment. Several states, such as New York and Kansas, regularly conduct a safety investigation as part of the project scoping. The purpose of this investigation is to identify any particular locations (for an existing road) that are more hazardous (higher accidents) than would be expected (i.e., greater than critical accident rates for similar facilities).

In many states, 3R projects receive more scrutiny for safety. For example, the Arizona Department of Transportation (ADOT) has a procedure for identifying existing roadway design features and relating them to the applicable AASHTO-recommended design guidelines. Its procedure directly resulted from the FHWA requirement that federally funded projects conform to the design parameters of the AASHTO Green Book (*1*); if any one element does not, a formal design exception must be approved. ADOT follows the procedure, regardless of funding, for the following types of projects:

- New construction — grade, drain, and surfacing or grade and drain on new alignment
- Reconstruction of existing roadway
  - Realignment
  - Widening
- Resurfacing—overlays thicker than 1 in., mill and replace.

The procedure does not apply to projects that are normally singular in scope, are maintenance type, or are not spot improvements. Hence, it would not apply to projects involving seal coats, guardrail installation, and the like. In the procedural guide, ADOT requires the engineer to examine the following design criteria: lane and shoulder widths, vertical alignment, horizontal alignment, superelevation, SSD, design speed, grades, cross slopes, vertical clearances, bridge width, structural capacity, bridge rail, design traffic volume, and intersection sight distance. For these criteria, differences between existing and the desired AASHTO features are determined and evaluated so that recommendations can be made on the selected design level. No analysis procedure is prescribed other than "good engineering judgment." Accident history is among the factors considered.

For 3R projects in Alaska, a design study report is required that includes, among other considerations, the following:

1. A list of all existing horizontal and vertical curves that do not meet the current minimum design requirements of AASHTO for new construction
2. A discussion of the determination of lane widths and clear zone in accordance with their prescribed procedures
3. A discussion of horizontal curve and crest vertical curve treatments in accordance with their prescribed procedures
4. A discussion of accidents at intersections and what improvements may be made.

The report is to provide supportive calculations as appropriate. Figures 1 and 2, extracted from the *Highway Preconstruction Manual* (*3*) of the Alaska Department of Transportation, show the procedures for determining lane and shoulder width and cross-sectional elements, respectively, for rural two-lane paved highways. As shown in Figure 1, lane or shoulder width widening and/or improvements to the cross-sectional elements (i.e., sideslope, clear zone) are not required, if the accident rate for the project is equal to or less than the predicted accident rate, which is determined by applying a safety relationship model developed by Zegeer et al. (*4,5*). (This model is discussed in the next chapter.) If the accident rate is equal to or less than the predicted accident rate, then the width (lane and/or shoulder) is increased by 1 ft on each side for each 10 percent increment that the actual accident rate exceeds the predicted rate, with the limit being the width required for new construction. After the widening is established, then the cross-sectional elements need to be evaluated for change if the adjusted accidents exceed the predicted accidents.

If the roadway width is equal to or greater than that required for new construction, then the procedure outlined in Figure 2 applies. In this case, specific locations that have high accidents or other anomalies are evaluated site by site, but lane and shoulder width widening are not generally required. However, if the overall accident rate for the segment is greater than the predicted accident, again using the Zegeer model, then the cross-sectional elements need to be evaluated following specific design procedures.

This comparison of actual accidents to predicted accidents is also used in determining horizontal and vertical curve improvements. Reducing the degree of curvature and/or improving vertical curvature, and therefore SSD, is recommended if the actual accidents are equal to or greater than the accidents predicted from the appropriate model found in the Transportation Research Board (TRB) *Special Report 214* (*6*). However, the improvement must be found to be cost-effective following the procedures provided in Alaska DOT's manual. Both of these accident predictor models are discussed in the next chapter.

In all states there are improvement projects that merely involve resurfacing and, in most cases, changes are not made to the physical features of the road for safety purposes. In the early 1980s, resurfacing projects implemented by the New York State DOT (NYSDOT) were classified as either "Fast-Track" projects or as "Reconditioning and Preservation (R&P)" projects. Fast-Track projects consisted of simple resurfacing and restriping. R&P projects consisted of resurfacing with roadway and roadside safety improvements (e.g., slope flattening, removal or relocation of fixed objects, shoulder repairs, guardrail repairs, and superelevation changes).

At NYSDOT's request, an FHWA research study (*7,8*) was undertaken to evaluate the safety effects of resurfacing. Using accident and traffic data from 1975 to 1987 for roadway sections, FHWA developed statistical models for nonintersection accidents, intersection accidents, and fixed-object accidents. The models accounted for possible bias due to regression-to-the-mean and changes in traffic volume and uncontrolled factors, such as weather. The results indicated a negative safety impact from resurfacing at Fast-Track locations. The impact was most significant during the 30-month period immediately after resurfacing. Nonintersection accidents at Fast-Track locations increased by 21 percent during this period, while accidents remained relatively constant for the R&P projects. It was hypothesized that, after resurfacing, drivers may get a false sense of increased safety and may drive faster and less carefully. On the R&P projects, the perceived short-term decrease in safety from resurfacing was offset by the improvements to the roadway and roadside.

As a result of these research findings, NYSDOT developed the "SAFE-TRAK" program, which provides a process that includes safety criteria in selecting, scoping, and designing paving projects. SAFE-TRAK applies only to preventive and corrective maintenance resurfacing projects, typically consisting of a top and binder course. If a project passes the SAFE-TRAK screening criteria, it can be designed without having to do a complete 3R safety analysis. Appendix B provides the key elements of the process, including the checklist and accident worksheet.

It should be noted that the consensus on the states interviewed is that they are designing to minimums in all cases, because of budget constraints, limitations imposed because of right of way, environmental issues (e.g., wetlands), and other impediments. Also, safety considerations generally are not the overriding factors in selecting specific design features.

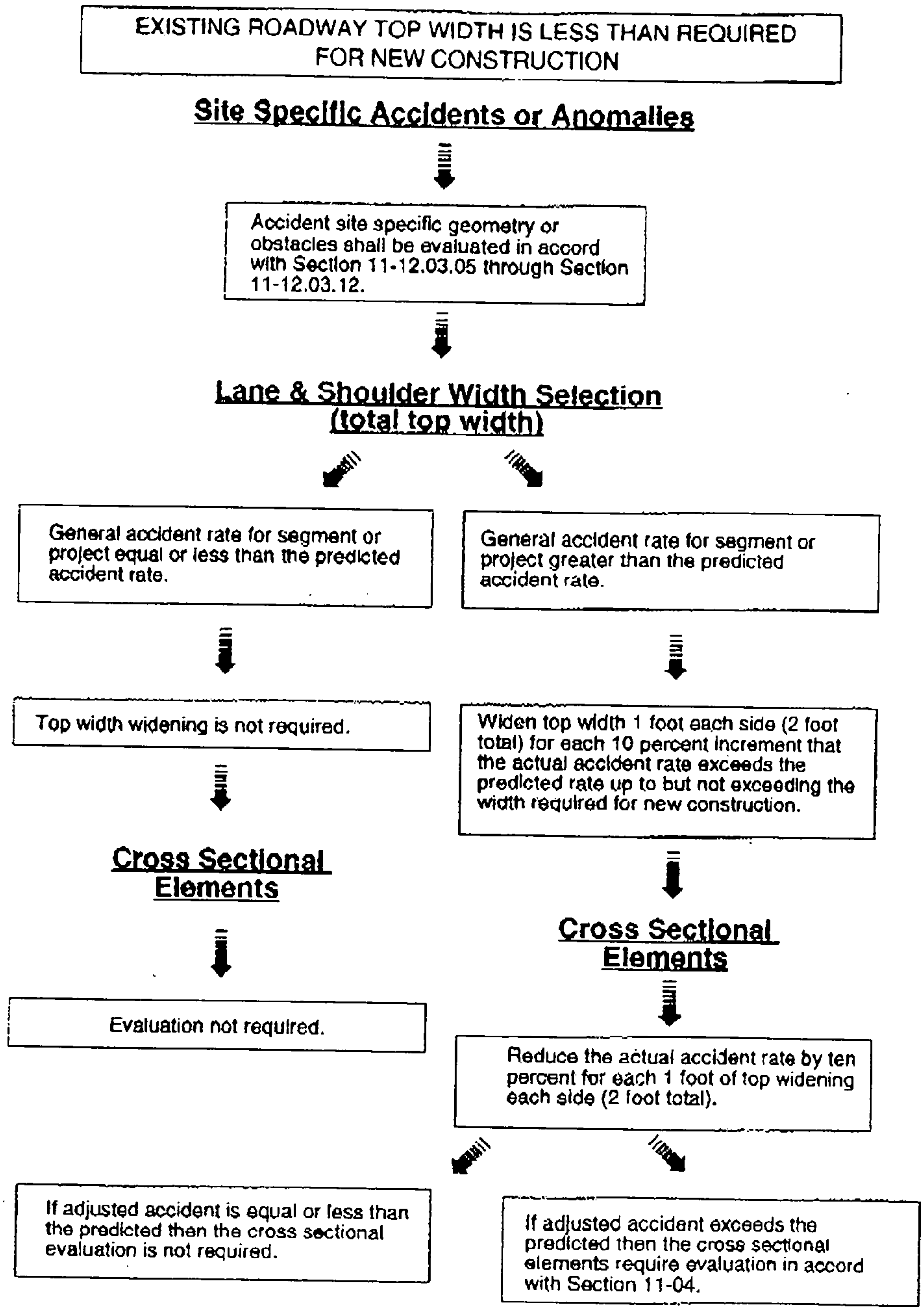

Figure 1. Alaska DOT procedure for determining lane and shoulder width on 3R projects (3).

Question 4: Does your state have a policy or procedure for conducting a cost-effectiveness analysis of alternative design levels considering the construction costs versus accident potential?

Thirteen states responded "yes" to having a policy or procedure for conducting a cost-effectiveness analysis that considers accident potential. Several indicated that they use the ROADSIDE program from AASHTO's *Roadside Design Guide* (9), although during the interviews some states indicated they found the procedure not applicable to their situation.

Several states use a cost-effectiveness or benefit/cost analysis to establish if a highway improvement is economically viable, and such analyses are frequently done specifically for safety improvements. Of the states that provided information, Alaska, Iowa, Minnesota, and New York appear to have the most formal, analytical approach. Iowa's benefit/cost analysis procedure,

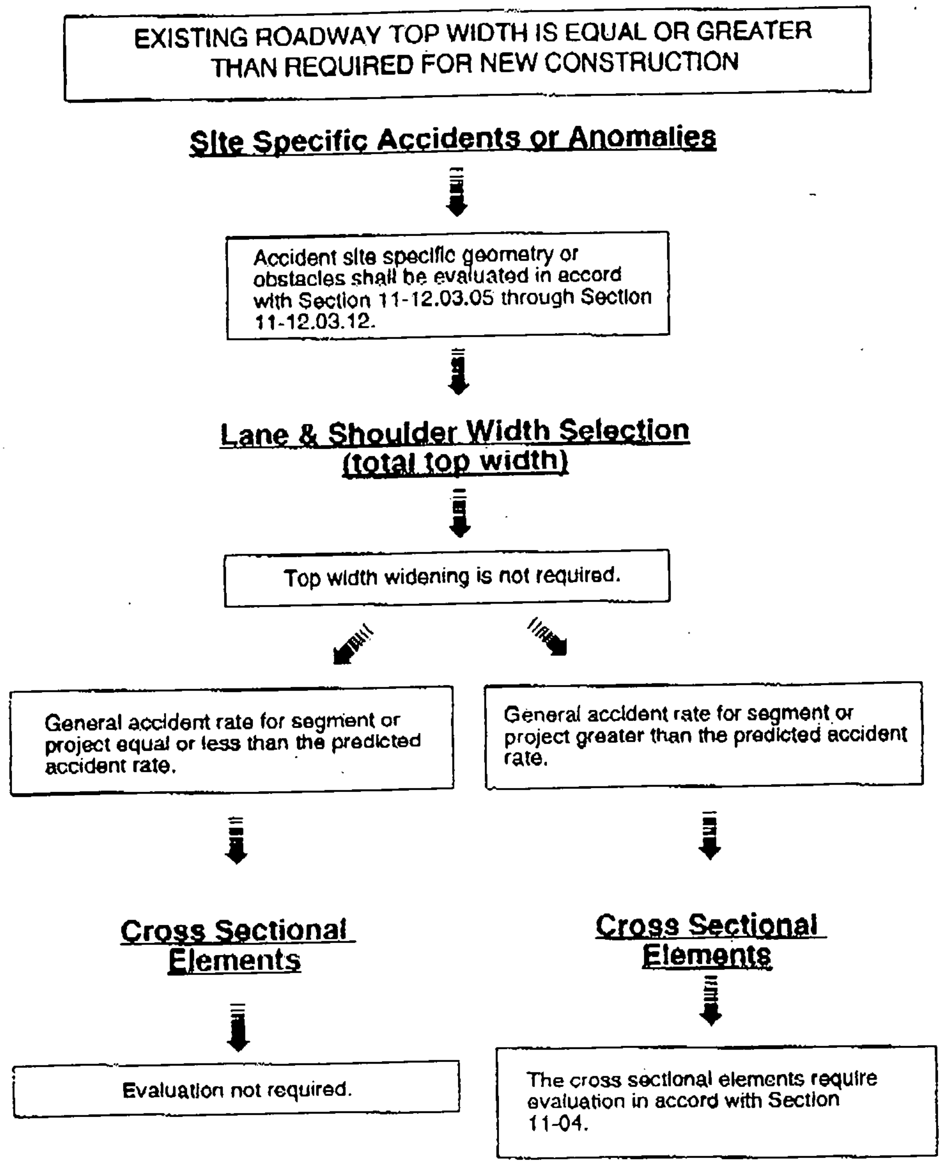

Figure 2. Alaska DOT procedure for determining need for cross-sectional improvements on 3R projects (3).

which is shown in the form in Figure 3 for a rural roadway section, is fully described in its Instructional Memorandum presented in Appendix C. Although the memorandum refers to rural secondary roads, the procedure is also followed on Iowa's primary system.

To determine the safety benefits, ARFs are assigned to the improvement. Table 2 lists ARFs for roadway improvements that are used by NYSDOT in its cost-effectiveness analysis procedure. The factors come from either its own safety evaluations or from other sources (*10*). Iowa also uses ARFs, which are listed in Appendix C. Several states indicated the need to improve upon (in terms of applicability and reliability) the ARFs.

Question 5: Does your state have a formal design review process that specifically considers safety concerns?

A majority of the states (25 of 37) responded "yes" to having a formal design review process that specifically considers safety. Most responded that other offices (e.g., traffic, construction) review the plans for areas of their concern. Both Ohio and North Dakota indicated that for 3R projects they conduct a specific safety study and issue a report. In all the states the reviews appear to be by experienced personnel from different departments. No checklists or documented procedure for conducting the review were uncovered.

Question 6: For which design elements do you frequently conduct trade-off analyses?

A tabulation of the items mentioned is as follows:

- Flatter sideslopes versus barriers—20 responses
- Roadside obstacle removal versus protection—5
- Lane width and/or shoulder width—7

```
                                        ROAD SECTION
                                  BENEFIT/COST DETERMINATION

COUNTY   ENTER COUNTY                                              PREPARED BY DRE        DATE 06/10/92
LOCATION FROM  - TO

================================================= IMPROVEMENT ACTION =================================================

PROPOSED IMPROVEMENT       RECONSTRUCT VERTICAL CURVES AND FLATTEN FORESLOPES
ESTIMATED IMPROVEMENT COST (EC)      $2,583,000                    ESTIMATED IMPROVEMENT LIFE (Y)      20 YEAR
ESTIMATED ACCIDENT
          LOSS REDUCTION    (LR)            36%
    AVERAGE ANNUAL COST= EC/Y                           $129,150
          OTHER COSTS(if applicable)                          $0
                                                     ---------
      TOTAL ANNUAL COST (C)                             $129,150

==================================================== TRAFFIC DATA ====================================================

SOURCE   VOLUME OF TRAFFIC ON PRIMARY ROAD SYSTEM                                      YEAR      1990
ADVM(VM)=    11521
PRESENT AVERAGE ANNUAL VEHICLE MILES   (AM)=(VM)(365)(1E-08)   =        0.042 HMVM
PROJECTED ANNUAL GROWTH (G)                    2%
PROJECTED AVERAGE ANNUAL VEHICLE MILES   (PM)= AM{1+(1+G)^Y}/2  =       0.052 HMVM

=   ===================================================================================================================

TIME PERIOD    (T)          JULY 1,1986 THROUGH JUNE 30, 1991                                =     5 YEARS

     0  FATAL ACCIDENTS          0  FATALITIES                        @ $500,000 =          0
     5  INJURY ACCIDENTS         1  MAJOR INJURIES                    @ $100,000 =     100000
                                 3  MINOR INJURIES                    @ $6,000   =      18000
                                 5  POSSIBLE INJURIES                 @ $1,500   =       7500
    14  PROPERTY DAMAGE ONLY                                                            39932
    19  (TA) TOTAL ACCIDENTS                                     TOTAL $ LOSS  ($L) =  $165,432
$ LOSS PER ACCIDENT ($A)= $L / TA   =      $8,707
ACCIDENT RATE (AR)= TA /{(AM)(T)}   =          90

=======================================================================================================================

PROJECTED TOTAL VEHICLE MILES (TM)= (PM)(Y)                =         1.05  HMVM
PROJECTED TOTAL ACCIDENT LOSS (P$)=($A)(AR)(TM)            =     $822,510
PROJECTED TOTAL BENEFIT (PB)= (P$)(LR)                     =     $292,814
PROJECTED ANNUAL ACCIDENT BENEFIT (AB)= PB/Y               =      $14,641
OTHER PROJECTED ANNUAL BENEFITS (if applicable) (OB)   =               $0
                                                              ---------
   TOTAL PROJECTED ANNUAL BENEFIT (B)=(AB)+(OB)        =          $14,641

                                BENEFIT/COST           =             0.11
```

Figure 3. Benefit/cost analysis procedure followed by Iowa DOT.

- Vertical alignment for more sight distance versus excavation cost—2
- Change in posted speed—1
- End treatments for culverts—1
- Horizontal offset to fixed objects versus alignment shift—1
- 3R/4R projects—1
- Narrow medians with barriers versus wide medians without barriers—1
- Level of service—1.

As indicated above, by far the states responded that issues of roadside design, such as clear zone, sideslope, and obstacle removal/protection, most often require a trade-off analysis. On the basis of discussions during the state interviews, researchers found that states are more likely to use guardrail or other protective devices rather than provide a wide clear zone with flat slopes for the median or roadside. They would like to have as much guidance as possible in making decisions on alternatives for roadside design.

The second most frequent trade-off analysis relates to either

TABLE 2. Accident reduction factors used by New York State Department of Transportation

IMPROVEMENT DESCRIPTION	ALL ACCIDENT REDUCTION FACTORS %	REMARKS
PAVEMENT WIDENING, NO LANES ADDED	25	(Ref 1)
Widen travelway from 9 feet	21 (N)	PIES data
Widen travelway from 10 feet	41 (N)	PIES data; reduces collisions with fixed objects 47%, head-on 47%
DIVIDED HIGHWAY, FLUSH MEDIAN ADDED	44	Limited PIES data
SHOULDER WIDENING OR IMPROVEMENT	25 (N)	Limited LCAC data
Widen Existing Shoulder	17	(Ref 2); for two-lane roads only
FLATTENING OF SIDESLOPES	46	Reduces collisions with fixed objects 67%, limited PIES data
Widen Existing Bridge or Major Structure	-	Reduces 65% of collisions with bridge structure (Ref 1)
ALIGNMENT WORK		
Horizontal Alignment Changes	60	Reduces fixed-object accidents 84%, ROR 91%, and head-on 71%
Vertical Alignment Changes	-	No PIES data
Combination of Horizontal & Vertical	32 (N)	Limited PIES data. General reconstruction 20% (Ref 3), 21% (Ref 1)
INSTALL MEDIAN BARRIER	19	
IMPROVE DRAINAGE AND/OR DRAINAGE STRUCTURES	31	Reduces collisions with culvert hard wall, ditch 85%

Notes:
N = Not statistically significant
PIES = Post Implementation Evaluation System
LCAC = Low Cost Accident Countermeasure Evaluation

References:
1. FHWA/DOT, Evaluation of the Highway-Related Safety Program Standards, 1977. (Compilation of safety project evaluations reported by states)
2. Calif. Dept. of Transp., Accident Rates vs. Shoulder Width, CALTRANS 1977. (Before and after studies of projects in Calif. with tabulated statistics included)
3. Tamburri, Thomas N., "Accident Reduction Factors for Highway Safety Projects," State of Calif. Transp. Agency, Dept. of Publ. Works Div. of Highways, 1969. (Before and after studies of 500 projects in California)

the lane width or shoulder width or the two combined. The issue of how narrow can travel lanes and shoulder widths be and still provide an acceptable level of safety was mentioned during the state interviews.

Question 7: Which design elements most frequently require design exception reports?

The following are the elements for which there was more than one response:

- Shoulder width—21 responses
- Vertical alignment (curvature)—12
- Lane width—11
- Horizontal alignment (curvature)—11
- SSD (relates to vertical and horizontal alignment)—7
- Bridge width—6
- Maximum grade—6
- Clear zone—5
- Sideslopes—5
- Lateral clearance—4
- Superelevation—4
- Reduced design speed—3
- Existing bridge rail—2
- Cross slopes—2
- Vertical clearance—2.

The responses to this question and the previous question indicate which design elements are more critical than others and for which design guidance related to safety is most needed. According to the responses from the previous question, trade-off analyses are most often conducted for issues related to the roadside, specifically the removal versus protection of obstacles (i.e., barriers) and flattening of sideslopes. According to the responses to this question, design exceptions are required most often for shoulder and lane width and for horizontal and vertical curvature. Hence, emphasis should be placed on these basic elements of design.

It is worth noting that the FHWA has established 13 controlling criteria for which formal approval is needed for a design exception. These criteria are design speed, lane and shoulder width, bridge width, structural capacity, horizontal and vertical alignment, grade, SSD, cross slope, superelevation, and vertical and horizontal clearance (other than the clear zone).

Question 8: Do you have a formal procedure/format for design exception reports?

A majority of the states (26 of 37) indicated they do have a formal procedure/format for design exception reports. Several of the states cited the FHWA policy that requires certain information to approve a design feature that is less than the minimum AASHTO design level for federal-aid highway projects. The policy calls for an analysis of related accident data and even a cost-effectiveness analysis of alternatives, if the data are available. The procedures in Ohio, Texas, North Carolina, New York, Maine, Arizona, Alabama, and Iowa appear to be more formal. Appendix C provides the Instructional Memorandum on the design exception approval process followed by Iowa DOT.

On the basis of discussions during the state interviews, it would appear that this project can be of most benefit in this area. The states need guidance on appropriate procedures and accident-design relationships to conduct the required analyses.

Question 9: Please rank which of the following would be of most help to designers or reviewers as an aid for considering safety in design?

The purpose of this question was to establish what the states believe would be most helpful to designers in considering safety in design. This question was probably difficult to respond to without some explanation of the kind of information that would be provided for each of the options. Indeed, one respondent said "would need examples of each before I could rank the options." This lack may be the reason for a wide variation in the responses. Also, two states that were interviewed modified their answers to this question after it was discussed.

Sixteen of the 37 respondents ranked the "step-by-step process with built-in accident/design element relationships for conducting cost/safety trade-off analysis for design elements" as their number one choice. Of those, nine would prefer to have the procedure computerized. During the state interviews, it was nearly unanimously stated that "research documents, even manuals," rarely get used in a meaningful way. Because of this situation, some of those interviewed thought that a computer program would facilitate or increase the probability that the procedure would be followed.

The second highest option (12 of 37) was for a "concise listing of minimum (or maximum) values which would define limits for 'safe' designs for different types of roads." While such a list would be easy to incorporate into design manuals or design policies, a concern expressed by those interviewed was that the values suggested by this project might not be acceptable to specific states, especially if the values were higher than those already established.

Surprisingly, only two states gave option c) nomograph, tables, or figures for inclusion into design manuals, a number 1 ranking. However, this option was mentioned as a desirable product by at least two states during the interviews.

Question 10: Has your state conducted or sponsored any research on the safety effects of any design elements which has resulted in a change in your design standard?

No states offered any research that they sponsored that would be relevant to this project.

KEY POINTS FROM STATE INTERVIEWS

On-site interviews were conducted with representatives of the following states: California, Washington, Louisiana, North Carolina, Maryland, New York, and Michigan. The complete visit report for each of the states was provided in the interim report (*2*) and will not be repeated here. This section presents by state some key points and issues resulting from those interviews.

California

1. The project should identify which design elements are most critical to safety and, therefore, should not be varied.
2. California would like guidance on how to deal with design speed because in some cases (especially level, tangent sections) actual speed can be higher than the required design speed for the selected class of road.
3. Is bridge widening always necessary? It is a high-cost item that can preclude implementing a project with other safety enhancements.
4. A frequent design choice, where guidance is needed, is median width versus use and design of barrier.
5. California would like to see "design thresholds" suitable for a design manual.
6. The state expressed skepticism of research-based mathematical relationships of safety versus design levels unless they are based on state accident statistics.

Washington

1. As a product, Washington would like to see a nomograph, table, or chart that would provide "minimum/desirable" standards for various design elements. Whatever is developed must be easy to use to promote acceptance by the designer.
2. A key trade-off for design is the choice of protecting versus removing versus designing breakaways for roadside obstacles.

Louisiana

1. The state relies on AASHTO standards, which it believes provide a safe design. Louisiana is reluctant to consider any procedure that would require it to evaluate its design decision on safety impacts.

North Carolina

1. Safety becomes a design consideration only if the accident rate for the project is above the statewide average for the type of facility.
2. As to needed information, North Carolina is particularly interested in specific information and guidance on the safety relationships between pavement and shoulder widths, on the degree of horizontal curvature, and on roadside slopes. It needs better information relating the safety benefits of higher than minimum design values to justify increased construction costs.

Maryland

1. Designers need to know the "threshold values" of design for specific elements below which they should not go because of safety concerns.
2. Safety concerns should not be limited to just a specific design element, but to the entire project limits (i.e., design consistency).
3. One of Maryland's most frequent trade-off issues is safety grading versus barrier installation.

New York

1. For most of its projects, New York requires a scoping document that defines the intended range of a project's physical, operational, financial, and environmental requirements. The state requires an accident analysis, which is to include an analysis of the 3 previous years of accident data, an analysis of the clear zone, and nonstandard features.
2. The design elements most frequently requiring design exceptions include SSD related to vertical curvature, shoulder width, and horizontal curvature.

Michigan

1. Michigan has used the ROADSIDE computer program but finds it too subjective and too easily manipulated to arrive at "wanted" conclusions. The state believes that procedures or models, such as the ROADSIDE program, need to be calibrated to individual states' experiences.
2. Michigan would like better guidance on the volume level in areas where flatter roadside or guardrail is warranted. There are too many low-volume roads where guardrail has never been hit.
3. Design elements most frequently requiring design exception reports include superelevation, shoulder width, and bridge width.
4. The state's preference for a product is a step-by-step process for conducting an accident analysis (i.e., predicting accident change) possibly coupled with construction cost for conducting a benefit/cost analysis. Also, it believes it needs good ARFs for alternative improvements.

CHAPTER 3

MODELS TO PREDICT SAFETY EFFECTS OF DESIGN ELEMENTS

One of the objectives of this research was to identify and describe the relationships between safety and geometric design elements that have been developed from research. In this context, safety was defined in terms of the frequency and severity of motor vehicle crashes. For this research, geometric design elements that were investigated were categorized into the following groups:

- Roadway cross-section — including lane width, shoulder width, and pavement width
- Horizontal alignment — including degree of curvature or radius, superelevation, and spiral transition curves
- Vertical alignment — including grade, length of grade, and lengths of crest vertical curves
- Median width
- Roadside — including clear zone width and sideslopes.

Appendix D provides the complete findings of the literature review. In this chapter, an assessment is made for each of those five categories of design elements, as well as the applicability and viability of the "best" models available for evaluating the safety impacts of alternative design features. Also, the results of the application of each model to a case study are presented.

ROADWAY CROSS-SECTION DESIGN

Assessment of Literature Findings

Despite the assumption that pavement width significantly affects safety, there is still little empirical information on the relationship of lane or pavement width, by itself, to safety. Some empirical evidence, and engineering judgment, indicate that 12-ft lanes are "safe" (13-ft lanes are probably safe too but not cost-effective, and even wider lanes may be less safe), 11-ft lanes are "safe enough" for urban situations, and 10- and even 9-ft lanes will "work" under conditions of low speed, low volume, and little wide-vehicle (e.g., trucks and buses) traffic.

ARFs that were developed by Zegeer et al. for FHWA studies (*4,5*) represent the best information for two-lane rural roads until more data can be collected and analyzed; however, because the research considered other interrelated design features that logically affect safety, one should be cautious in applying the results to determine the safety effects of lane widths alone. Decisions on changes to lane (travelway) width for two-lane roads are usually made considering shoulder width as well.

On the basis of the literature, substantial evidence indicates that, in general, increasing the shoulder width will effect an accident reduction. This general statement applies for existing roads with shoulders of fewer than 6 ft and up to 8 ft. Because the data base is much more extensive, the ARFs for two-lane rural roads reported by Zegeer are probably the best estimate to be used cautiously for determining the safety effect of shoulder widening. However, decisions on additional shoulder width are usually not made without considering changes in lane width as well.

Accident Prediction Model

A 1986 FHWA study (*4*) by Zegeer et al. attempted to establish a relationship of safety to lane width, shoulder width, and other factors on two-lane rural roads. The researchers quantified the effects of lane width, shoulder width, and shoulder type on highway crash experience based on an analysis of data for nearly 5,000 mi of two-lane highway from seven states. The following accident prediction model resulted from that study:

$$AO/M/Y = 0.0019\,(ADT)^{0.8824}\,(0.8786)^{W}\,(0.9192)^{PA}\,(0.9316)^{UP}\,(1.2365)^{H}(0.8822)^{TER1}\,(1.3221)^{TER2} \quad (1)$$

where

$AO/M/Y$ = related accidents (i.e., single-vehicle plus head-on plus opposite-direction sideswipe plus same-direction sideswipe accidents) per mile per year
ADT = average daily traffic
W = lane width
PA = average paved shoulder width
UP = average unpaved (e.g., dirt, gravel, turf, stabilized) shoulder width
H = roadside hazard rating, which is a subjective measure of hazard associated with the roadside environment. The user must assign a value on a scale of 1 to 7 (least to most hazardous) based on a visual assessment of the section. For sections with varying roadsides, the roadside hazard rating should represent a "middle" value.
$TER1$ = 1 if terrain is flat, otherwise 0
$TER2$ = 1 if terrain is mountainous, otherwise 0

An *Informational Guide* (*5*) includes a step-by-step procedure for applying the model. It also describes the procedure for conducting an economic analysis to determine project cost-effectiveness.

A microcomputer program that automates this cross-section procedure has been developed and is available. The ECSD program, which stands for Evaluation of Cross-Section Design (Version 1.1), allows users to input data on the existing or proposed cross-section design and then modify selected parameters to create design alternatives. The program is fairly simple to use and does not require extensive learning or training to be properly and efficiently applied. Moreover, there are several embedded quality control checks in the program. One check compares the number of related accidents entered by the user with the number that would be estimated by applying the accident prediction model. If the difference in the annual average related accident frequency is more than 30 percent of the expected value, a warning message is issued. The suggestion is to use the accident prediction approach rather than the actual data.

Assessment of Model

The model is applicable only to two-lane, rural highways. It cannot be applied to multilane highways or freeways. Because the estimation of safety benefits relies on a set of ARFs, the procedure appears to be more appropriate for evaluating alternative cross-section improvements to existing two-lane rural roads.

The authors caution that the model and, therefore, the ARFs that are presented are limited to the following:

- Lane widths of 8 to 12 ft and shoulder widths of fewer than or equal to 10 ft
- Two-lane, two-way paved rural roads on state primary and secondary systems
- ADTs of fewer than 10,000 vpd
- Homogenous roadway sections, which do not include the additional accidents expected at intersections.

Besides the caveat that these reduction factors apply only to two-lane rural roads of ADT of up to 10,000 vpd, the researchers note that the predicted accident reductions are valid only when the roadside characteristics (sideslope and clear zone) before widening are reestablished. The model was determined to have a relatively low R^2 (squared value of the multiple correlation coefficient that establishes the amount of the variation in the independent variable accounted for by the model); therefore, the accuracy of the reduction factor is questionable.

The procedure does not consider the effects of horizontal or vertical alignment, the frequency of horizontal curves of greater than 3 degrees, the frequency of sight-restricted vertical crest curves, the percent grade, the frequency of access points, driveways and intersections, average operating speeds, or design speeds.

Although no minimum section/project length is specified in the *Informational Guide*, the application of the procedure to individual spot locations appears to be limited. The procedure does not consider the effects of upstream alignment or grade on the frequency or severity of run-off-road accidents at a spot location. The procedure does not consider the degree of curvature or length of individual horizontal curves. On the basis of accident data findings, one would expect that horizontal alignment does influence run-off-road accidents.

Cross-Section Model Case Study

The cross-section model was applied to a 3R project provided by NYSDOT. The functional classification of the two-lane highway is minor arterial. The project length was 5.3 miles through rolling terrain in a rural/residential area. The existing pavement had 10-ft lanes with approximately 2 ft of paved shoulders. Additionally, there was an unpaved 3-ft shoulder. Traffic volumes on the road ranged from approximately 9,500 to 10,000 vpd.

In addition to restoring the surface condition of the pavement, the project also widened the lanes to 11 ft and widened the paved shoulders to 6 ft. Numerous other improvements, not considered by the cross-section model, were included as well (e.g., installation of new guide wire, pavement markings, signing, and improvements to drainage).

Three years of accident data were available for the period preceding the reconstruction project. According to the design report, the overall accident rate for the section was within 5 percent of the statewide average at that time for that type of facility. There were 86 accidents of the type related to the model (i.e., single-vehicle, head-on, same-direction and opposite-direction sideswipes) during the period for which accident data were available.

No photographs of the existing or as-built highway section were available for use in assigning the roadside hazard rating that is part of the model. On the basis of the description of the highway section in the design report for this project, the roadside hazard rating was taken to be 5 for both the "before" and "after" conditions.

Table 3 shows the actual and predicted related accident rates for the existing conditions. Also shown are the accident rates predicted by the model for the five design alternatives (i.e., the design as constructed and the four additional designs considered for this case study). The ARFs shown are relative to the predicted accident rate for the existing conditions, not the actual accident rate, because of the significant difference between the actual and predicted accident rates for the conditions. No accident data for the "after" condition were available for comparison.

In reviewing the data in the table, the following observations were made. The model predicted a lower accident frequency than what actually occurred for the existing conditions. Although the predicted accident frequency (54.86) was only 64 percent of the actual, this difference may be an acceptable error when considering the merits of the alternatives. For the five alternatives, the improvement should have reduced the number of related accidents (compared with the lower predicted value) by 22 percent. However, by adding another foot of lane width (alternative 4) the accident reduction is estimated to be 32 percent. The other options have smaller safety improvement values. This additional 10 percent reduction means that about 27 more accidents would be eliminated in 15 years (a project life span). At an average accident cost of $53,700 (recommended by Zegeer in the *Informational Guide*), that would be a savings of $1,449,900 in 1987 dollars. A more formal economic analysis, as suggested in Zegeer's *Informational Guide*, might reveal that this savings would warrant the cost of additional widening.

TABLE 3. Existing and predicted accident rates for case study employing the cross-section model

	Lane Width (ft)	Paved Shoulder Width (ft)	Unpaved Shoulder Width (ft)	Accidents per Mile per Year	Accidents per 5.3 Miles per 3 Years	Accident Reduction Factor
Existing	10	2	3	5.41 (Actual)	86.00 (Actual)	N/A
				3.45 (Predicted)	54.86 (Predicted)	
As Built	11	6	0	2.68	42.56	22%
Alt. 1	12	0	5	2.74	43.50	21%
Alt. 2	12	5	0	2.56	40.68	26%
Alt. 3	12	4	2	2.42	38.41	30%
Alt. 4	12	6	0	2.35	37.40	32%

VERTICAL ALIGNMENT DESIGN

Assessment of Literature Findings

The available data and documented studies are not sufficient to allow any definitive conclusions about the relationship of vertical alignment elements to highway safety. A study (*11*) that used data from FHWA's Highway Safety Information System (HSIS) appears to indicate that crest curves with large grade differentials have noticeably higher accident frequencies. However, data on the available SSD, measured from a 3.5-ft eye height to a 6-in. object height, were not known and, therefore, were excluded from that analysis. In the available documentation, it was not explicitly stated if these crest vertical curves were from all roadway types or only rural roads or only two-lane, rural roads. It was also unclear if the effect was because of other factors (e.g., the presence of an intersection). Moreover, it is not clear what the lengths of vertical curve were or if they conformed to current AASHTO minimum length standards.

It should be noted that lengthening substandard curves may not necessarily be cost-effective, especially if an extremely deficient crest is upgraded to provide SSD that corresponds to a design speed that is still below the highway operating speed. Recognizing the substantial costs to lengthen existing vertical curves, one report (*12*) concluded that "lengthening vertical curves to eliminate stopping sight distance deficiencies may only be cost-effective on roadways with high ADT levels where other significant hazards are present within the sight obstruction."

In summary, the available information suggests the following with respect to the vertical alignment:

1. Crest vertical curves with large grade differentials (i.e., greater than 6 percent) pose a higher risk in terms of accident potential to drivers than crest vertical curves with small grade differentials.
2. Steep (i.e., greater than 4 percent) upgrades and downgrades pose a greater hazard, especially with respect to accidents involving trucks.
3. The accident potential is much greater for horizontal curves on or immediately after grades steeper than 3 percent.

Accident Prediction Model

In *Transportation Research Record 923*, a paper by Neuman and Glennon (*13*) described a theoretical model that related accidents on crest curves to available sight distance. The development of this model was not based on accident data. Rather, the model relied on intuitively logical relationships and engineering judgment. The model can be used by highway designers to systematically evaluate the cost-effectiveness of spot improvements for locations with deficient SSDs. The model, which was also described in *Special Report 214* (*6*), is as follows:

$$N = AR_h\,(L)\,(V) + AR_h\,(L_r)\,(V)\,(F_{ar}) \qquad (2)$$

where

- N = number of accidents on a segment of highway containing a crest curve
- AR_h = average accident rate for the specific highway, or alternatively for the related general highway class, in accidents per million vehicle miles (PMVM)
- L = length of highway segment in miles
- V = traffic volume, in millions of vehicles
- L_r = length of restricted sight distance in miles
- F_{ar} = a hypothetical accident rate factor that varies according to both the severity of the sight restriction and the nature of the hidden hazard

The length of sight restriction, L_r, can be estimated as follows:

$$L_r = (a_o + a_1 A)\,(1/5280) \qquad (3)$$

where

a's = constants identified in Table 4

TABLE 4. Constants used for determining length of restricted sight distance (L_r) by equation 3 (5)

Highway Operating Speed on Vertical Curve (mi/h)	Highway Design Speed (mi/h)							
	60	55	50	45	40	35	30	25
	Values of a_o							
60	-524	-138	-25	113	202	256	305	382
55		-452	-163	11	111	172	221	301
50			-405	-65	45	115	169	248
45				-332	-76	21	82	167
40					-272	-55	15	110
35	No sight restrictions					-231	-74	51
30							-193	19
25								-130
	Values of a_1							
	207.3	152.6	120.9	80.2	56.6	28.6	29.4	15.3

A = absolute value of the grade differences, in percent

To use Table 4, the SSD for existing curvature conditions must first be calculated and then used to determine the applicable highway design speed. The SSDs can be calculated using the following equations:

$$SSD = [(7.017 \times 10^6)(L_{vc})/A]^{0.5} \text{ for } SSD < L_{vc} \quad (4)$$

$$SSD = 2{,}640(L_{vc}) + 664.5/A \text{ for } SSD > L_{vc} \quad (5)$$

where

L_{vc} = length of vertical curve in ft

With respect to the accident rate factors, the severity of the SSD restriction was defined to be the difference between the prevailing running speed and the design speed that corresponds to the available SSD. For example, the available SSD may correspond to a design speed of 40 mi/h. If the prevailing speed is 55 mi/h, then the severity of the restriction would be computed as /40-55/ = 15. Three categories were defined for the nature of the hidden hazard, which can be categorized as a minor hazard (e.g., shallow curve or mild downgrade), a significant hazard (e.g., a low-volume intersection, an intermediate curve, or a moderate downgrade), or a major hazard (e.g., a narrow bridge, a sharp curve, a steep downgrade, a high-volume intersection, or a Y-diverge). The hypothesized accident rate factors are presented in Table 5.

Although not validated, this model represents the best known relationship at this time, because of the few logically supported relationships between crest vertical curve length and accidents. More detailed documentation on how to properly apply this model can be found in the two cited references (*6,13*).

Assessment of Model

The model is only applicable to existing two-lane, rural roads with crest vertical curves that do not meet current AASHTO SSD standards. The procedure does not appear to be useful if the designer is performing trade-off analyses of different vertical alignment schemes, ranging from crests that satisfy or even exceed existing curve length minimums to crests that, because of physical constraints, violate (but not greatly) current AASHTO minimums. The major criticism of this model is that it has not been validated using real accident data. Hence, the relationship, albeit logical, requires a degree of faith. According to the authors, the model is likely to overestimate the detrimental effects of restricted sight distance. Consequently, care is urged when applying it. Designers should understand that it probably yields an upper bound for accident reductions resulting from increasing SSD on vertical curves on which conditions do *not* meet AASHTO standards.

Vertical Curve Model Case Study

The case study presented here to illustrate the use of the vertical curve model is hypothetical because of the lack of an appropriate actual project from a state. For this case study, the following assumptions were made regarding the conditions:

1. The vertical curve is provided to modulate from a 4 percent upgrade to a 4 percent downgrade.
2. The length of the vertical curve, L_{vc}, is 455 ft.
3. The operating speed is 55 mi/h.
4. The traffic volume is 5,000 vpd (equates to 1.825 million vehicles for V for a 1-year analysis period).

TABLE 5. Hypothesized accident rate factors for evaluating SSD restrictions (5)

Character of Geometric Condition within SSD Restriction	Severity of SSD Restriction—Amount Design Speed Is Less than Prevailing Speed (mi/h)				
	0	5	10	15	20
Minor Hazard	0.0	0.3	0.5	1.2	2.0
Significant Hazard	0.4	0.8	1.1	2.0	3.0
Major Hazard	1.0	1.4	1.8	2.8	4.0

TABLE 6. Vertical curve model case study summary

Design Alternative	AASHTO SSD (ft)	Length of Vertical Curve, L_{vc} (ft)	Accident Reduction Factor
Existing	275	455	N/A
Design Speed = 45 mi/h	325	635	26%
Design Speed = 50 mi/h	400	965	31%
Design Speed = 55 mi/h	450	1220	52%

5. The degree of hazard in the sight-restricted area is classified as significant.
6. The average accident rate, AR_h, is 2.4 accidents PMVM.

For the purposes of this case study, the degree of hazard for each improvement alternative was assumed to remain the same as that in the existing conditions. In other words, improvements intended to decrease the degree of hazard in the sight-restricted area would not be implemented. Rather, this case study assumed improvements related to increasing the SSD as a result of flattening the vertical curve.

Using equations 4 and 5 and the AASHTO criteria for SSD, it was determined that the existing geometry corresponds to a design speed of 40 mi/h, yielding a 15 mi/h deficiency between the operating speed and the design speed. Three alternative improvements to upgrade the vertical curve were considered for this case study. These alternatives were to provide SSD appropriate for either 45, 50, or 55 mi/h design speeds.

Table 6 summarizes the results of this case study. For each of the design alternatives, the corresponding SSD, length of vertical curve, and predicted ARF are shown. These ARFs should be interpreted as the upper limit of the potential safety benefits from flattening the curve. According to the documentation, these potential benefits are the result of optimistic assumptions built in the model for evaluating countermeasure effectiveness.

The ARFs shown in Table 6 were calculated according to the method presented in *Special Report 214 (6)*, as follows:

$$ARF = \frac{\Delta N}{N} = \frac{\Delta\,(L_T\,F_{ar})}{(L_{vc}) + (L_T\,F_{ar})} \qquad (6)$$

In this equation, the denominator represents the existing conditions while the numerator represents the changes due to improvements. The effect of vertical curve improvements is best estimated by applying this ARF to the known number of accidents. The next best estimate, in the absence of historical accident data, is to use the most reasonable estimate for the average accident rate, AR_h, in the following equation:

$$\Delta N = AR_h(V)\,[\Delta(L_T\,F_{ar})] \qquad (7)$$

As seen by the ARFs, a significant accident reduction may be realized by increasing the SSD, especially if the design speed is brought up to the operating speed. However, this case is hypothetical and these findings should be checked with an actual project with "after" accident data to find if either alternative is cost-effective.

HORIZONTAL ALIGNMENT DESIGN

Assessment of Literature Findings

On the basis of the available literature, sufficient evidence appears to indicate that, in general, horizontal curves experience higher accident rates than tangents and that the accident rate generally increases as a function of increasing degree of curvature. However, the relationship between horizontal curvature and accident rate is influenced by other interrelated variables. A synthesis of past research (*14*) has identified a wide variety of traffic, roadway, and geometric factors that have an effect on the safety of horizontal curves. These factors include the following:

- Traffic volume on the curve and traffic mix (e.g., percent trucks)

- Curve features (e.g., degree of curve, length of curve, central angle, superelevation, presence of spiral or other transition curves)
- Roadside hazard on the curve (e.g., clear zone, sideslope, rigidity, types of obstacles)
- Cross-sectional curve elements (e.g., lane width, shoulder width, shoulder type, shoulder slope)
- SSD on curve (or on curve approach)
- Vertical alignment on horizontal curve
- Distance to adjacent curves
- Presence/distance from curve to nearest intersection, driveway, bridge, etc.
- Pavement friction
- Presence and type of traffic control devices (e.g., signs and delineation).

With respect to the effect of traffic and geometric variables on the accident occurrence on horizontal curves, a 1985 FHWA research study (*15*) concluded the following:

1. The proportion of accidents that are single-vehicle, run-off-road accidents substantially increases as ADT decreases.
2. Roadside character appears to be the most dominant contributor to the probability that a highway curve has a high reported accident rate.
3. Other measurable contributors to the probability of high reported accident rate are highway curve radius, highway curve length, shoulder width, and pavement skid resistance. No identifiable contributions were found for roadway width, superelevation rate, shoulder type, approach alignment and sight distance, superelevation runoff length, or superelevation runoff distribution.
4. Most curves with a high probability of being a high-accident location usually have one or more factors in combination with roadside hazard that contribute to the total hazard (i.e., sharper curves or longer curves, narrower shoulders, and lower pavement skid numbers).

As others have pointed out (*12,15*), the length of curve, at the very least, needs to be considered, because it affects the exposure. As was stated in *State of the Art Report 6*, (*12*) "although most designers would agree that flatter curvature is more desirable, the effect of trading more curved roadway for tangent roadway can negate some of the advantage of the flatter curve."

The available information also suggests that grade influences the rate of accidents on horizontal curves. Curves located at the end of downgrades appear to have a greater accident potential than curves on level terrain.

While there was only limited support in the literature, accident occurrence on horizontal curves is also affected by the upstream and downstream alignment. Research on geometric design consistency may reveal more insight on this subject, especially for isolated sharp curves and for longer and/or sharper curves on winding road sections of two-lane rural roads. The available literature suggests (though not conclusively) that a sharp horizontal curve may be more hazardous when it is located on a two-lane rural road segment with relatively few horizontal curves (e.g., curve frequency less than one per mile) than when it is located on a section with a higher frequency of sharp curves. ARFs developed by Zeeger et al. (*16*) suggest that there is a greater benefit to improving an isolated curve compared with a nonisolated curve, especially if the central angle is large.

The results of documented safety studies also suggest that the potential for a run-off-road accident is significantly higher on curves than on tangents. Thus, there is a greater need to provide some form of "forgiving" roadside on the outside of curves compared with tangents.

Accident Prediction Models

Glennon's Horizontal Curve Model

Building on the work reported in the 1985 FHWA report (*15*), an accident relationship was developed and presented in *Special Report 214* (*6*). The model is presented below:

$$A = AR_s(L)(V) + 0.0336\,(D)(V) \text{ for } L \geq L_c \quad (8)$$

where

A = total number of accidents on the segment
AR_s = accident rate on comparable straight segments in accidents
L = length of highway segment in miles
V = traffic volume in millions of vehicles
D = curvature in degrees
L_c = length of curved component in miles

In the development of this model, cross-tabulations and data analysis supported the following findings:

1. Lane width may have a minor effect on reported accident rates on 0.61-mi sections.
2. Volumes appear to have a small effect as well.
3. The data showed no consistent and pronounced relationship between accident rate and either curve length or curve central angle.

The model can be applied to estimate the reduction in accidents from flattening a horizontal curve while maintaining its lines of tangency (or central angle). The net reduction in accidents, ΔA, can be estimated as follows:

$$\Delta A = AR_s\,(\Delta L)V + 0.0336\,(\Delta D)V \quad (9)$$

where

ΔL = change in highway length (expressed in miles)
= $[(2.170 \tan I/2) - (I/52.8)]\,[(1/D_n) - (1/D_o)]$
I = central angle
D_o = degree of curvature corresponding to the original alignment
D_n = degree of curvature corresponding to the new or improved alignment
ΔD = change in degree of curvature

Zegeer's Horizontal Curve Model

The following accident prediction model was developed by Zegeer et al. for the 1991 FHWA study (*16*) of cost-effective improvements for horizontal curves.

$$A = [(1.552)(L)(V) + (0.014)(D)(V) - (0.012)(S)(V)]\,(0.978)^{W-30} \quad (10)$$

where

A = number of total accidents on the curve in a 5-year period
L = length of the curve, in miles
V = volume of vehicles in million vehicles passing through the curve (both directions) in a 5-year period
D = degree of curve
S = presence of spiral
S = 0 if no spiral exists
S = 1 if there is a spiral
W = width of the roadway (twice the lane width plus shoulder width) on the curve, in feet

As suggested by the authors, the model is to be applied for existing curves only if no available accident data are available.

Assessment of Models

Zegeer's Horizontal Curve Model

The Zegeer model relating accidents to horizontal alignment appears to represent the best *available* relationship to estimate the number of accidents on individual horizontal curves on two-lane, rural roads, although it does have limitations. While the model explicitly considers curve length, degree of curvature, roadway width, and presence of a spiral transition, it does not explicitly consider roadside parameters or the effect of upstream or downstream alignment. The fact that it does not consider roadside or even some surrogate rating for roadside is a major limitation, especially because accident research has shown that roadside design is a determinant of horizontal curve safety.

Because the model does not consider a roadside hazard rating, the true safety benefit of adding guardrail to curves with hazardous roadside obstacles or sideslopes cannot be estimated with this model. Consider, for example, adding guardrail on the outside of a 3-degree horizontal curve with a 2:1 sideslope. The installation of the guardrail neither flattens the sideslope nor increases the roadside recovery area. Thus, the application of this model would yield $0 as a safety benefit. Intuitively, this result is illogical. At the very least, the installation of guardrail should reduce the severity of run-off-road accidents. However, because there are no guidelines to suggest otherwise, it is highly unlikely that a user would assume a different average curve accident cost for the "before" condition versus the "after" condition.

The Zegeer model is limited to evaluating individual horizontal curves. Although there are two sets of suggested ARF adjustments (i.e., one for an isolated curve and the other for nonisolated curves), the model does not lend itself to an evaluation of highway sections with varying alignment. For example, the procedure cannot be easily used to analyze a combination of curves and tangents.

The model does not consider the effect of vertical alignment or the consistency with respect to the design of all curves within the highway section (e.g., geometric design consistency). The model also does not consider the frequency of horizontal curves greater than 3 degrees within the section, the frequency of sight-restricted vertical crest curves, or the percent grade. The average operating speeds or design speeds are also not considered explicitly. The model does not consider the influence of access points, driveways, or intersections that may be close to the subject curve.

Glennon's Horizontal Curve Model

As noted in *Special Report 214* (*6*), the accuracy of Glennon's horizontal curve model "may be diminished for curves sharper than about 15 degrees, the approximate limit recorded in the data base from which the model was calibrated." However, this model does not consider the following factors and curve design parameters:

- Curve length
- Superelevation and superelevation run-off
- Spiral transitions
- Cross-slope break
- Roadside
- Geometric design consistency (e.g., a sharp curve immediately following an extended tangent section is likely to experience a higher number of accidents than a similar curve in a winding road section)
- Other factors.

Horizontal Curve Models Case Study

The roadway improvement project for this case study was a reconstruction of 0.59 miles of a two-lane, rural state highway in Washington classified as a minor arterial. The design report describes the original section as having 10-ft through lanes with 3-ft shoulders. The original horizontal alignment consisted of six curves, which bypassed a steep hill. Two of the six original curves were very shallow, while the remaining four were fairly sharp. Although the posted speed for this section was 50 mi/h, advisory signing for 25 mi/h was located at some of the curves.

In the design report three alternatives were considered and are listed below:

1. Alternative P1 — Construct 2,850 ft of new alignment straight over the hill, with 12-ft lanes and 3-ft shoulders.
   Cost (50 mi/h design speed) $650,000 total
   Cost (70 mi/h design speed) $840,000 total
2. Alternative P2 — Construct 3,100 ft of new alignment around the hill, using three 800-ft radius curves (0.07 superelevation) with 12-ft lanes and 3-ft shoulders.
   Cost (50 mi/h design speed) $460,000 total
3. Alternative P3 — Construct 3,100 ft of new alignment around the hill, using three 1,500-ft radius curves (0.10 superelevation) with 12-ft lanes and 3-ft shoulders.
   Cost (70 mi/h design speed) $940,000 total

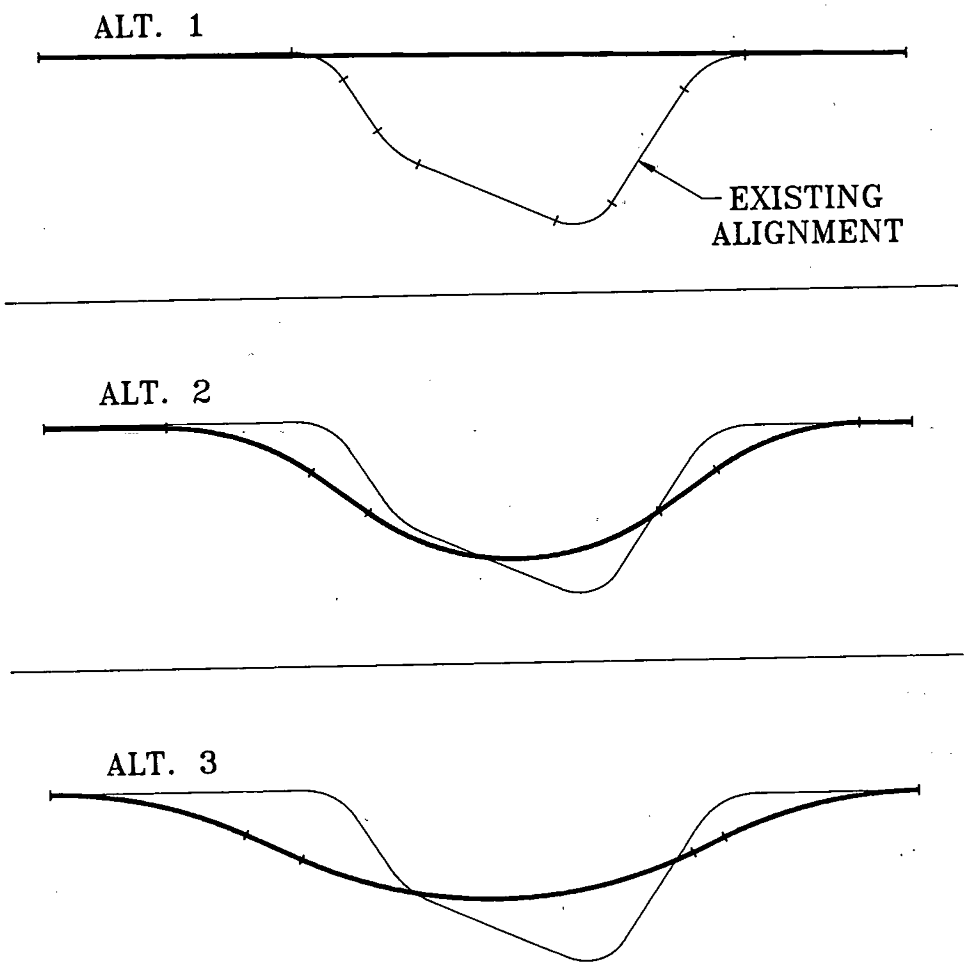

Figure 4. Three alternative alignments used for case study.

TABLE 7. Accidents by time of day and weather (5 years before to 5 years after)

	Accidents				
	Dawn	Daylight	Dusk	Dark	Total
Dry	0-0	3-1	1-0	4-0	8-1
Wet	0-0	6-1	0-0	3-0	9-1
Ice/Snow	0-1	0-2	0-0	0-0	0-3
Total	0-1	9-4	1-0	7-0	17-5

Figure 4 shows the three design alternatives relative to the original alignment. Alternative P2 was selected for the actual reconstruction project.

The available accident data covered approximately 7.5 years before and 7.5 years after the project was completed. Because Zegeer's horizontal curve model was developed for 5-year periods, only the accident data for the 5 years immediately before and after the reconstruction were considered. These accident data, categorized by time of day and weather conditions, are summarized in Table 7, while Table 8 shows the distribution of accidents by accident type.

The design report listed a 20th-year design volume of 2,450 vpd. The existing traffic for the roadway section was given as 1,420 vpd. This case study analysis assumed a constant growth of traffic throughout the design life of the project. On the basis of the initial and design volumes, the growth rate was determined to be 2.7 percent per year.

Application of Zegeer's Horizontal Curve Model

The results of the accident study of horizontal curves (*16*) of Zegeer et al. led to the horizontal curve accident prediction

TABLE 8. Accidents by accident type (5 years before to 5 years after)

Accident Type	Before	After
Opposite direction—sideswipe	3	1
Opposite direction—head on	2	-
Same direction—rear end	1	-
Same direction—sideswipe	-	1
Vehicle overturned	2	2
Guardrail—face of, not through	1	-
Over embankment—not guardrail	3	-
Earth bank or ledge	1	1
Roadway ditch	1	-
Fence	1	-
Tree or stump	1	-
Breakage of vehicle part	1	-
Total	17	5

model shown as equation 10 and was the basis of the guide for evaluating the reconstruction and upgrading of horizontal curves. The 1991 FHWA *Informational Guide* (*17*) shows a procedure or model for evaluating the following roadway improvements for horizontal curves:

- Flattening curves
- Widening roadways
- Providing spiral transitions to curves
- Improving superelevation
- Flattening sideslopes
- Improving roadside obstacles.

The model is typically applied by determining the appropriate ARFs for each improvement by using "look-up" tables. These ARFs represent the expected safety benefits for each incremental improvement in curvature and roadside characteristics. The combination of the individual ARFs results in the overall expected safety benefit as a result of all improvements.

The model was developed to analyze the effects of improvements to an individual curve. No procedure is given, however, for the case in which a series of curves is replaced by a completely different alignment. For this case study, a procedure for applying the model for this situation was developed.

Curve Flattening—One of the look-up tables presents the expected safety benefits as a result of flattening a curve. For a single curve, it is merely a matter of locating the correct ARF, based on the "before" and "after" degrees of curvature, the central angle, and whether the curve is considered isolated. However, there is obviously no table for completely changing the alignment of a segment (e.g., from two shallow and four sharp curves to three curves having desirable design standards).

It was decided, therefore, to use the predictive equations for accident rates from which the ARFs had been derived. These predictive equations would then be applied to both the "before" and "after" conditions. This move would allow the calculation of the expected safety benefit, or the effective ARF, for improving the horizontal alignment.

As mentioned above, normal application of the model considers simple flattening of an individual curve. The ends of the new curve serve as common points between the old and new alignment, between which accident rates are compared. The new curve is compared with the section of the old alignment that consists of the shorter old curve and the tangents on either side of it extending to the ends of the new curve. The actual change in the overall length of the new alignment is negligibly small for central angles of fewer than 90 degrees and is not included in the accident reduction calculations.

The model uses two equations for accident prediction. Equation 10 (shown earlier) is used to predict the number of accidents on curved sections, while the equation below predicts accidents for tangents sections:

$$A_t = (1.55)\ (L_t)\ (V)\ (0.978)^{(W-30)} \qquad (11)$$

where

A_t = number of accidents on the tangent section
L_t = length of the tangent section
V = volume of vehicles passing through the tangent section during the time period being considered
W = total width of the pavement

These equations were applied to the combination of curved and tangent sections of the original alignment. The three design alternatives were treated the same. The "before" and "after" predicted accident rates were then used to calculate expected safety benefits as a result of changing the horizontal geometry of the roadway. Table 9 presents the results of these calculations.

All the calculations for the results presented in Table 9 used the traffic volume for the 5 years preceding the reconstruction and the original pavement width. Although the design alternatives include the provision for 2 ft of lane widening, the safety benefits as a result of roadway widening are treated separately. Therefore, the original width of the pavement was used in the predictive equations for the new alignments, even though they would be constructed with wider lanes. Similarly, the expected increase in accidents due to increased traffic volumes is treated later in the model. The traffic volume associated with the original alignment is thus used in the calculations for the design alternatives, even though they would have a higher traffic volume themselves.

Pavement and Shoulder Effects—The safety benefits (ARFs) presented by this model as a result of roadway widening could not be determined solely from equation 10 because the roadway width variable in that equation includes both the travel lanes and the shoulders. Zegeer sought to differentiate the safety benefits of widening lanes from those of widening various types of shoulders.

To conduct this analysis, the cross-sectional model presented by equation 1 was used. This model had been developed by analyzing rural roadway sections that included both curves and tangents. Zegeer combined it with equation 10 to isolate the effects of roadway widening at curves, this resulted in the ARFs presented by the model. Therefore, the ARFs for pavement and shoulder widening given in Zegeer's horizontal curve model are not entirely appropriate for this roadway project. For the purposes of this case study, it is more appropriate to use equation 1 by itself, because the roadway improvement project in question is indeed a section, including both curves and tangents.

The design report indicated the reconstruction of this roadway section would widen both lanes from 10 ft to 12 ft with the shoulders remaining at 3 ft. Keeping all the other parameters in equation 1 equal, the ARF for the 2-ft lane widening is calculated as the following:

$$ARF_{lw} = 1 - (0.8786)^{(W_{new} - W_{old})}$$
$$= 1 - (0.8786)^{(12-10)} = 0.23$$

Spiral Transitions to Curves—The presence of spiral transitions to curves was found to reduce accident rates by as much as 9 percent, depending on the degree of the curve and the central angle. The procedure in the *Informational Guide* (*17*) for applying Zegeer's horizontal curve model suggests using an ARF of 5 percent when a spiral transition is added to a curve. This value is based on equation 10 as well as other, unidentified analyses. For the roadway section in this project, however, there was no indication that spirals existed on either the original alignment or any of the design alternatives that were considered. Thus, no expected safety benefit is a result of this type of improvement.

Superelevation—Analysis that led to the development of Zegeer's horizontal curve model indicated that superelevation deficiency was associated with increased accident rates at curves. The magnitude of the effect was found to vary with the amount of the deficiency, compared with the values suggested in the AASHTO Green Book. The procedure for applying the model suggests an ARF of 0.05 for correcting superelevation deficiencies of 0.019 or less and 0.10 for correcting superelevation deficiencies of 0.02 or more.

According to the design report for this case study, a superelevation rate of 0.07 was used for all curves in the new alignment, and a superelevation rate of 0.10 would have been used for the curves in design alternative P3. Design alternative P1 would have no curves and therefore no superelevation. The superelevation rates of the curves in the original alignment were not given. On the basis of the extremely low posted advisory speeds for

TABLE 9. Expected safety benefits due to curve flattening based on Zegeer's model

Alignment	Number of Predicted Accidents	Accident Reduction Factor—ARF_{cf}
Original	7.47	-
Alternative P1	2.48	0.67
Alternative P2	3.43	0.54
Alternative P3	3.03	0.59

the original curves, it was assumed that the superelevation was deficient by at least 0.02. Therefore, 0.10 was used as the ARF for the expected safety benefits as a result of correcting the superelevation deficiency. That would also be applied to design alternative P1, although it has no curves, because the straight alignment would essentially correct the superelevation deficiencies of the original alignment.

Roadside Improvements—Roadside improvements considered by the procedure to apply the model include increasing the roadside clear recovery distance and flattening the sideslopes. A table of ARFs is provided for sideslope flattening that is not accompanied by other roadside improvements. Another table is provided for improvements that increase the clear recovery distance. When both improvements are combined, the table for increased clear recovery distance should be used.

Sideslope data were available for the new alignment but not for the original alignments or design alternatives not selected for construction. The design report indicated that fixed objects in the new right-of-way would be relocated; however, data were insufficient to determine the amount of increased clear recovery distance.

It was assumed the clear recovery distance was increased by 10 ft, which yields 0.25 for the ARF. This accident reduction value was taken from the FHWA report, *Safety Effects of Cross-Section Design for Two-Lane Roads* (*4*), rather than Zegeer's horizontal curve model. As mentioned above, that research was based on highway sections that included curves as well as tangents, whereas Zegeer's horizontal curvature model was developed specifically for curves. Because the value is to be applied to the entire section rather than just to a curve, the value cited above was believed to be more appropriate.

Combining of ARFs—According to Zegeer (*16*), the overall effect of the individual ARFs can be determined by the following equation:

$$ARF_{\text{total}} = 1 - (1 - ARF_1)(1 - ARF_2)(1 - ARF_3)(1 - ARF_4)\ldots\ldots \quad (12)$$

where

ARF_x = the individual ARF for a single improvement

Therefore, the overall ARF for the combined improvements for design alternative P2 is calculated as follows:

$$ARF_{\text{total}} = 1 - (1 - 0.54)(1 - 0.23)(1 - 0.10)(1 - 0.25) = 0.76$$

Application of the ARF—The ARF must be applied to the number of future accidents that could be expected if no improvements were made. As noted above, there were 17 accidents on the original alignment in the 5 years before the reconstruction. One of these accidents, however, was because of a broken vehicle part, and should not be included in the analyses of safety benefits due to roadway improvements. The number of accidents is assumed to increase proportionally to the expected increase in traffic volumes. For the 5 years after the project was completed, the expected number of accidents on the unimproved original alignment would be calculated as follows:

$$A_{\text{exp unimp}} = 16 \text{ acc } \frac{(3.1283 \text{ mil veh})_{\text{before const}}}{(2.7139 \text{ mil veh})_{\text{after const}}} = 18.44 \text{ acc}$$

Applying the ARF, the expected number of accidents in the 5 years after the reconstruction is calculated as follows:

$$A_{\text{exp imp}} = (1 - ARF_{\text{total}})(A_{\text{exp unimp}}) \quad (13)$$

$$A_{\text{exp imp}} = (1 - 0.76)(18.44) = 4.43 \text{ acc}$$

There were actually five accidents on the new alignment during the 5 years after the reconstruction. The error between the expected and actual number of accidents for design alternative P2 is 11 percent. Table 10 presents the results of the analysis for each of the design alternatives.

Application of Glennon's Horizontal Curve Model

The model developed by Glennon, shown as equation 8 earlier, is repeated below:

$$A_c = AR_s(L_c)(V) + (0.0336)(D)(V) \quad (8)$$

where

A_c = number of accidents on a curve
AR_s = accident rate PMVM for a straight section of road
L_c = length of the curve, in miles
V = traffic volume, in millions of vehicles
D = degree of curvature

The first component of this model accounts for the steady state turning effect and is directly proportional to the vehicle miles of travel on the curve, without regard to the degree of curvature. The second component accounts for the transitional effects or those due to entry and exit of the curve. This second component is directly proportional to the degree of curvature and the traffic volume but is not affected by the length of the curve. The value 0.0336 is the calibration constant that was determined from the analysis of the data base during development of the model. It represents the expected effect on accident rates for a 1-degree change in curvature.

As in the procedure used for Zegeer's horizontal curve model, the expected number of accidents for the overall alignment was calculated as the sum of predicted accidents for the individual curves and tangents. The above equation was used to determine the accidents for curve sections, while the following equation estimated accidents on tangent sections:

$$A_t = AR_s(L_t)(V) \quad (14)$$

where

A_t = number of accidents on a tangent
AR_s = accident rate PMVM for a straight section of road
L_t = length of the tangent, in miles
V = traffic volume, in millions of vehicles

During the development of the model, analysis of the straight sections in the data base yielded an accident rate (AR_s) value of 0.902 accidents PMVM. However, this value is suggested to be

TABLE 10. Overall expected safety benefits due to combined improvements based on Zegeer's model

Alignment	Overall Accident Reduction Factor	Expected Number of Accidents (5 Years)	Actual Number of Accidents (5 Years)
Original	-	-	16
Alternative P1	0.83	3.13	-
Alternative P2	0.76	4.43	5
Alternative P3	0.79	3.87	-

TABLE 11. Expected safety benefits due to curve flattening based on Glennon's model

Alignment	Accident Reduction Factor (curve flattening)
Alternative P1	0.68
Alternative P2	0.53
Alternative P3	0.61

replaced, where possible, with a value representative of local conditions for the highway section under consideration. The above equations were applied to the original alignment, in conjunction with the actual number of accidents for the 5 years preceding the reconstruction, and solved for the value of AR_S. The value obtained for AR_S using this approach was 3.479 accidents PMVM.

The value obtained for AR_S was used with the geometric data for the new alignment to estimate the expected number of accidents for the period before reconstruction. The *ARF* due to curve flattening, ARF_{cf}, was then calculated on the actual number of "before" accidents (*16*) and the predicted number of "before" accidents as follows:

$$ARF_{cf} = \frac{(16 - 7.50)}{(16)} = 0.53$$

This value closely matches the value of 0.54, as determined by Zegeer's model. The ARFs due to curve flattening for the other design alternatives were also very close to those that were determined by Zegeer's model. Table 11 summarizes the ARFs due to curve flattening for all the design alternatives.

For the effects of curve flattening, the differences between the results of Zegeer's model and Glennon's model are not significant for this case study.

Conclusions—The approach used to apply Zegeer's horizontal curve model to highway sections, including both curves and tangents, provided good results for this case study. The difference between the actual number of accidents and the expected number of accidents was only 11 percent. Additionally, Glennon's model provided results close to those from Zegeer's model.

The main problem experienced was not with the application of the models or the results obtained from them; the biggest obstacle to using the models was getting the necessary information (i.e., the data input needed by the models). This problem was probably more significant in this situation because of the long time period between the reconstruction of the roadway and this analysis. Some of the information needed by the models does not exist any longer, if it ever existed at all.

It is unlikely that the designer of an actual project will experience the same type of problem. The designer should have better access to the available data for a project and could possibly collect any additional data for the existing conditions that are necessary for safety analysis. The designer will definitely have better access to information on the "after" conditions for alternatives that are being generated and considered by the designer.

In spite of the difficulties encountered with data acquisition, the models were an effective tool in estimating the safety benefits for this case study. It is important to recognize that this analysis carried the validation of the models one step farther. The models describe the relationship between accidents and roadway characteristics, based on data for many existing curves (i.e., the model was developed using only "before" data). The models were applied to an actual site, however, using both "before" and "after" data. This type of analysis is necessary to check the validity of the models under actual conditions.

MEDIAN DESIGN

Assessment of Literature Findings

For fully controlled access highways, elements of median design that may influence accident frequency or severity include median width, median cross slope(s), median type (raised, flush, or depressed), presence (or absence) of a median barrier, presence (or absence) of one-sided roadside barriers, and clear zone within the median. The reported results indicate that fully controlled access highways with medians wider than 30 ft generally have lower accident rates than those with medians narrower than 30 ft. Roads with deeply depressed medians and 4:1 slopes were also found to have a higher crash severity and a higher proportion of vehicle overturn accidents than more shallow slopes. In general, wider medians achieve a higher degree of safety. Documented findings from accident studies support the use of median widths in the range of 60 to 80 ft or more with flat slopes on fully controlled access facilities.

Using data from FHWA's HSIS, researchers recently studied medians without barriers (*18*). The analysis used accident, traffic, and roadway data for four-lane, rural, and urban Interstate, freeway, and major highway road sections in Utah and Illinois with a posted speed limit of at least 35 mi/h. It was concluded that accident rates do decrease with increasing median width for unprotected medians and that medians need to be at least 30 ft wide to have a positive safety effect. Although it was difficult to determine the exact median width where the safety effect is lost, the report suggested that decreasing existing median width to fewer than 20 to 30 ft to enhance capacity may decrease the level of safety on the road. The HSIS data set could not be used to determine the median width at which a positive barrier should be used. The current HSIS contained only a limited number of miles with barrier, and the variation in median width on these roadways was judged to be inefficient for a statistically valid study.

Accident Prediction Model

On the basis of the available documented literature, the results from the aforementioned HSIS study represent the best known relationships for median width. For the HSIS study, sophisticated statistical modeling techniques were applied to develop relationships between the relative occurrence of accidents as a function of median width. The relative effect of median width on serious (i.e., fatal accidents and A-injury accidents), all-injury accidents (i.e., fatal, A-, B-, and C-injury accidents), and property-damage-only accidents are shown in Figures 5 and 6 for Utah and Illinois, respectively. It should be noted that the data pertain solely to four-lane highways and that adjustments were made for functional class, posted speed limit, right shoulder width, ADT, section length, and other factors.

Assessment of Model

On the basis of the available documentation, the relationships appear to be valid for four-lane, divided highways. However, it is not clear whether roadways with fully controlled access (e.g., Interstate and other freeways) were segregated from roadways without full control of access (e.g., divided arterials) in this analysis. The selection of a median width for non-fully controlled roadway must also consider the presence of intersections, the need to accommodate left-turn lanes, at-grade conflict points associated with median openings, and the flexibility in design to ultimately accommodate dual left-turn lanes at intersections and/or future construction of additional through lanes in the median for capacity purposes. This last point is especially important in rapidly developing areas such as high-growth, suburban corridors. AASHTO's *A Policy on Geometric Design of Highways and Streets* (*1*) recognizes the distinctly different needs and functions of medians for arterials as opposed to freeways.

Median Width Case Study

While an accident prediction model to evaluate median widths for urban/suburban arterials currently does not exist, the median

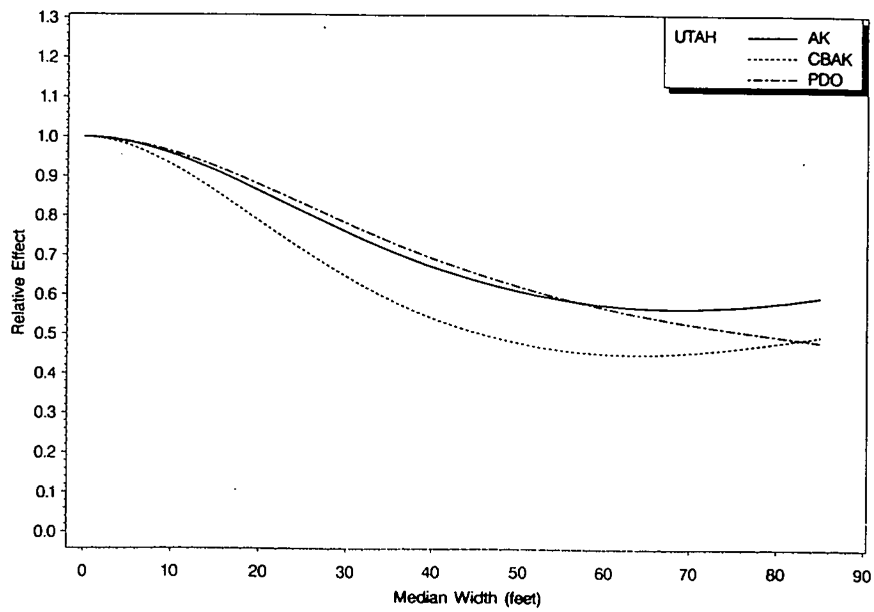

Figure 5. Estimated relative effects of median width on serious, injury, and property-damage-only accident rates for Utah four-lane, two-way sections (18). AK = severe, CBAK, = all injury, PDO = property damage only.

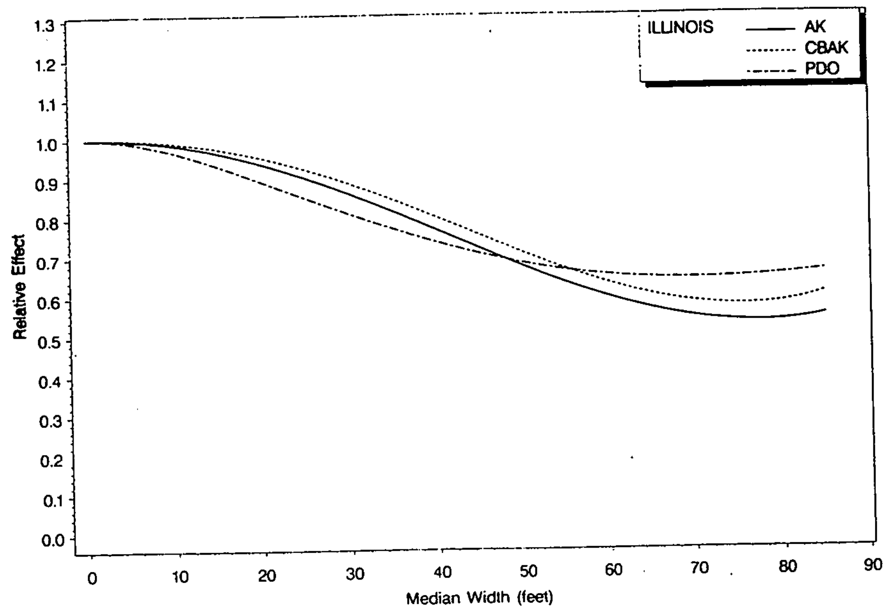

Figure 6. Estimated relative effects of median width on serious, injury, and property-damage-only accident rates for Illinois four-lane, two-way sections (18). AK = severe, CBAK = all injury, PDO = property damage only.

width-accident relationships that were developed for the recent HSIS study could be applied. The relationships shown in Figures 5 and 6 were derived from data for four-lane road segments in Utah and Illinois, respectively. The data base from which the relationships were developed included rural Interstates, urban Interstates, urban area-other freeways and expressways, rural principal arterials, urban-other principal arterials, and a category of road that Illinois classifies as "non-urban or urban area major highways." Although functional classification was "controlled" by making statistical adjustments, the relationships may be more applicable to Interstate freeways and rural principal arterials with limited access than suburban arterials with frequent at-grade intersections and driveways. The relationships were nonetheless applied to a case study for illustration.

The case study selected was a relocation project for a four-lane, divided, suburban arterial with partial control of access in Maryland. Pertinent details for the project are summarized below:

- Terrain = rolling
- Design speed = 60 mi/h
- Posted speed limit = 50 mi/h
- Projected year 2006 ADT = 53,000
- Project length = 1.2 mi
- Lane width = 12 ft
- Paved shoulder width = 10 ft
- Maximum degree of curvature < 2.1 degrees
- Maximum grade < 4 percent
- A monolithic concrete median required where median width was 4 ft or less.

At the eastern project limit, the road modulates to match the existing two-lane road. At the western project limit, the road modulates to match the existing four-lane, undivided, 44-ft-wide road. Three unsignalized, three-legged intersections and eight driveways are within the project limits. No median openings are provided for the driveways. The typical cross-section for the project consists of the following:

- A 16-ft-wide median. (At intersections and median openings, 12-ft-wide left-turn lanes and a 4-ft-wide raised concrete median were provided.)
- Four 12-ft-wide lanes (i.e., two in each direction).
- Outside paved shoulders that are 10 ft wide and a raised curb and gutter on the median side that is 1 ft wide.

Because accident data were not available either before or after construction for this road segment, basic accident rates for a four-lane, undivided, suburban arterial were assumed. Using data from *NCHRP Report 282, Multilane Design Alternatives for Improving Suburban Highways* (*19*), the following were assumed to apply to the four-lane, undivided section that existed before widening:

- Average annual accident rate = 2.45 accidents PMVM of travel. This value was derived as the basic accident rate minus an adjustment for fewer than 30 driveways, and minus an adjustment for fewer than 5 intersections per mile, minus an adjustment for 5 percent trucks.
- Average severity distribution:
  - -38% Fatal + A-injury + B-injury + C-injury accidents
  - -62% Property-damage-only accidents

In addition to evaluating the preexisting and implemented improvement project, the potential safety effects of two additional alternatives were also estimated. The alternatives included providing a 30-ft-wide median (i.e., a median that could accommodate future additional lanes in each direction and single left-

TABLE 12. **Illustrative results from the application of median width/accident relationships from Illinois**

Design Alternatives	Predicted Average Annual Number of Accidents by Severity Based on Illinois Relationships		
	Fatal, A-, B- & C-Injury	Property Damage Only	Total
BASE CASE— Conditions that existed before the project (i.e., four-lane, undivided)	18.0	29.4	47.4
IMPLEMENTED DESIGN— (i.e., four-lane divided with a 16-ft median)	17.3	27.0	44.3
ALTERNATIVE A— (i.e., four-lane divided with a 30-ft median)	15.8	23.5	39.3
ALTERNATIVE B— (i.e., four-lane divided with a 42-ft median)	14.0	21.5	35.5

TABLE 13. **Illustrative results from the application of median width/accident relationships from Utah**

Design Alternatives	Predicted Average Annual Number of Accidents by Severity Based on Utah Relationships		
	Fatal, A-, B- & C-Injury	Property Damage Only	Total
BASE CASE— Conditions that existed before the project (i.e., four-lane, undivided)	18.0	29.4	47.4
IMPLEMENTED DESIGN— (i.e., four-lane divided with a 16-ft median)	15.5	27.0	42.5
ALTERNATIVE A— (i.e., four-lane divided with a 30-ft median)	11.5	22.9	34.4
ALTERNATIVE B— (i.e., four-lane divided with a 42-ft median)	9.4	20.0	29.4

turn lanes at the intersections) and a 42-ft-wide median (i.e., a median that could accommodate future additional lanes in each direction and ultimately dual left-turn lanes at the intersections). Applying the relationships yielded the results shown in Tables 12 and 13.

ROADSIDE DESIGN

The *Roadside Design Guide* (*9*) defines roadside as "that area between the outside shoulder edge and the right-of-way limits." Roadside design includes the design of the hinge point, fore-

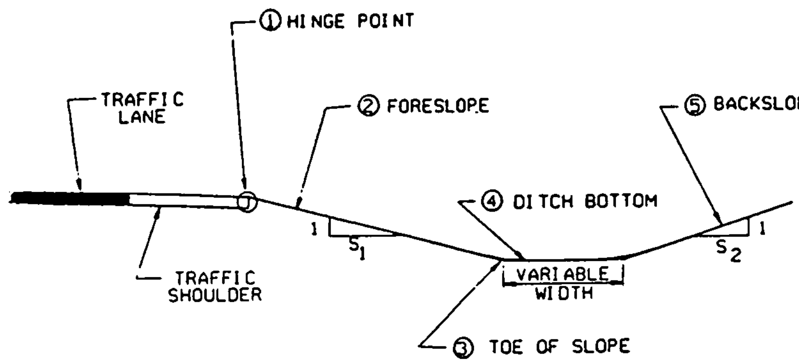

Figure 7. Designation of roadside regions (1).

slope, drainage channel/ditch, and backslope, which are shown in Figure 7. Roadside design also encompasses the design of longitudinal traffic barriers, signs, signal and lighting support structures, off-roadway drainage structures and inlets, utility poles, and other fixed objects. It should be noted that this section does not present information on bridge railing systems or crash cushions. Moreover, it does not focus on specific types of guardrail or specific types of median barriers. These topics are covered in great detail in the *Roadside Design Guide* and other sources.

On the basis of the inputs received from a survey of state highway agencies, highway designers desired more information about the relationships between safety and roadside elements and features. Highway designers wanted to know the safety effects of clear zones, sideslopes, guardrail, medians, and median barriers. Many inquired about the relative safety benefits of providing clear zones with traversable sideslopes compared with guardrail. Out of 37 states responding to the survey, 20 indicated trade-off analyses are frequently required for flatter sideslopes rather than barriers. Recognizing that guardrail is generally lower in cost than extensive modifications to the roadside, several wanted to know what is sacrificed, in terms of safety benefits, by providing guardrail rather than relatively flat sideslopes (e.g, 4:1) and a 30-ft clear zone free of potentially hazardous fixed obstacles. On divided highways, a few designers wanted to know when the safety benefits of median barriers outweigh their costs. In terms of safety benefits, designers asked about the relative safety benefits of wide (e.g., > 30 ft) traversable medians compared with narrower medians with a median barrier. Many states expressed a desire for as much guidance as possible to help them make decisions on alternatives for roadside design.

Assessment of Literature Findings

On the basis of the available literature documenting accident research studies of roadside features and design elements, it appears that providing clear zones with traversable slopes greatly enhances roadway/roadside safety. The need for a forgiving roadside is paramount on the outside of horizontal curves that are greater than 6 degrees, where the probability of an errant vehicle running off the travelway is highest. Accident data support the claim that sideslopes steeper than 4:1 pose a greater hazard than flatter sideslopes to motorists. One study contends that slopes should be 5:1 or flatter to significantly reduce the hazardousness of the roadside. The use of 6:1 slopes with a 30-ft clear zone generally provides a greater level of safety than the use of 4:1 slopes with a 30-ft clear zone.

Accident Prediction Models

ROADSIDE Model

AASHTO's *Roadway Design Guide* (*9*) presents a procedure that can be used by highway designers to select the most cost-effective roadside treatment at a spot location. ROADSIDE is a computer program that automates this cost-effectiveness selection procedure. The ROADSIDE program can be used to estimate the impacts (i.e., run-off-road, hit fixed object) per year, stratified by impacts with the sides of a hazard, the corners of a hazard, and the face of the hazard, and the average accident costs based on the average accident severity of impacts with the sides, corners, and face of a roadside hazard.

In estimating total costs, the key calculation is determining average annual impacts (i.e., "hit-hazard" accidents per year). These impacts are calculated as follows. First, the encroachment frequency is calculated for adjacent and opposing traffic using the following equation:

$$EF = ER * TVeff^{EP} * EF_g * EF_c * EF_u \text{ (15)} \qquad (15)$$

where

EF = encroachment frequency (encroachments/mi/yr)
ER = encroachment rate (encroachments/mi/yr/vehicle/day)
$TVeff$ = effective traffic volume (vehicles/day)
EP = encroachment power parameter (default = 1.0)
EF_g = grade adjustment factor
EF_c = curve adjustment factor
EF_u = user adjustment factor

Then, the average annual collision frequency is calculated using the following equations:

$$CF_t = CF_1 + CF_2 + CF_3 + CF_4 + CF_5 + CF_6 \qquad (16)$$

$$CF_1 = EF_{adj} * (1/\tan\theta) * \left[\sum_{i=1}^{W} LEP(A + SW * \cos\theta + \{i-1\}) \right] \quad (17)$$

$$CF_2 = EF_{adj} * (1/\sin\theta) * \left[\sum_{i=1}^{SW} LEP(A + \cos\theta + \{i-1\}) \right] \quad (18)$$

$$CF_3 = EF_{adj} * (L/5280) * LEP(A) \quad (19)$$

$$CF_4 = EF_{opp} * (1/\tan\theta) * \left[\sum_{i=1}^{W} LEP(A + (NL*LW) + SW * \cos\theta + \{i-1\}) \right] \quad (20)$$

$$CF_5 = EF_{opp} * (1/\sin\theta) * \left[\sum_{i=1}^{SW} LEP(A + \cos\theta + \{i-1\}) \right] \quad (21)$$

$$CF_6 = EF_{opp} * (L/5280) * LEP[A + (NL*LW)] \quad (22)$$

where

- CF_t = total collision frequency ("hit hazard" accidents per year)
- CF_1 = frequency of collisions/impacts with upstream side of hazard by adjacent traffic
- CF_2 = frequency of collisions/impacts with upstream corner of hazard by adjacent traffic
- CF_3 = frequency of collisions/impacts with face of hazard by adjacent traffic
- CF_4 = collision frequency of impacts with downstream side of hazard by opposing traffic (if undivided road)
- CF_5 = collision frequency of impacts with downstream corner of hazard by opposing traffic (if undivided road)
- CF_6 = collision frequency of impacts with face of hazard by opposing traffic (if undivided road)
- EF_{adj} = frequency of encroachments by adjacent traffic
- EF_{opp} = frequency of encroachments by opposing traffic. (If road is a divided road or a one-way road, then $EF_{opp} = 0$.)
- θ = encroachment angle
- W = width of hazard
- $LEP(Y)$ = lateral extent probability of an encroachment exceeding lateral extent Y (e.g., a distance y ft from the edge of the travelway)
- A = lateral offset from the edge of the nearest driving lane to the hazard
- SW = swath width, which is the effective width of a vehicle based on the length of the vehicle, the width of the vehicle, and the yaw angle
- L = length of hazard
- NL = number of lanes
- LW = lane width

The key assumptions to the model include the following:

- Average baseline ER = 0.0005 encroachments per mile per year per vehicle per day
- The encroachment angle is a function of design speed as follows:

Design Speed (mi/h)	Encroachment Angle (degrees)
40	17.2
50	15.2
60	13.0
70	11.6

- Although it can be overridden, the default swath width (SW) assumed is 12 ft.

The major inputs and procedural steps to input the data necessary and run ROADSIDE are illustrated in Figure 8.

Zegeer's Cross-Section Analysis Procedure

In *Safety Cost-Effectiveness of Incremental Changes in Cross-Section Design—Informational Guide* (*5*), the authors present a procedure to analyze improvements on two-lane, rural roads that either reduce the roadside hazard rating, increase the roadside clear recovery area, and/or flatten sideslopes in addition to changes in lane and/or shoulder width. Treatments that increase the roadside clear recovery area and, therefore, can be evaluated in conjunction with cross-section changes using their procedure include the following:

- Removing trees
- Relocating utility poles
- Flattening sideslopes and removing obstacles
- Providing traversable drainage structures.

Measures to reduce the hazard rating include the following, in addition to all those cited above:

- Installing guardrail in front of a steep slope or fixed object
- Providing breakaway bases to light poles and/or sign posts.

The accident reductions that were developed for this procedure for reductions in roadside hazard ratings and for changes in sideslopes are presented in Tables 14 and 15, respectively.

It should be noted that the roadside recovery area is defined in the *Informational Guide* (*5*) as follows:

> A relatively flat, unobstructed, and smooth area adjacent to the outside of the shoulder within which there is reasonable opportunity for safe recovery of an out-of-control vehicle. The width of the roadside recovery area is the lateral distance from the edgeline to the nearest of the following:
> - A hinge point where the slope first becomes steeper than 4:1.
> - A longitudinal element such as a guardrail, bridge rail, or barrier curb
> - An unyielding and hazardous object
> - The ditch line of a non-traversable side ditch (considering as an approximation that a ditch is traversable if both foreslope and back slope are 4:1 or flatter)
> - Other features, such as a rough or irregular surface, loose rocks, or a watercourse, that pose a threat to errant vehicles.

The *Informational Guide* suggests that measurements (or estimates) of the roadside recovery distance be made every 0.1

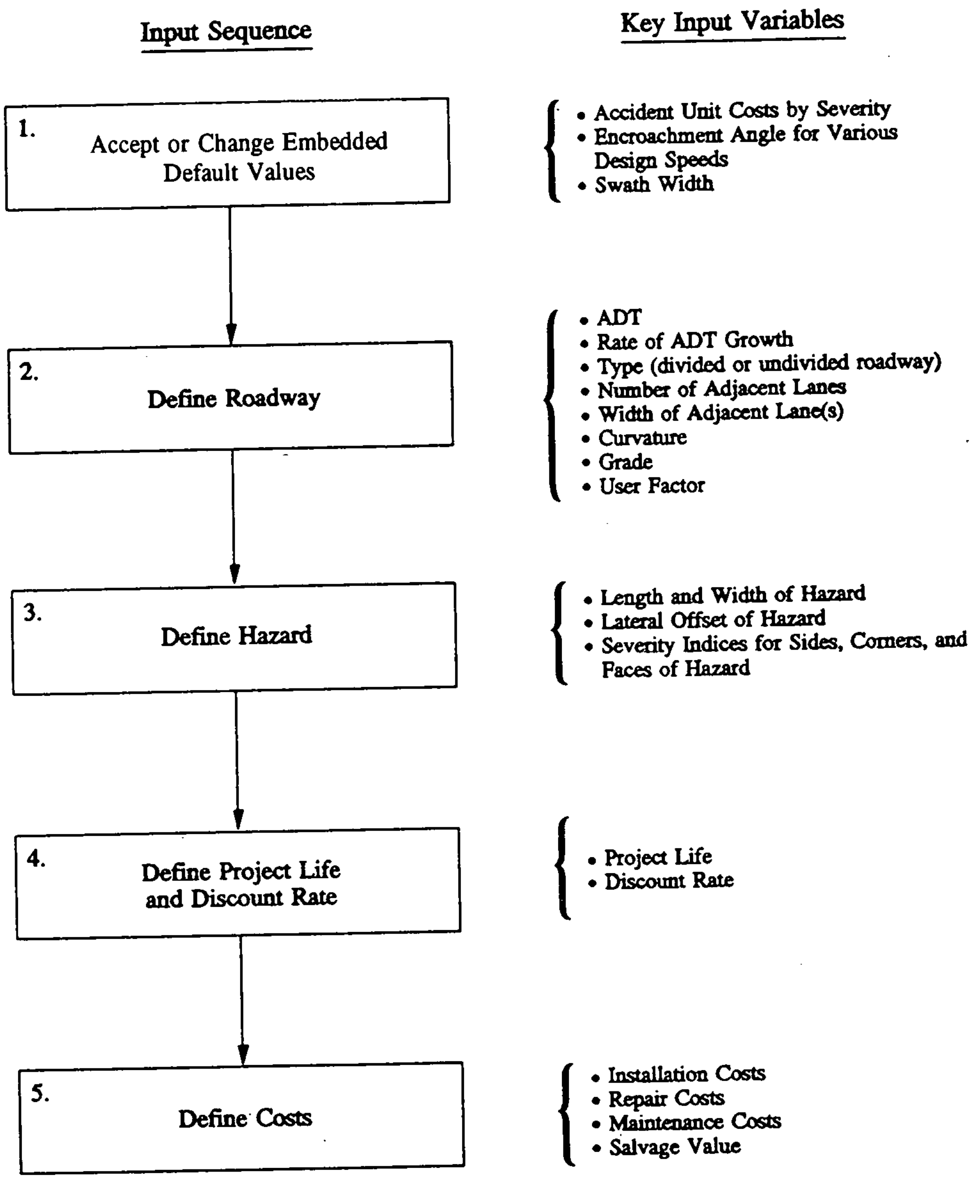

Figure 8. Procedural steps to execute the ROADSIDE model.

TABLE 14. Accident reduction factors for reductions in the roadside hazard rating (5)

Reduction in the Roadside Hazard Rating	Percent Reduction in Related Accident Types
1	19
2	34
3	47
4	52
5	65

miles throughout the section. The *Informational Guide* recommends the following:

1. Within each 0.1-mi section, identify the obstacle or steep slope that is closest to the roadway.
2. Measure (or estimate) the distance from the edge of the shoulder to that obstacle or steep slope.
3. Average these measurements for the entire section length and use the average as an input to the procedure.

For long sections, though, the *Informational Guide* indicates that a representative sample of subsections may be used to make measurements.

Zegeer's Horizontal Curve Analysis Procedure

As was discussed under *Application of Zegeer's Horizontal Curve Model*, a procedure can be followed to assess changes in

TABLE 15. Accident reduction factors for changes in sideslopes (5)

Sideslope in "Before" Condition	Sideslope in "After" Condition	Percent Reduction in Related Accident Types
2:1	3:1	2
	4:1	7
	5:1	11
	6:1	15
	7:1	20
3:1	4:1	6
	5:1	10
	6:1	14
	7:1	19
4:1	5:1	4
	6:1	9
	7:1	14
5:1	6:1	4
	7:1	10
6:1	7:1	6

TABLE 16. Expected reductions in curve accidents due to changes in sideslopes (*17*)

Sideslope in "Before" Condition	Sideslope in "After" Condition	Percent Reduction in Total Curve Accidents
2:1	4:1	6
	5:1	9
	6:1	12
	7:1	15
3:1	4:1	5
	5:1	8
	6:1	11
	7:1	15
4:1	5:1	3
	6:1	7
	7:1	11
5:1	6:1	3
	7:1	8
6:1	7:1	5

TABLE 17. Reduction in curve accidents due to increases in the roadside recovery distance (*17*)

Amount of Increased Roadside Recovery Distance (ft)	Percent Reduction in Total Curve Accidents
5	9
8	14
10	17
12	19
15	23
20	29

roadside design at single horizontal curves on two-lane, rural roads. The roadside design changes would include flattening sideslopes and/or removing roadside obstacles to increase the "clean" roadside recovery area. Tables 16 and 17 present the predicted accident reductions derived from the procedure for changes in sideslopes and increases in roadside recovery distances, respectively. With respect to the percent reduction values in Table 17, it should be emphasized that, according to the researchers, these values apply no matter what the initial or base condition was. For example, one would expect a 17 percent reduction in total curve accidents whether the roadside recovery distance was increased from 0 to 10 ft or from 10 to 20 ft. However, because in the first scenario the base accidents will likely be so much higher than the base accidents for the second scenario, the absolute accident reduction should be higher.

Utility Pole Model

As part of an FHWA research project, a model was developed to aid in selecting cost-effective countermeasures for utility pole accidents (*20*). In addition, a microcomputer program was developed that replicates the manual procedure described in the FHWA research report. The program, which is called UPACE, is available from the McTrans Center at the University of Florida and the PC Trans Center at the University of Kansas.

The UPACE model can be used to estimate the benefits of a reduction in the occurrence and/or severity of utility pole accidents for specific utility pole countermeasures (i.e., increasing the lateral offset, providing protective devices, reducing the number of poles, and/or using breakaway poles). The key inputs include the average pole offset and pole density. The procedure is limited to those roads with ADTs between 500 and 60,000 vpd and can be used with or without historical utility pole accident data. An accident prediction equation and nomograph are provided in the *Users Manual* (*20*) to allow a user to estimate utility pole accidents per mile per year based on a number of factors including ADT, average pole offset, and pole density. The equation is presented below:

$$ACC/MI/Y = \frac{(9.84 \times 10^{-5}) * (ADT) + (0.0354 * DEN)}{(OFF)*0.6} - 0.04 \quad (23)$$

where

$ACC/MI/Y$ = utility pole accidents per mile per year (both directions of travel)
ADT = average daily traffic volume
DEN = number of utility poles per mile for both sides of the road
OFF = average pole offset, in ft

The reduction in accident costs due to a reduction in accident occurrence can be subsequently estimated as the product of the average accident cost and the predicted change in accidents due to a change in pole density and/or pole offset. The equation below states this in mathematical terms:

$$B_A = (\Delta A) * (C_A) \quad (24)$$

where

B_A = accident benefits in dollars per year based on the net reduction in accident occurrences
C_A = average cost of a utility pole accident, in dollars
ΔA = net reduction in accidents, which is calculated as follows:
= $(A_B) * (ARF_A) * (H_R) * (L)$, where
A_B = number of utility pole accidents per mile per year before improvement
ARF_A = accident reduction factor
H_R = roadside adjustment factor
L = section length

If accident severity data were not readily available, an average accident cost of $7,007 was recommended. This value was based on 1981 National Safety Council unit accident costs and average severity distribution for utility pole accidents from a 1983 FHWA study.

The model also allows for a reduction in accident costs due to a reduction in accident severity. This reduction is estimated for utility pole accident countermeasures (except breakaway poles) on roads with average speeds of less than 45 mi/h as follows:

$$B_S = (A_B) * (1-H_R) * (ARF_A) * (\Delta C_A) * (L) \quad (25)$$

where

B_S = accident benefits per year based on the net reduction in accident severity
ΔC_A = net reduction in average cost of a utility pole accident

For countermeasures involving only breakaway poles, the accident benefits due to a reduction in accident severity are computed as follows:

$$B_S = (A_B) * (\Delta C_A) * (L) \quad (26)$$

Thus, the total benefits are the sum of the reduction in accident costs due to a reduction in the occurrence of utility pole accidents and the reduction in accident costs due to a reduction in the severity of utility pole accidents.

Assessment of Models

The ROADSIDE model is designed for evaluating specific treatments for a unique roadside feature or spot location. The model is primarily applicable to evaluating alternative treatments for hazards along existing roadways. Although it can be used to evaluate roadside designs for new construction along new alignment, it does not lend itself to evaluating long segments of roadway with varying roadside and/or median designs.

The model does not explicitly consider the effect of upstream or downstream geometry (e.g., isolated sharp horizontal curve versus a series of horizontal curves). Other weaknesses are related to the theoretical basis and empirical basis of the model. These include the following:

1. The baseline 0.0005 encroachments/mile/year/vehicle/day is based on two limited studies.
2. The assumed angle of encroachment is not affected by curvature.
3. Accident severity is not affected by curvature.
4. The angle of encroachment assumed for a left-side departure does not differ from the angle of encroachment assumed for a right-side departure.
5. Documentation on how well the estimates of accident frequency (impacts per year) and accident severity distribution compare with actual data is limited.

The model is not appropriate for evaluating median width. While it can be used to evaluate medians with barriers, it cannot be used to evaluate alternative median widths without median barriers because it does not explicitly consider the potential of head-on accidents.

One of the major limitations associated with the current version of the ROADSIDE microcomputer program is that it was developed to evaluate alternative roadside designs for individual features or hazards on one side of the road. It cannot be used easily for designing and evaluating long highway segments. If a designer wanted to evaluate two alternative highway designs with different roadsides, then the designer would have to apply the model to each and every homogenous roadside section and individual roadside feature. For example, the designer would have to evaluate the design of the right roadside and then the design of the left roadside. Also, the designer would have to manually account for shielding (i.e., when one roadside object is located so that part or all of another roadside object cannot be struck by an errant vehicle). Then, the designer would have to manually total the sum of the results. If the highway is divided, then the designer/ROADSIDE user would have to apply the model to evaluate for each unique homogenous roadway section within the project limits the following:

- The roadside to the north, due to encroachments to the right from the westbound direction of travel, assuming the road runs east-west

• The median for encroachments to the left from the westbound direction of travel

• The median for encroachments to the left from the eastbound direction of travel

• The roadside to the south, due to encroachments to the right from the eastbound direction of travel.

An assessment of both Zegeer's cross-section model and Zegeer's horizontal curve model were discussed earlier in this chapter. Both models apply only to two-lane rural roads and are limited in their application to evaluating alternative roadside designs.

The utility pole model appears to be valid, although the procedure is applicable only to utility poles. It is intended to evaluate alternative utility pole locations on existing roads but can be used to evaluate proposed locations of utility poles on new roads as well. However, the procedure cannot be used to evaluate other roadside fixed objects or roadway design elements, either alone or in combination. Hence, its applicability to highway design is limited. As a design tool, it can only be used to evaluate utility pole placement. Moreover, the procedure does not consider the effects of horizontal or vertical alignment; the frequency of horizontal curves greater than 3 degrees; the frequency of sight-restricted vertical crest curves; the percent grade; or the frequency of access points; driveways; and intersections.

Roadside Case Study

The ROADSIDE computer program was applied to an improvement project provided by the Washington DOT. The highway, (a two-lane, principal arterial through rural, mountainous terrain), runs north/south along the shoreline of a canal. The posted speed limit for this section of roadway is 50 mi/h.

In addition to restoring the surface condition of the roadway, this project included several safety improvements at spot locations. While the overall project covered 3.8 mi, this case study focused on the safety improvement for one location. At this location, the traffic lanes are 11-ft wide with 3-ft shoulders. The embankment on the eastern side of the road that leads down to the canal has a slope of approximately 2:1. The safety improvement for this location consisted of installing 656 ft of guardrail along the edge of the shoulder.

Accident data were available for 5 years before and 5 years after the roadway improvement project. At this location during the period preceding the project, there were three reported single-vehicle, run-off-road accidents that were described as either "earth bank or ledge" or "over embankment—no guardrail." These accidents resulted in four injuries, of which one was classified as "disabling injury" while the others were classified as "evident injury." During the post-project period, there was only one reported accident at this location. This accident, described as "face of guardrail—not thru," resulted in three injuries, all of which were classified as "evident injury." There were no fatalities in either the pre- or post-project periods at this location. It is possible that there were additional minor collisions with the guardrail that were not reported, which, in the absence of guardrail, may have resulted in serious accidents.

In using the ROADSIDE computer program to analyze this safety improvement, all global default values were retained. The embankment was modeled as a 2:1 foreslope, 3 ft from the edge of the traffic lane, and 656 ft long. Because there is no real face associated with the embankment to give it "width," as there would be with other fixed objects such as a bridge pier, a nominal width of 1 ft was used for analysis. This corresponds to the width of the guardrail that was installed. Using the actual width of the embankment would yield a predicted number of collisions greater than those predicted for the guardrail, because of the larger dimensions of the embankment. Because the guardrail was placed at the same lateral offset as the embankment was located and they were the same length, there should be the same number of expected collisions for both cases. All the safety benefits from this improvement are a result of reduced severity, not reduced collision frequency.

For the purpose of this case study, an alternative safety improvement was considered. Because of the topography (i.e., a steep embankment leading down to a canal), it would not be feasible to flatten the sideslope. It would be possible, though expensive, to shift the centerline of the roadway away from the canal. This shift would create a wider shoulder in which some errant vehicles could recover before reaching the nonrecoverable embankment. Thus, the safety benefits of this improvement, unlike the installation of guardrail, would be a result of reduced collision frequency and not reduced accident severity. For this hypothetical improvement, it was assumed that the centerline of the roadway could be shifted 5 ft farther from the canal to the right, creating a shoulder 8 ft wide.

Table 18 summarizes the actual and predicted accident rates, for the "before" and "after" conditions for all three design alternatives (i.e., do nothing, install guardrail, and shift the centerline of the roadway away from the canal). Also shown is the expected accident costs during the first year of each period. These costs are the result of the predicted collision frequency, the average severity for each type of object, and the costs associated with accidents of varying severity. The severity indices were taken from AASHTO's *Roadside Design Guide* (*9*), and the associated costs as a function of severity were the defaults in the ROADSIDE computer program.

As shown in Table 18, the model underpredicted the number of accidents for the "before" period. Comparison of the predicted number of accidents with the "after" period, however, still provides some insight into the expected relative benefits provided by the differing design alternatives. For instance, the model predicts a slight increase in the number of accidents for the "after" period under the "do nothing" alternative. This increase is a result of increased traffic. For the guardrail alternative, the model predicts no reduction in accidents, but a significant drop in associated costs caused by lower-severity accidents. Finally, the "move road" alternative shows the expected decrease in the predicted number of accidents. However, because the remaining steep slope accidents will still be far more severe than those involving guardrail, the safety benefit is not nearly as large as for the guardrail alternative.

TABLE 18. Expected and actual number of accidents for roadside case study

	Before Improvement Project			After Improvement Project		
	Total Number of Collisions During 5 Years		Predicted Accident Costs During 1st Year	Total Number of Collisions During 5 Years		Predicted Accident Costs During 1st Year
	Actual	Predicted		Actual	Predicted	
Existing Conditions	3.00	0.46	$7,024	N/A	0.51	$7,771
Install Guardrail	N/A	N/A	N/A	1.00	0.51	$798
Move Road	N/A	N/A	N/A	N/A	0.36	$5,467

CHAPTER 4

FURTHER RESEARCH REQUIREMENTS

Two of the objectives of this research were to identify the major deficiencies in the state of the art and to develop research plans to address the deficiencies. This chapter describes these deficiencies. The scope of this study limited the deficiencies to items pertaining to highway geometric design-safety relationships. To identify deficiencies, the researchers critically reviewed documented accident relationships for specific highway geometric design features and/or elements, alone and in combination. While a variety of measures of effectiveness (e.g., traffic conflicts, erratic maneuvers, driver workload, changes in operating speed/average speed profile, roadside encroachments, lane departures) have been used to investigate the relationship between safety and geometric design, the primary measure has been accident based (e.g., accident rates, accidents per mile, annual accident frequencies, accident severity distributions). Accidents and injury severity are appropriate primarily because they are measurable, observable events for which data are compiled and maintained, and they can be converted to a monetary value that can be used in a benefit/cost analysis.

Using results from the survey of state practices, the researchers assessed the relative importance of the relationship and the need for additional information or improved relationships as expressed by the respondents. In addition, inputs and value judgments of the research team were incorporated into the deficiency identification analysis. This chapter concludes with a presentation of ranked research plans that address the major deficiencies. Criteria considered in developing a list of proposed research include the following:

- The chance for success of the research
- Geometric highway designers' need for the information
- Potential usefulness of the results.

DIFFICULTIES IN ESTABLISHING MEANINGFUL SAFETY RELATIONSHIPS

The traditional approaches to assess safety performance from accident data have involved a variety of techniques. These approaches have included simple "before" and "after" accident studies, "before" and "after" accident studies with control or comparison groups, comparative studies, and studies that have attempted to develop statistical relationships through the use of regression between variables. Many of the accident research studies that have been conducted in the past have been subject to numerous criticisms including the following:

- Inadequate sample size
- Improper application of statistical analysis techniques
- Application of inappropriate statistical analysis techniques
- Poor quality of the crash data
- Poor location information related to reported crashes
- Unreported crashes
- Changes in accident reporting thresholds, forms, and practices
- Failure to account for changes to the physical environment
- Failure to properly account for confounding factors
- Failure to consider other factors or variables
- Failure to properly account for maturation and age effects
- Failure to properly account for regression-to-the-mean effects.

In addition to these criticisms, the cost to conduct accident research is fairly high. Actions required to properly control for numerous confounding factors further increase the costs of accident research.

Many of these criticisms of past accident-based highway safety research on geometric design were indeed justified. In general, although previous research has produced estimates of the apparent safety effects of geometric designs and/or traffic control treatments (e.g., 6:1 slopes are safer in terms of accident experience than 4:1 slopes, which in turn are safer than 3:1 slopes), these research efforts did not yield empirically supported and definitive safety relationships between design variables. However, many of the difficulties that have haunted accident research are now being addressed. Research is underway to develop more appropriate statistical analysis methods and guidelines for their application to accident analyses. Research is also underway to demonstrate the benefits from applying new and emerging technology to the accident data collection process. Promising applications include the use of improved geographic location systems, such as the Global Positioning System, and portable computers by police officers at the crash scene. In the future, identification technologies, such as driver's licenses with magnetic stripes, vehicles with bar-coded vehicle identification numbers, "smart" cards with radio frequency chips, and other automated vehicle identification systems, may produce further improvement in accident data quality. Many states are implementing improvements to their accident data systems. Several have been able to successfully integrate traffic, accident, and roadway data files. The FHWA has established the HSIS. Currently, accidents, traffic, roadway, and other data (e.g., intersection files, interchange files, guardrail files) from five states (Illinois, Maine, Michigan, Minnesota, and Utah) are maintained and supported under contract to FHWA by the University of North Carolina's Highway Safety Research Center. More than 8 years of accident data (1985 to 1992) for each of the five states are now accessible in SAS-compatible formats. By the end of 1994, the HSIS will be expanded to include four more states (not yet selected at the time this report was prepared). The expansion will result in a more geographically diverse and larger sample. Data from the HSIS are available and have been used in many recent accident research studies.

Thus, it can be seen that efforts are underway to address many of the deficiencies associated with traditional accident research approaches. While data accuracy and underreporting of property-damage-only accidents will continue to pose a problem, it appears that the quality of the accident research and subsequently the resulting relationships will improve in the future. Therefore, it is concluded that there is merit to continuing to conduct accident research studies of geometric design features and elements.

DEFICIENCIES IN THE STATE OF THE ART

While information about accidents and selected geometric design elements does exist, very few definitive safety relationships for a combination of geometric design features have been established, identified, and/or documented. Some within the transportation engineering community would say that none of the documented relationships is definitive. The apparently complex relationships between the driver, vehicle, roadway, roadside, traffic, environment, and safety are not well understood.

Several studies have attempted to develop accident relationships for selected geometric variables (e.g., lane width, shoulder type and width, degree of curvature, sideslope) for specific road situations (e.g., two-lane rural road sections, individual horizontal curves). Many of these studies have focused solely on one aspect of the design (e.g., degree of curvature for individual horizontal curves) without considering other geometric design parameters (e.g., upstream and downstream horizontal alignment, vertical alignment). Examining the relationship between accidents and individual highway geometric design variables without considering the interactive effect of other parameters can yield biased or masked relationships. For example, a simple relationship between accident rates and clear zone width without considering sideslope, horizontal alignment, and vertical alignment would have limited utility to the designer. Intuitively, a 10-ft clear zone with a 6:1 sideslope for a long tangent section on a level, two-lane rural road is "safer" than a 10-ft clear zone with a 4:1 sideslope for a short, sharp curve on a two-lane rural road in rolling terrain.

Research efforts that have attempted to investigate the interactive effects of combinations of geometric variables have not produced meaningful results. The reasonableness and applicability of relationships that were developed many years ago have also been questioned. Factors that intuitively influence safety have changed significantly over the years. Factors such as automated braking systems, improved impact protection systems, passive and active occupant restraint systems, and public awareness campaigns against drunk driving have contributed to decreases in average rates for accidents, fatalities, and personal injuries. Consequently, during the development of accident relationships for geometric characteristics, the issue of how the influence of nonroadway factors should be considered needs to be addressed.

In general, research efforts that have attempted to develop relationships between accidents and geometric variables have not explicitly considered driver, vehicle, or environmental characteristics. One possible approach to improve upon this situation would be to develop relationships that would include driver and vehicle variables that could change significantly over 20 years. However, this approach is limited because of sample size availability and experimental/statistical considerations. To produce a meaningful and valid statistical model that employs a large number of independent variables requires a very large sample. If the sample size is limited, the confidence that one can place in the relationship is weakened. Another approach would be to re-calibrate accident-geometric models every few years as nonroadway factors change. Thus, the influence of nonroadway factors can be more effectively considered over time.

There are still voids in the body of knowledge that constitutes the state of the art. It should be clearly understood that the focus of this study was on roadway segments. Intersections and interchanges were deemed to be outside the scope of this study. Consequently, deficiencies related to geometric design elements and features for at-grade intersections, grade-separated interchanges and structures, railroad grade crossings, and bridges were not identified. Research plans for intersections and interchanges were not developed.

The major deficiencies found through this research are described in the following paragraphs. The deficiencies have been stratified in terms of their application to both new construction and reconstruction projects, or primarily to reconstruction projects.

Deficiencies Applicable to Both New Construction and Reconstruction Projects

It is important to recognize that after the first item in the list below, the remaining items can be considered to be subsets of the first one.

1. The absence of reliable tools that designers can use to assess the effects of their design alternatives and design decisions to prevent crashes, fatalities, personal injuries, and accident costs. The ideal would include a reliable accident prediction model that allows the designer to quantify the safety effects of different combinations of horizontal and vertical alignment, cross-sectional elements, and roadside design parameters for various functional classifications and highway types.

- The lack of an adequate relationship of accidents to sideslope *in combination with* clear zones as a function of functional classification, terrain, horizontal *and* vertical alignment, number of lanes, presence of median, paved shoulder width, lane width, and ADT volume for primarily higher-speed, rural roads without curbs or longitudinal barriers such as guardrail
- The lack of adequate information about the relative safety effectiveness of longitudinal barriers such as guardrail versus "clear" roadside as a function of sideslope(s), cut versus fill section, distance to nearest nonbreakaway objects (both manmade objects and natural potentially hazardous obstacles), drainage ditch shape and depth, functional classification, horizontal alignment, vertical alignment, paved shoulder width, ADT, lane width, presence of median, and degree of access control for primarily higher-speed rural roads with open sections

- The lack of relationships between accidents and cross-sectional elements (including roadside design aspects) for various functional classifications of *multilane* urban and rural highways, especially nonfreeway facilities
- The lack of information about the relative safety effectiveness of median barriers as a function of median width, number of lanes, terrain, combination of horizontal and vertical alignment, average highway speed, traffic volumes, frequency of access points for freeways (e.g., with full control of access) and nonfreeways (e.g., with partial or no control of access) facilities
- The lack of a relationship between safety and geometric design consistency. The concept of design consistency has been embraced by many highway agencies; however, there is a great deal of debate about whether design-inconsistent locations manifest themselves as high-accident locations. In addition, relatively few specific guidelines exist to identify design inconsistencies.

Deficiencies Applicable Primarily to Reconstruction and Rehabilitation Types of Highway Design Projects

- The lack of information about the relative safety effectiveness of restriping narrower lanes and/or allowing the use of shoulder lanes (with and without pull-out areas) to create additional travel lanes on urban freeways, urban and suburban arterials, and other roadways
- The lack of definitive information about the relative safety effectiveness of alternative cross-sections—including a 16-ft-wide raised median; a 16-ft-wide two-way left-turn-only lane (TWLTL); a 28-ft-wide median, a 40-ft-wide median, and a 52-ft-wide median—for reconstruction projects in which two-lane roads are widened to four or more lanes
- The lack of information on effects of specific safety improvements (e.g., minor widening on the outside of curves, increases in selected curve radii, lengthening of sight-restricted crest vertical curves) implemented in conjunction with resurfacing projects.

The items cited above can be considered to be specialized problems that may not be readily addressed as part of future accident research efforts on geometric design variables.

CRITICAL NEEDS AND AN OVERALL FRAMEWORK TO ADDRESS THOSE NEEDS

During the course of this research, highway designers, planners, and engineers expressed the need for more detailed and accurate information on the effects of their design decisions on safety. While available traffic models can be used to assess the impact of geometric changes (e.g., adding lanes, changing lane width, lengthening turn lanes at intersections) on traffic flow and service level, no nationally accepted methodologies exist to assess the impact on safety and accidents. Similarly, while traffic models can be applied to predict operational measures of effectiveness for new highway facilities, intersections, and interchanges, there are no nationally accepted procedures to predict accidents for proposed highway design alternatives. Many in the highway engineering community have expressed the need for procedures that can be applied consistently and logically to analyze and quantify the projected accidents for their designs. Researchers judged the lack of safety assessment tools to be one of the most pressing critical needs. Improved knowledge of the relationships between safety and geometric design is highly desirable. Designers would certainly benefit if they had the ability to directly apply the relationships to assess their designs.

FHWA has recognized the need to develop the safety analysis tools and the underlying safety-design element relationships on which they should be based and has initiated a program to develop those tools. For FHWA's Office of Safety and Traffic Operations Research and Development, three contractors independently developed concept reports (*21,22,23*) for an IHSDM that relates safety to highway design. In a subsequent effort (*24*), one of the contractors consolidated the recommendations made in the three separate plans as well as for roadside safety research from another effort (*25*). The IHSDM "will provide information on safety and geometrics in a format that a highway designer can use. It will guide the designer in evaluating the safety of the design (*26*)." The model's exact format was not yet specified at the time that this report was prepared.

The plan for the IHSDM continues to evolve. The highway design process within most states can be divided into a preliminary design phase, which is often associated with preparing environmental impact statements (EISs), and a detail design phase, which is associated with preparing plans, specifications, and estimates. Consequently, because of the type of data available at each phase, two versions of the IHSDM are envisioned. The first is a level 1 model that would be applicable during the preliminary phase of a highway design project. It is expected that the application of the level 1 model would produce the expected number of accidents on the basis of basic geometric design information such as number of lanes, ADT, speed, and urban/rural environment. The level 1 model is planned to consist of a series of accident prediction submodels that would be applicable to roadway sections, intersections, interchanges, and roadsides by roadway type. It is envisioned that the individual estimates would then be summed to predict the total (i.e., roadside as well as roadway). The level 2 model would be used to evaluate and finalize geometric design details during the development of the plans, specifications, and estimates. The level 2 IHSDM is anticipated to be a shell (computer software) that would provide an interface between specific modules and a commercial computer-aided design (CAD) package. The concept for the IHSDM in 1994 called for the following modules, which could be interfaced with data found in current CAD packages:

1. An accident prediction module will estimate the expected number and severity of accidents for different geometric design alternatives for specific highway projects, including both new construction and improvements to existing highways.
2. A policy review module will assist designers in evaluating design elements that are not addressed by the other modules. This module will provide a means for explicitly documenting decisions related to design exceptions.
3. A consistency module will pertain to the issues of consistency between design speed and operating speed.
4. A benefit/cost module is aimed at giving designers the ability to determine if incremental increases in construction costs could be justified on the basis of reduced accident costs.

5. A roadside safety structure module will enable designers to design roadside safety structures that reduce injury severity.
6. A driver module will be prepared, but its specific function and purpose were not specified when this report was prepared.
7. A vehicle dynamics module will allow a designer to "drive" the design vehicle, which would be one of the design vehicles listed in the AASHTO Green Book (*9*), through the highway alternative design and develop a speed profile and data on lateral accelerations. The ability to travel through the design will give the designer a visual method of looking for poor design situations.
8. A traffic module will provide data on vehicle operations, notably ADT, to help establish the accident-ADT-geometrics relationship.

The IHSDM, if properly developed, ultimately will serve as an analysis tool to estimate safety impacts. Consistently applying such a model would allow designers and decision makers to make more informed decisions about the need for and safety consequences of design exceptions. Moreover, applying the IHSDM should improve how safety is considered and incorporated into geometric design.

It is important to understand that the final recommended concept incorporated several different frameworks for assessing the safety of alternative geometric designs. The first module would be based on both future accident research and documented relationships between accidents and geometric design elements. Thus, the proposed approach to create this module would involve the development of accident prediction statistical models. However, most of the other modules do not involve accident prediction. It is envisaged that the policy review module, the consistency module, and the vehicle dynamics module, along with the graphics package, would function within a CAD platform. For example, the graphics package would allow highway designers to view a three-dimensional representation of their design while working on a CAD system. The policy review module would basically use the CAD files for a proposed design as input and "flag" items that violated AASHTO or specific state design standards. In a very similar manner, the consistency module would use the CAD files and "flag" locations where design inconsistencies exist. Perhaps the most intriguing of the modules is the vehicle dynamics module, because it is likely to attempt to model driver behavior. It is envisaged that the user of the IHSDM could visually or analytically track the movement of single or multiple vehicles along the proposed highway design within the CAD environment.

The proposed concept for an IHSDM addresses many of the deficiencies related to safety-geometric design relationships. In fact, the development of the proposed model could serve as an overall framework for future research that would fill the voids in the knowledge data base, provide greater in-depth insights into the relationships between design and accidents, and produce much needed tools for the highway designer.

RELEVANT ONGOING RESEARCH

The needs for future research were developed recognizing that several relevant projects were being conducted when this report was prepared. The following paragraphs describe these revelant research efforts.

One of FHWA's research and development programs pertains to highway safety design practices and criteria. The objective of the program is to reduce the number and severity of single- and multivehicle accidents on U.S. highways by designing the appropriate level of safety into the highway infrastructure at the lowest cost. Within this FHWA research program, a study entitled "Vehicle Dynamics Programs for Roadway and Roadside Studies" was underway in 1994. This study is selecting vehicle dynamics model(s) for incorporation into the IHSDM and for related research applications. In 1993, a geometric design laboratory was established within FHWA's Turner-Fairbank Research Center in McLean, Virginia. The laboratory will provide administrative and technical support in developing, evaluating, operating, and supporting the IHSDM. Plans for 1994–1995 FHWA-funded research include the following: Development of a series of level 1 IHSDM modules to assess the safety impacts of alternative highway designs for use at the planning or preliminary design stage. In 1994, initial work was performed by FHWA and on-site support contractor staff to develop preliminary relationships using accident, traffic, and roadway data from the HSIS and other sources.

On a slightly different topic, another FHWA research study that was underway in 1994 deals with geometric design consistency, which has been defined as the avoidance of abrupt changes in geometric features for contiguous highway elements and the use of design elements in combination that meet driver expectancies. The scope of this FHWA study, "State-of-the-Practice: Geometric Design Consistency," included a review of Canadian, United States, European, and Australian literature; a human factors test of driver workload; the collection and analysis of speed and highway geometry data; and the collection and analysis of accident and geometric data for curve sites on two-lane rural roads. Preliminary findings indicate that accidents increase as the required speed reduction increases. The required speed reduction was derived as the difference in the speed on the tangent approach and the speed required to safely negotiate the curve.

Two related NCHRP studies were also underway in 1994. One of them, Project 22-9, "Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features," was initiated in late 1991. The objective of this project was to develop improved microcomputer-based, cost-effectiveness analysis procedures for use in the following:

- Assessing alternative roadside safety treatments at both point locations and along sections of roadway. (Note: The current ROADSIDE model is primarily applicable to points.)
- Developing warrants and guidelines, including those which consider performance levels of safety features. (Note: *NCHRP Report 350* [*27*], which basically supersedes *NCHRP Report 230*, recommended procedures for the safety performance evaluation of highway features.)

It is anticipated that, as a minimum, the study will produce improvements and enhancements to the ROADSIDE model so it can be applied to evaluate continuous sections of roadside rather than spot locations.

The other NCHRP study is Project 17-11, "Determination of Safe/Cost-Effective Roadside Slopes and Associated Clear Distances," which was initiated in early 1994. The objective of this research is to develop relationships between recovery-area distance and roadway and roadside features, vehicle factors, encroachment parameters, and traffic conditions for the full range of highway functional classifications and design speeds.

PROPOSED RESEARCH PLANS

The plans for future research were developed with the following underlying assumptions:

1. Designers need and would use information about the safety relationships between design parameters.
2. Despite the limitations associated with accident research analysis, improved relationships between safety (expressed in terms of accidents per exposure or per distance) and design elements are needed *and* could be developed.
3. It is recognized that any and all models that could be developed would *not* perfectly fit the data. Even the best accident-design element relationship that could be expected realistically would *not* account for all the variation in the data.

On the basis of the surveys that were conducted for this project and inputs from the research team, the key research topics in order of descending priority are summarized as follows:

1. Develop a computer-based tool(s) that would allow designers to vary a wide range of different design parameters (e.g., cross-section, horizontal and vertical alignment, median, and roadside elements) and quantify the effect on safety, specifically accidents. In terms of ranking, the following summarizes the recommended order for establishing those relationships for roadway segments:

   - Two-lane rural roads with ADTs > 2,000 vpd
   - Rural, multilane nonfreeways
   - Two-lane rural roads with ADTs < 2,000 vpd
   - Urban, multilane nonfreeways
   - Rural freeways
   - Urban freeways and expressways.

2. Develop explicit relationships between accidents and roadside-related design elements and features for rural roads.
3. For two-lane, paved roads with ADTs of greater than 2,000 vpd, develop relationships between 1) accident frequency, rate, and severity and 2) appropriate combinations of the following variables:

   - Clear recovery area distance and roadside features
   - Roadway features and characteristics (e.g., cross-section, alignment, functional classification)
   - Roadside slopes
   - Traffic factors
   - Vehicle factors (e.g., vehicle type, safety equipment used/deployed).

4. For two-lane rural roads with ADTs of fewer than 2,000 vpd, determine the relationship between 1) accident frequency, rate, and severity and 2) the combination of roadside features and characteristics, roadway characteristics, and traffic variables.
5. Determine the specific conditions that contribute to the increase in accidents that can and often do occur after a two-lane rural road is resurfaced without any accompanying safety improvements. In a recent TRB paper (*8*), which summarized the findings from a study of sites in New York State, it was reported that resurfacing two-lane rural roads without any other additional reconstruction or safety improvements resulted in a 21 percent increase in accidents over the first 30 months after resurfacing.
6. Develop a model/procedure to estimate the safety effectiveness of alternative cross-sections (with and without median barriers) for multilane, nonfreeway highways in urban, suburban, and rural areas. Cross-section variables will include median width and type, sideslope, foreslope, drainage ditch depth and design, and clear zone, among others.
7. Develop a model/procedure to estimate the safety effectiveness of alternative cross-sections (with and without median barriers) for median-divided freeways. Cross-section variables will include foreslope, backslope, drainage ditch depth and design, median width and type, and clear zone, among others.
8. Conduct additional research on geometric design consistency. As noted in the discussion of ongoing research, an FHWA study is investigating geometric design consistency and attempting to develop a model that relates geometrics to accidents for horizontal curves on two-lane rural roads. While the initial findings appear promising, additional research should be conducted.

These proposed research topics pertain to combinations of different highway/functional types (i.e., two-lane rural roads, freeways, multilane nonfreeways) and design element categories (e.g., cross-sectional elements, alignment elements, roadside elements). Table 19 correlates the proposed research plans as a function of area/highway type and of design category.

For each research plan, more detailed discussions of the objectives, the critical factors to consider, data requirements, projected work elements, and anticipated costs to conduct the research are presented on the subsequent pages.

RESEARCH PLAN 1. Accident Prediction Submodels for Roadway Segments, Intersections, Interchanges, and Roadside

Background. The FHWA has embarked on a program to develop an IHSDM that will operate within the CAD environment. When the IHSDM is available, the designer will be able to input the data for a design alternative (e.g., horizontal alignment, vertical alignment, typical cross-sections) into the CAD platform and then use a variety of IHSDM modules to assess and quantify the safety of that design. The designer will also be able to vary the design parameters and assess the impact of those design changes on safety. It is anticipated that the IHSDM can be applied to assess safety at the project planning/EIS stage, the preliminary design stage, and the final design stage. To support that model development effort, research is needed to develop accident prediction models for roadway segments, intersections, interchanges, and roadside for a variety of functional classifications and highway types.

Objectives. The objective of this research would be to develop a level 1 IHSDM accident prediction module and then a level

TABLE 19. Recommended research plans categorized by highway type and design category

	HIGHWAY TYPE	RECOMMENDED RESEARCH PLAN NUMBER BY HIGHWAY DESIGN CATEGORY			
		Alignment	CROSS-SECTION	MEDIAN	ROADSIDE
Urban & Suburban	Multilane, Divided Freeway	1	1,8	1,8	1
	Multilane, Divided Nonfreeway	1	1,6	1,6	1
	Multilane, Undivided Nonfreeway	1	1,6	N/A	1
	Two-lane, Undivided Nonfreeway			N/A	
Rural	Multilane, Divided Freeway	1	1,8	1,8	1
	Multilane, Divided Nonfreeway	1	1,6	1,6	1,2
	Multilane, Undivided Nonfreeway	1	1,6	N/A	1,2
	Two-lane, Undivided Nonfreeway (ADT > 2000)	1,3,5*,7	1,3	N/A	1,2,3
	Two-lane, Undivided Nonfreeway (ADT < 2000)	1,4	1,4	N/A	1,4

*Project 5 applies to two-lane rural road resurfacing projects. While the scope will extend to include cross-section and roadside design parameters, it is expected that the primary emphasis will be on alignment.

2 IHSDM accident prediction module for highway segments for the following highway types, which are listed in order of priority:

- Paved, two-lane rural roads with ADTs > 2,000 vpd
- Multilane, rural arterial and collector roads
- Multilane, urban arterial and collector roads
- Rural freeways
- Urban freeways and expressways.

The level 1 IHSDM would represent a preliminary model and be applicable to the project planning/EIS corridor-level stage of design. The level 1 IHSDM would consider only a limited number of variables and not reflect detailed aspects of the ultimate design. The accident prediction module of the level 2 IHSDM would be applicable to the preliminary and final stages of design. Consequently, it would be much more detailed than the level 1 IHSDM in that it would consider numerous design features and parameters.

The last plan pertains to geometric design consistency for rural roads. Because the scope includes intersections and interchanges in addition to basic segments, it is not shown in the table.

Critical factors. It is envisaged that for the accident prediction module for the level 2 IHSDM, the highway environment would be stratified into roadway segments, intersections, interchanges, and roadside. For the purposes of statistical model building for this proposed research, separate models are proposed for roadway segments, intersections, interchanges, and roadsides. The intersection area can be defined to include 200 ft of all approach legs. Similarly, interchange areas can be defined to include a distance 200 ft beyond the terminals of the outer ramps.

The final concept report for the IHSDM recommended that accident prediction models be developed that relate on-roadway accidents to design and traffic features related to cross-section, horizontal curves, and others. Roadside accidents would be estimated separately. To support the IHSDM development effort, it is recommended that the statistical models that would be developed as part of this proposed research effort consider only on-roadway accidents for the roadway segment, intersection, and interchange submodels in accordance with the IHSDM concept. A submodel for roadsides would also need to be developed.

- *Data requirements.* Data requirements include at least 3 years of reported accident, roadway alignment, cross-section, median (if a divided highway), and traffic data.
- *Projected work elements.* To meet the objectives, a two-phased research approach is planned. The tasks associated with each phase are described as follows:

Phase I

Task 1. Review relevant literature on accident rates and injury severity for basic highway sections. Identify and compile information on available accident-roadway-traffic data bases. Develop objective criteria to select data bases. Apply the criteria to available national, state, or other data bases and identify the most promising. Solicit the cooperation of agencies or entities responsible for maintaining the data bases. For developing representative and national relationships, the desirable minimum is three geographically distributed state data bases.

Task 2. Develop an experimental plan(s) to create a level 1 IHSDM that can be applied to predict accidents by severity as a function of cross-section, alignment, traffic, and other variables for each of the following facility types:

- Paved, two-lane, rural roads with ADTs > 2,000 vpd
- Multilane, rural, arterial and collector roads
- Multilane, urban, arterial and collector roads
- Rural freeways
- Urban freeways and expressways.

Task 3. Collect and analyze accident data in accordance with the experimental plans. Develop the preliminary level 1 IHSDM for roadway segments, intersections, and interchanges for each facility type. Validate the model.

Task 4. Convene a panel of experts in geometric highway design. Review the preliminary level 1 IHSDM. Discuss the potential applications, needs, data requirements, level of accuracy, and other issues for an accident prediction module for the level 2 IHSDM that can be applied at both the preliminary and final design stages. Solicit inputs from a panel of experts.

Task 5. Develop a detailed plan to develop the roadway segments, intersections, interchanges, and roadside submodels of the accident prediction module for the level 2 IHSDM, including a proposed data collection and analysis plan.

Task 6. Prepare an interim report that presents and describes the preliminary level 1 IHSDM. The interim report should also contain the detailed plan to develop the level 2 module.

Phase II

Task 7. Collect the data in accordance with the proposed plan that was contained in the interim report.

Task 8. Perform statistical analysis of the accident-roadway-traffic data base. Develop appropriate accident prediction submodels for basic segments, intersections, interchanges, and roadsides. Validate the submodels.

Task 9. Develop a user's manual and software to apply the accident prediction model.

Task 10. Prepare a final report documenting the efforts undertaken and the findings of the study.

Associated costs: $600,000 for Phase 1 and $1,250,000 for Phase 2

RESEARCH PLAN 2. Accident Prediction Model for Roadside Features and Elements

Background. Many respondents to the state survey indicated that they frequently perform trade-off studies of using guardrail or longitudinal barriers versus providing a "clear" roadside (i.e., a roadside with a traversable sideslope that is void of fixed obstacles or potentially hazardous objects within a specified distance from the edge of travel lane). Consequently, the need is critical to provide designers with meaningful accident relationships for roadside-related elements. Currently, the most widely used model for predicting roadside accidents was developed over 20 years ago. The ROADSIDE model, which is available as a stand-alone software program and is based on *NCHRP Report 148* (*28*), is described in the AASHTO *Roadside Design Guide* (*9*). The current ROADSIDE model and the benefit/cost procedure presented in the AASHTO *Roadside Design Guide* (*9*) employ a predictive methodology in which the annual number of vehicle impacts with a roadside hazard is estimated on the basis of the following:

- ADT
- Lateral offset from the edge of the travel way to the object
- Length of the hazard (parallel to the roadway)
- Width of the perpendicular face of hazard
- An underlying average rate of vehicle encroachments into the roadside.

While the procedure is mathematically appealing in that it can be used to evaluate a wide variety of offsets and shapes (i.e., length and width) of roadside hazards, it is based on limited empirical encroachment data that were obtained on freeway medians nearly 30 years ago. The proposed concept for an IHSDM calls for the development of an improved encroachment-based model to evaluate roadside designs, features, and objects. Research plans for the IHSDM roadside evaluation model development effort include the following:

> . . . validation of the roadside safety model using data that are independent of the data used in its development. In addition, model validation by other than probabilistic modeling based on encroachment and accident severity data should be considered. (*24*)

Consequently, the accident-based research proposed for this project could later be used as a data source for the calibration of the IHSDM.

It is recognized that NCHRP Project 17-11, "Determination of Safe/Cost-Effective Roadside Slopes and Associated Clear Distances," and NCHRP Project 22-9, "Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features," address this topic. NCHRP Project 22-11, "Evaluation of Roadside Features to Accommodate Vans, Mini-Vans, Pick-up Trucks, and 4-Wheel Drive Vehicles," also is related to this topic.

Objectives. The objectives of this research are 1) to ascertain the relationship between reported accidents and the combination of sideslope and clear zone, 2) to ascertain the relationship between reported accidents and guardrail, and 3) to perform a cost-effective comparison of guardrail with "clear" roadside designs as a function of sideslope, critical traffic, and other geometric parameters.

Critical factors. In general, most freeways have fairly wide (e.g., 30 ft) and forgiving roadsides (i.e., devoid of unprotected and unyielding fixed objects; the objects that are present are either breakaway or crashworthy) with wide, paved shoulders and relatively flat, recoverable sideslopes. Consequently, there is a relatively low rate of roadside accidents. Right-of-way constraints, utility requirements, and additional roadside hardware often restrict the degrees of freedom for roadside design on urban arterial and collector streets. However, the number of fatalities resulting from roadside hazard crashes on rural roads excluding freeways is much higher than the numbers for freeways and other urban roads. A summary of the deaths in roadside hazard crashes by type of road from 1991 is shown in Table 20. Accounting for vehicle exposure, the difference in fatality rates between rural road types is even more pronounced.

Given the relative number of fatal roadside crashes on rural roads, the scope of this study should be limited to paved, two-lane and multilane rural roads (excluding freeways).

The final concept report for the IHSDM proposes that a roadside accident submodel be developed. The purpose of this submodel is to estimate the annual number of accidents by severity level in which the first harmful event is a vehicle leaving the roadway. As stated in the conceptual plan for the IHSDM,

> The severity-increasing effects of roadside design on vehicles that leave the roadway after a multiple-vehicle collision should also be considered. Generalized safety predictions based on a roadside rating system like the 1-to-7 scale used by Zegeer et al. could suffice for application of the IHSDM in a level 1 analysis. However, a model that addresses the safety effects of specific design features is needed for level 2 analyses.
>
> It should be recognized that roadside features are, strictly speaking, severity-increasing rather than causative factors in run-off-road accidents. The cause of a roadside accident is the vehicle, driver, or roadway factor (or combination of factors) that caused the vehicle to leave the roadway and encroach on the roadside. (*24*)

While it is readily acknowledged that underreporting and data quality are problems that beset run-off-road accidents in particular, accident data and accident relationships still provide valuable feedback on highway safety performance.

Data requirements. Accident, sight distance, geometric, roadside, median, and traffic data need to be collected or compiled for this research.

Projected work elements. The anticipated tasks associated with this research effort are as follows:

Task 1. Review relevant accident research on roadside crashes. Identify and compile information on available accident-roadway-traffic data bases. Develop objective criteria to select data bases. Apply the criteria to available data bases. Identify and solicit the cooperation of a minimum of three states to participate in the study.

Task 2. Develop an experimental plan that includes specification of the types of roadside data to be collected, the methodology to collect roadside data, the sample sizes, the proposed statistical analysis procedures and techniques to be applied, and the contingency plans/methods to address the anticipated problems with the accident-based approach.

Task 3. Collect and analyze accident data in accordance with the experimental plan. The sample size should be sufficient to ensure sufficient diversity in terms of functional classification, ADT, terrain, geographic location, cross-section design, roadside design practices, driver population, and accident reporting practices.

Task 4. Develop statistical models that relate roadside (and median if the road is divided) accidents to design variables pertaining to the roadside (e.g., sideslope, clear zone), cross-sectional elements (e.g., paved shoulder width, unpaved shoulder width), alignment (e.g., degree of curvature), and the median if the road is divided for the following:

- Two-lane rural roads
- Undivided, multilane rural roads
- Divided, multilane rural roads (excluding freeways).

Task 5. For a small sample of sections from a separate accident data base that was not used in the development and initial

TABLE 20. Deaths in roadside hazard crashes for 1991 by type of road (*29*)

Type of Road	Deaths in 1991 Roadside Hazard Crashes*	
	Urban	Rural
Freeway	997	709
Major Road	1,718	4,264
Minor Road	1,351	2,676

* Excludes 38 deaths for which the land use was "unknown"

calibration of the roadside accident prediction model, apply the model to estimate the number of accidents by severity and compare the results with the actual reported accidents. Using the same sample data set, apply the updated ROADSIDE model (i.e., the anticipated product that will be produced by NCHRP Project 22-9) to generate estimates of accidents. Compare the results of an application with actual accident data. Determine the relative validity of both the roadside accident prediction model and the anticipated updated ROADSIDE model. Identify potential enhancements.

Task 6. Develop a user's manual and software to apply the accident prediction model.

Task 7. Prepare a final report documenting the efforts undertaken and the findings of the study.

Associated costs:

Two-lane rural roads	$250,000
Multilane, undivided rural roads	$150,000
Multilane, divided nonfreeway rural roads	$100,000
Total	$500,000

RESEARCH PLAN 3. Accident Prediction Model for Paved, Two-Lane Rural Roads with ADTs > 2,000 vpd

Background. The anticipated results from research plan no. 2 would pertain primarily to the relationship between safety and roadside design parameters for multilane and two-lane rural roads. Research plan no. 3 would build upon that effort by attempting to incorporate the effect of additional cross-section, alignment, and other design parameters into the accident prediction model for paved, two-lane rural roads with ADTs of greater than 2,000 vpd. It should be noted that 2,000 vpd has frequently been used as a threshold value to define "low-volume" two-lane rural roads (*30*).

In accordance with the concept for the IHSDM that was proposed in 1994, the accident prediction module of the level 2 IHSDM will estimate the expected number of accidents for any design alternative. The accident prediction module has been divided into four separate submodels: roadway segments, intersections, interchanges, and roadside. The overall accident rate would be the sum of the accident rates for each individual road segment, intersection, interchange, and roadside area that make up the design alternative (*24*). The final concept report proposed that accident prediction models be established for different functional classifications that would estimate on-roadway accidents as a function of the following:

- Safety adjustment factors for the effects of cross-sectional elements such as lane width, shoulder width, and shoulder type
- Safety adjustment factors for horizontal curves based on radius of curve, length of curve, superelevation, etc.
- Safety adjustment factors for other geometric and traffic control elements that can vary longitudinally along the highway including grades, auxiliary lanes, speed limits, passing/no-passing zones, and driveway densities.

Thus, this proposed research plan differs from the proposed IHSDM research in the following ways:

1. Two-lane rural roads would be categorically segregated into high volume (i.e., greater than ADTs of 2,000 vpd) and low volume (i.e., less than ADTs of 2,000 vpd)
2. Roadside accidents and roadside characteristics would be included in the accident prediction model for two-lane rural road segments. Whereas the accident prediction module for the level 2 IHSDM is expected to consist of a submodel that estimates on-roadway accidents for highway segments and a submodel that estimates off-roadway accidents for roadside areas, this proposed research plan would effectively combine the two submodels. There is a great deal of difficulty in differentiating on-roadway from off-roadway accidents. Often they are not mutually exclusive, as some crashes involve multivehicle impacts within the travelway and subsequent impacts with fixed objects that are located beyond the travelway.

Objective. The objective of this plan is to develop relationships between reported accidents by severity level and appropriate combinations of the following for paved rural road segments with ADTs of greater than 2,000 vpd:

- Roadside features (e.g., clear recovery area distance, sideslope)
- Roadway features and characteristics (e.g., cross-section, alignment, functional classification)
- Traffic factors (e.g., ADT).

Critical factors. The study could build upon the work that was done by Zegeer et al. and previous accident prediction models for two-lane rural roads. The designer would prefer an accident prediction model for which explicit values of sideslope and clear zone can be input and evaluated. In lieu of sideslope and clear zone, Zegeer's cross-section model and horizontal curve model employ a roadside hazard rating as a surrogate for roadside design. Desirably, the final form of the accident prediction model should have the capacity to assess different combinations of clear zone and sideslope with and without guardrail.

Data requirements. This study requires a relational data base for paved two-lane rural roads with ADTs of greater than 2,000 vpd that includes, as a minimum, the following:

- Horizontal alignment (e.g., location of point of curvature, degree of curvature, length of horizontal curve, superelevation rate, presence of a spiral transition curve)
- Vertical alignment (e.g., location of the point of vertical curvature, length of vertical curve, approach grade, departure grade)
- Roadside data (e.g., sideslope, drainage ditch depth, distance to nearest fixed object, mean recovery distance, whether road is in cut or on fill)
- Cross-section data (e.g., paved roadway width, lane width, paved shoulder width, unpaved shoulder width)
- Traffic data (e.g., ADT, truck traffic as a percentage of the total daily traffic, posted speed limit)
- Accident data (e.g., injury severity, type of accident).

Projected work elements: The scope of work should include the following tasks:

Task 1. Review relevant research and documented safety relationships for paved, two-lane rural roads. Identify and compile information on available accident-roadway-traffic data bases and select the most appropriate one(s).

Task 2. Develop an experimental plan. The plan should build upon the research results of Zegeer et al.(*4,19*), including the horizontal curve procedure and the cost-effective cross-section procedure for two-lane rural roads. The plan must address, as a minimum, the following two issues:

- How roadside-related variables, including sideslope(s), clear zone width, and presence and type of roadside barrier, will be explicitly considered.
- How alignment design parameters will be integrated with cross-section, traffic, and other variables.

Task 3. Meet with NCHRP panel and discuss proposed plan.

Task 4. Collect and analyze accident data in accordance with the experimental plan.

Task 5. Perform statistical analysis of the accident-roadway-traffic data base.

Task 6. Develop an accident prediction model for paved two-lane rural roads with ADTs of greater than 2,000 vpd.

Task 7. Validate the model.

Task 8. Develop a software package that will facilitate the application of the accident prediction model. Develop a user's manual for the software package.

Task 9. Prepare a final report documenting the efforts undertaken and the findings of the study.

Associated costs: $500,000

RESEARCH PLAN 4. Accident Prediction Model for Paved and Unpaved Two-Lane Rural Roads with ADTs < 2,000 vpd

Background: Frequently, lower design criteria are applied to low-volume rural roads in the interest of cost-effectiveness. Clearly, the potential for certain types of accidents are much lower on low-volume, two-lane rural roads compared with other roads. However, that does not imply that low-volume, two-lane rural roads can be reconstructed, resurfaced, or rehabilitated without any minimum design standards. While low volume may translate into low accident counts and low probability, safety still needs to be designed into the road. Therefore, the segregation of two-lane rural roads into high volume and low volume (i.e., fewer than 2,000 vpd) was deemed necessary.

Several recent reports have dealt with the relationship of accidents and geometric design elements for low-volume, two-lane rural roads. FHWA published two reports for design engineers who are involved with the construction of new highways and the reconstruction of existing highways on federal lands. One of the reports is a user's manual (*31*), which was oriented toward problems faced by design engineers concerned with evaluating and documenting design exceptions for special cases where full design standards are difficult to meet. In addition, a research report (*30*) that focused solely on the geometrics of low-volume (i.e., ADTs <2,000 vpd), two-lane rural roads has also been produced for NCHRP Project 15-12, "Roadway Widths for Low-Traffic-Volume Roads." That study comprehensively investigated the effect of cross-section variables such as total roadway width, lane width, and shoulder width of paved and unpaved roads on related accidents. However, these reports did not comprehensively investigate the *combined* effect of cross-section *and* roadside design (e.g., sideslope and clear zone) *and* alignment (e.g., length and degree of curvature for horizontal curves, length and grade differential of crest and sag vertical curves, grade).

Objective. In a manner similar to research plan no. 3, the objective of this research plan is to develop relationships between reported accidents by severity level and appropriate combinations of the following for paved and unpaved rural road segments with ADTs of fewer than 2,000 vpd:

- Roadside features (e.g., clear recovery area distance, sideslope)
- Cross-section features (e.g., total pavement width, unpaved roadway width, lane width, paved shoulder width, unpaved shoulder width)
- Alignment features (e.g., degree of curvature)
- Traffic factors (e.g., ADT).

Critical factors. A critical issue pertaining to this proposed research plan is unreported accidents. Many low-volume rural roads are traveled by drivers familiar with them. A large number of single-vehicle accidents likely are not reported in rural areas. Consequently, the results of this proposed research would be biased toward more severe, multivehicle accidents, which are likely to be low. Another critical issue is the expectation that many low-volume rural road segments are likely to have no reported accidents over a period of many years. That does not necessarily mean that these roads are "safer" than other roads. Rather, this phenomenon suggests that the statistical probability of an accident, which is relatively speaking a rare event, is very, very low.

Data requirements. The data requirements for this research are similar to the data requirements for research plan no. 3. The target population, however, is low-volume rural roads, including unpaved roads.

Projected work elements. The scope for this plan is also similar to the scope for research plan no. 3 and includes the following:

Task 1. Review relevant research and documented safety relationships for low-volume, two-lane rural roads.

Task 2. Obtain documentation on available data bases that could be used for this effort. Review and assess the appropriateness of these data bases for this effort.

Task 3. Develop an experimental plan that addresses critical aspects related to an accident-based analysis of low-volume paved and unpaved two-lane rural roads.

Task 4. Convene a meeting with NCHRP panel members and others. Solicit inputs on the plan.

Task 5. Collect and analyze accident data in accordance with the experimental plan.

Task 6. Perform statistical analysis of the accident-roadway-traffic data base.

Task 7. Develop an accident prediction model for paved and unpaved two-lane rural roads with ADTs of fewer than 2,000 vpd.

Task 8. Validate the model.

Task 9. Develop a software package that will facilitate the application of the accident prediction model. Develop a user's manual for the software package.

Task 10. Prepare a final report documenting the efforts undertaken and the findings of the study.

Associated costs: $375,000

RESEARCH PLAN 5. Safety Impact Assessment Procedure to Evaluate Resurfacing Projects With and Without Safety Improvements

Background: As noted earlier, it is desirable to determine the specific combination of geometric features that experience increases in accidents after resurfacing without safety improvement projects. If the locations could first be isolated and if the cross-section, alignment, roadside, and other conditions for those locations could be determined, then it would be possible to determine the safety relationship.

Objectives: The objectives of this research are as follows:

- To identify the specific geometric conditions on paved, two-lane rural roads that experience an increase in accidents after resurfacing
- To quantify the expected change in accidents
- To develop a relationship between the geometric variables and post-resurfacing accidents.

Critical factors. The success of this research depends on the development of an accurate data base that contains data on roads that were resurfaced and other comparable roads that were not resurfaced, dates and durations of the resurfacing project, a detailed description of all additional improvements implemented as part of the resurfacing project, and accident data before and after resurfacing.

Data requirements. The data requirements are limited to the collection and analysis of accident and other data before and after resurfacing of two-lane rural roads. Consequently, accurate accident location data, roadway alignment data, cross-section data, and roadside data including data on guardrail and other roadside hazards and obstacles are necessary.

Projected work elements. This research is to be conducted as follows:

Task 1. Review relevant research related to the safety effects after resurfacing two-lane rural roads. Identify and solicit the cooperation of a minimum of three states to participate in the study.

Task 2. Develop an experimental plan that will specify what data are required, how the data will be obtained or collected, the proposed techniques to analyze the data, and anticipated results.

Task 3. Collect data in accordance with the experimental plan.

Task 4. Perform statistical analysis of the data.

Task 5. Identify specific combinations of geometrics that experience an increase in accidents after resurfacing. Quantify the expected increase in accidents. Develop an accident prediction model that relates geometric variables to post-resurfacing accidents.

Task 6. Validate the model.

Task 7. Develop a software package that will facilitate the application of the accident prediction model. Develop a user's manual for the software package.

Task 8. Prepare a final report documenting the efforts undertaken and the findings of the study.

Associated costs: $250,000

RESEARCH PLAN 6. Safety Impact Assessment Procedure for Alternative Cross-Sections of Multilane, Nonfreeways

Background. In rapidly developing areas, increasing traffic volumes often dictate the need to consider widening two-lane roads to multilane roads. For many projects, the available right-of-way is limited, especially in urban areas. Wetland and other environmental factors can also constrain the ability to widen a road. For some cases, highway agency decision makers desire to design future additional capacity into the facility (e.g., a future lane in each direction can be accommodated within a 40-ft-wide median if only single left-turn lanes are required at intersections). For other projects, numerous cross-section alternatives ranging from undivided sections with TWLTLs to divided sections with raised concrete medians are currently being evaluated without consideration of quantified safety benefits. The designer should have the ability to evaluate various cross-section alternatives and generate order-of-magnitude estimates of the potential safety effects in terms of accidents by severity level.

Objective. The objective of this research is to investigate alternative cross-sections of multilane, nonfreeway facilities in both urban and rural areas to determine the relationship between accidents by severity and cross-sectional design elements.

Critical factors. Compared with the proposed plan for the development of a level 2 IHSDM accident prediction module for basic segments, the scope of this proposed research differs as follows:

1. Arterial and collector functional classifications are combined.
2. Roads do not need to be segregated into basic segments, intersections, and interchanges. It is envisaged that variables related to access and intersection density will be input variables to this model.

3. Off-roadway accidents as well as on-roadway accidents are included.

The final product of this research will be an accident prediction model that can applied to evaluate alternative multilane cross-sections for urban arterial and collector streets and for rural arterial and collector roads.

Data requirements. Key cross-section design and other elements include the following:

- Type of cross-section (e.g., divided, undivided, TWLTL)
- Presence of curb and gutter
- Number of travel lanes
- Lane width
- Right paved and unpaved shoulder width
- Left paved and unpaved shoulder width
- Median width
- Type of median (including provision of barriers)

ADT

- Intersection density
- Density of median "openings"
- Density of other access points.

Projected work elements. This research is to be conducted as follows:

Task 1. Review relevant research related to arterial and collector cross-sections. Identify and compile information on available accident-roadway-traffic data bases. Develop objective criteria to select data bases. Apply the criteria to available data bases and identify the most promising data base(s). Obtain the necessary data.

Task 2. Develop an experimental plan that will specify what additional data (i.e., data that are not contained in the data base) are required, how the additional data will be obtained or collected, the proposed techniques to analyze the data, and the anticipated results.

Task 3. Collect additional data in accordance with the experimental plan.

Task 4. Perform statistical analysis of the updated accident-roadway-traffic data base.

Task 5. Develop a procedure/accident prediction model to assess alternative multilane cross-sections for urban arterial and collector streets and for rural arterial and collector roads.

Task 6. Validate the procedure/accident prediction model.

Task 7. Develop a software package that would automate the application of the procedure. Develop a user's manual to accompany the software.

Task 8. Prepare a final report documenting the efforts undertaken and the findings of the study.

Associated costs: $375,000

RESEARCH PLAN 7. Safety Impact Assessment Procedure for Alternative Cross-Sections of Freeways

Background. Available results from research studies indicate that providing peak-period shoulder lanes through short, capacity-deficient freeway bottleneck sections appears to significantly reduce congestion-related accidents. However, accident data do not conclusively indicate that providing shoulder lanes over long segments without emergency pull-offs results in greater safety. The continual rise in traffic volumes and the resulting increase in congestion has placed a greater demand for projects that increase peak period capacity. Highway administrators have shown increased interest in projects involving lane width reductions with and without minor widening to create additional travel lanes on urban freeways. There is a concern that the combination of minimum designs and 11-ft (and narrower) lane widths may adversely impact safety. In addition, there is the concern that reducing the median width to provide additional through lanes (i.e., widening the roadway by using part of the median) may result in an increase in accidents, especially if a concrete safety-shaped median barrier is installed as part of the widening project.

Objective. The objective of this research is to investigate alternative cross-sections of freeways to determine 1) effect on accidents by severity of freeway projects involving lane width reductions, the provision of shoulder lanes, median width reductions, the installation of median barriers and 2) the relationship between accidents by severity and freeway cross-section design elements.

Critical factors: At first glance, this study appears to be very similar to the development of a IHSDM level 2 model for freeways. However, there are a few important differences. The current concept for the accident prediction module of a level 2 IHSDM calls for developing separate accident prediction models for basic segments versus interchanges. Moreover, it is expected that the accident prediction module for the IHSDM will operate on a CAD platform, and use the design parameters specified as inputs to the CAD.

The scope of this proposed research does not require segregating the basic segments from interchange areas (i.e., the segment of freeway between the outer ramp-freeway terminals). It is envisaged that the designer will input the existing freeway cross-section parameters and the existing accident experience, if available. Then, the designer can use the procedure to assess the expected impact of a variety of alternative cross-section designs. The major products expected from this proposed research are a stand-alone procedure and software that do not require the designer to develop detailed CAD-based design drawings.

It is envisaged that this model will be more detailed than IHSDM level 1 but not as detailed as level 2. The proposed research plan should produce a tool that can be applied to evaluate alternatives for existing freeway corridors and alternative cross-sections for new freeways on new alignment. For a majority of projects, physical and environmental constraints frequently force designers to consider cross-sections that minimize the total required right-of-way. Minimizing right-of-way widths for a freeway typically translates into minimizing the median width. The designer should have the ability to evaluate various median widths with and without median barriers and generate at least order-of-magnitude estimates of the potential safety effects in terms of accidents by severity level.

Data requirements. Key cross-section design and other elements include the following:

- Type of operation (e.g., peak-period shoulder use)
- Number of lanes

- Lane width
- Right paved shoulder width
- Left paved shoulder width
- Median width
- Median cross-slope and median type
- Type of barrier(s) in median
- Lateral offset to barrier in median
- ADT
- Percentage of trucks
- Interchange entrance/exit density
- Density of emergency pull-offs having adequate storage.

Projected work elements. This research is to be conducted as follows:

Task 1. Review relevant research related to freeway cross-sections, including median design aspects. Identify and compile information on available accident-roadway-traffic data bases. Develop objective criteria to select data bases. Apply the criteria to available data bases and select the most appropriate. Obtain the data.

Task 2. Develop an experimental plan that will specify the proposed techniques to analyze the data, anticipated results, and any other data that may be needed but are not available in the accident-traffic-roadway data base.

Task 3. Collect and analyze accident data in accordance with the experimental plan. Perform statistical analysis of the accident-roadway-traffic data base.

Task 4. Develop a freeway cross-section impact assessment procedure.

Task 5. Validate the procedure/accident prediction model.

Task 6. Develop a software package that facilitates the application of the procedure. Develop a user's manual to accompany the software.

Task 7. Prepare a final report documenting the efforts undertaken and the findings of the study.

Associated costs: $375,000

RESEARCH PLAN 8. Additional Research on Geometric Design Consistency

Background. Past research (*32*) has identified combinations of geometric elements that show the potential for violating driver expectancy. These potential design inconsistencies include the following:

- Vertical alignment changes
- Intersections preceded by vertical alignment changes
- Intersections preceded by horizontal alignment changes
- Combinations of horizontal and vertical alignment changes
- Intersections both channelized and unchannelized
- Lane drops
- Lane drops with alignment changes
- Divided highway transitions
- Divided highway transitions with alignment changes
- Lane width reductions
- Shoulder width reductions.

A majority of the research on geometric design consistency, however, has focused primarily on inconsistencies in horizontal alignment on two-lane rural roads. In 1987, Lamm and Choueiri (*33*) developed a promising relationship between operating speed and the following variables:

- Degree of curve
- Lane width
- Shoulder width
- Average annual daily traffic.

Between 1991 and 1993, an FHWA research study investigating geometric design consistency was conducted. One of the outputs of that research was a model that can be applied to evaluate operating speed consistency on two-lane rural alignment with design speeds of 60 mi/h and less.

The relationship between safety, specifically accident experience, and geometric design inconsistencies for not only two-lane rural highways but for all highway types has not yet been established. Although situations such as those listed above have been identified as being potentially problematic to drivers, relatively little research has been done on the specific design elements that contribute to the problem. For example, while "combinations of horizontal and vertical alignment changes" have been identified as a geometric design inconsistency with the potential to violate driver expectancy, the "minimum" alignment has not been quantified. Consequently, for designers to properly identify and correct for design inconsistencies, they need to quantify the maximum difference in adjacent degrees of curvature, the length of the "sharpest" horizontal curve, the superelevation rate, and the grade (including the algebraic difference in grade and curve length, if vertical curvature is present). In addition, they need to ascertain the order of magnitude of accident occurrence pertaining to these geometric design inconsistencies. It is highly desirable to determine the relative probability of accidents by severity level for the various types of geometric design inconsistencies for which design parameters (e.g., degree of curvature, taper length) can be specified.

Objectives. The objectives of this research are to determine the combinations of design parameters that result in potentially hazardous geometric design inconsistencies and to develop the quantitative relationship between safety (measured in terms of either accidents or, as a surrogate measure, the driver workload) and these parameters for a variety of types of design inconsistency. In essence, this research should be viewed as an extension of the current FHWA study on horizontal design consistency.

Critical factors. Research on design inconsistencies has focused primarily on the two-lane rural road environment. Although design inconsistencies can occur on other facility types (e.g., inconsistent interchange exit patterns on freeways, inconsistent left-turn treatments on urban arterials, and inconsistent intersection design on multilane rural roads), the diversity and magnitude of the two-lane rural environment dictates that the scope of this study be limited to two-lane rural roads, including transitions to multilane and divided sections. Unlike past research on geometric design consistency, the scope of this study should extend to consider the combination of intersections/interchanges, cross-section, and alignment. For example, tangential intersections on horizontal curves have frequently been identified as locations where driver expectancy is violated. Frequently, signing and marking treatments are retroactively applied as a countermeasure to the design deficiency. It would be desirable to quantify the safety relationship so that designers could make informed decisions about the need to retain a tangential intersection as part of a rehabilitation project as opposed to preparing an alternative design in which the intersection would not occur at the point of horizontal curvature or within the curve.

Data requirements. To develop an accident-based relationship, a relational data base that contains data on reported accidents (3-year minimum), roadway and intersection/interchange geometric characteristics, and traffic characteristics is needed. Key accident variables would include injury severity, accident type/manner of collision, and first harmful event. Key geometric variables would include curve location, horizontal curve length, degree of horizontal curvature, superelevation, grade, type of vertical curvature, vertical curve length, location of vertical curve, location of intersection, and type of intersection. Key traffic variables would primarily include daily traffic volumes. As part of the research being conducted for the FHWA study on geometric design consistency, the use of occluded vision tests to evaluate driver workload is being investigated. However, the models will apply solely to horizontal alignment (e.g., degree of curvature).

Projected work elements. The tasks for this research are as follows:

Task 1. Develop comprehensive list of the types of geometric design inconsistencies for the rural road environment. This effort should rely on documented studies and the results of ongoing studies.

Task 2. Develop an experimental plan that includes the definition of specific criteria that can be applied to assess the appropriateness of candidate data bases.

Task 3. Research available accident-roadway geometric-traffic data bases, determine the most appropriate one(s), and then obtain the data base(s). Determine the mean accident rates by severity for the overall sample, stratified into the following roadway types:

- Freeways
- Multilane, divided highways
- Multilane, undivided highways
- Two-lane highways.

Task 4. Develop criteria to identify and isolate geometric design inconsistencies. Apply the criteria and create an extract file for the specific locations.

Task 5. Perform statistical analysis of the extract file to determine the relationship of accidents by severity and geometric design parameters for each type of geometric design inconsistency. Compare the results with the mean rates calculated for the roadway types identified above.

Associated costs: $300,000

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APPENDIXES A THROUGH C

Appendixes A through C contained in the research agency's final report are not published herein. For availability, please contact the NCHRP.

APPENDIX A State Design Practices Survey Questionnaire
APPENDIX B Safety Analyses Procedure for Resurfacing Project in New York
APPENDIX C Instructional Memorandums from Iowa DOT for Economic Analyses and Design Exceptions Process
APPENDIX D Literature Review

APPENDIX D
LITERATURE REVIEW

INTRODUCTION

One of the objectives of this research was to identify and describe the relationships between safety and geometric design elements that have been developed from research. From that effort, models for evaluating the safety effects of alternative design features were to be identified. The "best" models available are presented in Chapter 3 of this report. This appendix provides the background literature review that formed the basis for the model identification.

The literature review is presented under five major design elements: 1) roadway cross-section, 2) vertical alignment, 3) horizontal alignment, 4) median design, and 5) roadside design.

ROADWAY CROSS-SECTION ELEMENTS

Over the years considerable research has attempted to quantify how accidents change with different lane widths for different types of roads. As with most accident studies, it has been difficult to isolate the effect of one factor, in this case lane width, from other influencing factors including shoulder width, number of lanes, and volume. Hence, the singular effect of lane width, or pavement width, is still not precisely defined. Usable findings from studies that have examined this issue are presented below.

For freeways, the predominant lane width is 12 ft. However, to obtain more total capacity, 11-ft and even 10.5-ft lanes are used on some urban freeways. The 1982 *Synthesis of Safety Research Related to Traffic Control and Roadway Elements* (*1*) reported on a study that examined 14 freeway projects in which lane widths were reduced to create additional travel lanes on the freeway. The "after" accident rates were lower for all 10 sites where "before" and "after" data were available. However, not accounted for is the fact that the additional lanes presumably provided for better level of service, i.e., less dense flow, which by itself should have improved safety. Also, it is possible that speed reduction resulted in fewer accidents. A definitive study of the relationship of safety in terms of accidents and lane widths is still not available.

The relationship of lane width to safety for urban/suburban arterials was the subject of *NCHRP Report 330.* (*2*) The literature review in that study determined that the empirical relationship of lane width to safety is not well established. The following excerpt from *NCHRP Report 330* provides evidence for this statement, at least for urban/suburban arterials.

> A 1959 study by the Oregon State Highway Department (*3*) and the 1983 North Carolina State University study (*4*)... found inconsistent relationships between lane width and accident rate on arterial streets. *NCHRP Report 282* (*5*) found no statistically significant relationship between lane width and accident rate on suburban arterials.... The lack of quantitative data for this relationship is one of the most significant gaps found in previous published literature concerning traffic operations and safety on urban arterials.

Given this lack of reliable information, the *NCHRP Report 330* researchers conducted a "before/after" accident analysis of 35 projects (in seven states) in which lane widths were reduced. Six types of lane conversions were analyzed, with four of them reducing the lane widths to accommodate a TWLTL. The other types added a lane in each direction with reduced lane width. The results indicated that the project types in which a center TWLTL was installed at a site previously without a TWLTL typically experienced accident reductions even if the project incorporated narrower lanes. For the projects in which lane widths were reduced to accommodate additional through lanes, the accident rate increased because of more accidents at the intersection. The researchers concluded that using narrower lanes does not have an adverse effect on safety when a TWLTL is installed in conjunction with the project. However, if the reduction in lane width is simply to provide an additional through lane, then a net increase in accidents *may* occur.

For two-lane rural roads there is enough empirical evidence to show that accidents increase with decreasing lane width. Figure D-1, extracted from the 1982 *Synthesis of Safety Research Related to Traffic Control and Roadway Elements* (*1*), shows the results of five studies of lane width and accidents during 1970 to 1980. Taken at face value, it appears that 11 ft may be

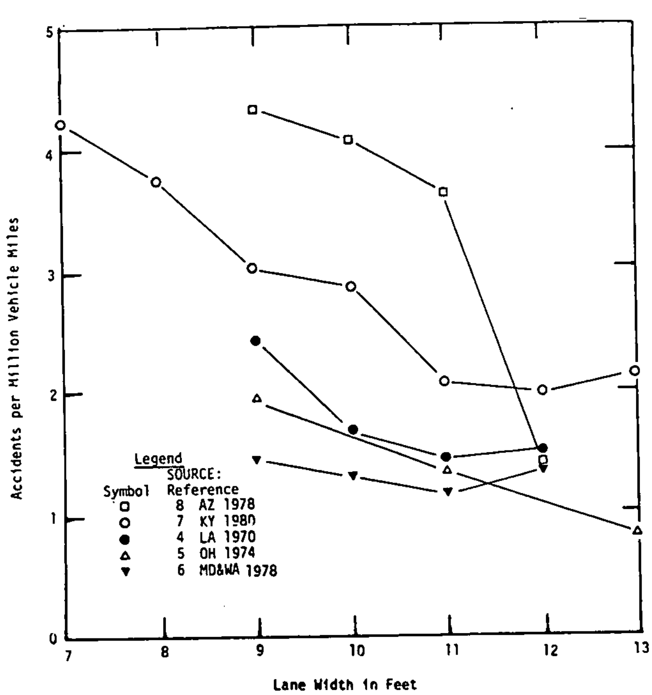


Figure D-1. Accident rates based on lane width for two-lane rural roads (1).

TABLE D-1. Percentage of accident reduction of related accident types for lane widening only (*6*)

Amount of Lane Widening (ft)	Percent Reduction in Related Accident Types
1	12
2	23
3	32
4	40

Note: These values are only for two-lane rural roads.

TABLE D-2. Percentage of accident reduction of "related" accident types for shoulder widening (*6*)

	Percent Reduction in Related Accident Types	
Shoulder Widening per Side (ft)	Paved	Unpaved
2	16	13
4	29	25
6	40	35
8	49	43

Note: These values are only for two-lane rural roads. "Related" accidents include run-off-road, head-on, and opposite-lane same-direction sideswipe collisions.

the threshold value; lesser widths would cause significantly higher accidents.

An analysis of the effect of lane width and shoulder width, among other variables, on accident frequency was performed by Zegeer et al. in 1987 (*6*). Predictions of accident reductions based on that research are shown in Table D-1. Predicted ARFs for 2-ft incremental widening of paved and unpaved shoulders are shown in Table D-2. For example, widening a 2-ft paved shoulder to 4 ft (e.g., a 2-ft widening) could reduce "related" accidents by 16 percent. It should be noted that these percent reduction values apply no matter what the base or "before" condition was. Under the just-stated example, a 16-percent reduction in related accidents would be expected if the 2-ft widening was on top of a 6-ft base shoulder width. However, in this latter case the absolute reduction in accidents would not be as high because significantly fewer accidents are likely with a 6-ft shoulder.

As reported in the 1982 *Synthesis of Safety Research Related to Traffic Control and Roadway Elements* (*1*), Zegeer et al. provided ARFs for shoulder widening based on their studies of low-volume (fewer than 1,000 vpd) two-lane roads in Kentucky. These reductions are shown in Table D-3. Compared with ARFs shown in Table D-2, these reductions are lower; however, they apply only to run-off-road and opposite-direction accidents.

In the 1982 *Synthesis*, Figure D-2 indicates that three referenced studies show that accident rates decrease with increasing shoulder width. However, Zegeer et al. noted in their Kentucky study that no additional benefit could be obtained for providing shoulder widths greater than 9 ft. Also, they noted that higher priority should be given to shoulder widening on horizontal curves and winding sections than to straight level sections.

Additional data on accident reductions for shoulder improvements on rural two-lane roads were reported in a 1992 synthesis document, *Safety Effectiveness of Highway Design Features, Volume III: Cross Sections* (*7*). As reported in that synthesis, Table D-4 shows the accident reductions that could be expected

TABLE D-3. Reduction in accident rates from shoulder widening on two-lane, rural roads in Kentucky (*1*)

Shoulder Width (ft)		Reduction in Run-off-Road & Opposite-Direction Accidents (%)
Before	After	
None	1 - 3	6
None	4 - 6	15
None	6 - 9	21
1 - 3	4 - 6	10
1 - 3	7 - 9	16
4 - 6	7 - 9	8

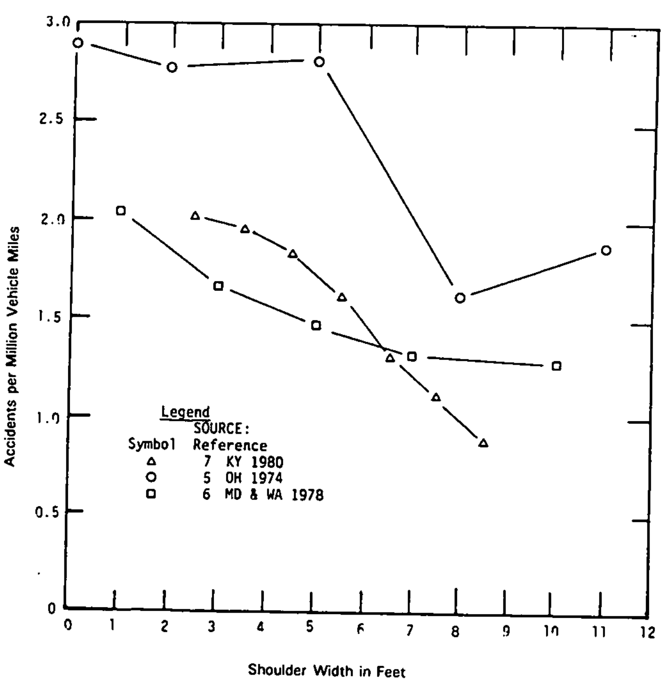


Figure D-2. Accident rates based on shoulder width for two-lane rural roads (1).

TABLE D-4. Accident reductions for shoulder improvements on Texas rural roads (*8*)

ADT Range	Percent Reduction (%)	
	All Accidents	Single-Vehicle Accidents
1,000-3,000	27.0 (s)	55.0 (s)
3,000-5,000	12.5	21.4 (s)
5,000-7,000	17.6 (s)	0.0

(s) = significant at 90 percent confidence level by adding full-width paved shoulders for three ADT classes of two-lane roads. The data came from a 1975–77 study (*8*) conducted in Texas that analyzed accident data for three classes of roads: two-lane roads with unpaved shoulders, two-lane roads with full-width paved shoulders, and four-lane roads with no shoulders (known as the "poor-boy" highway because a full-width paved shoulder is used as an additional lane with no shoulder provided). It should be noted that for this study, roads with shoulders narrower than 6 ft were considered as roads with no shoulders. Additional relevant findings from that study were the following:

1. Of the three classes studied, the highest accident rate was associated with two-lane roads without shoulders. Furthermore, on this class of road accident rates increased significantly as volume increased.
2. Within the same ADT levels, two-lane roads with shoulders had lower accident rates than four-lane roads with no shoulders.
3. Two-lane roads without paved shoulders were very sensitive to intersection accidents, especially at high traffic volumes.
4. The absence of full-width paved shoulders increased the rate of run-off-road accidents, especially at low traffic volumes.

These findings led the researchers to conclude that the presence of paved shoulders has a noticeable effect in reducing the accident rate.

Many two-lane rural road improvement projects involve the widening of the travel lanes and/or the shoulder. Accident research studies have been conducted to determine the effects on accidents when both the lane and shoulder width are changed. Most recent and notable of these effects is the aforementioned study by Zegeer et al (*7*). Table D-5 presents ARFs for various combinations of lane and shoulder widening and shoulder surfacing. These reduction factors apply to "related" accidents (i.e., run-off-road, head-on, and opposite- and same-direction sideswipe accidents). If only total accidents are known for the current condition, Zegeer et al. provide factors, shown in Table D-6, for converting total accidents to related accidents.

Recently, NCHRP Project 15-12, "Roadway Widths for Low-Traffic-Volume Roads," was completed (*9*). Several findings and recommendations of the project are relevant to this project, although the scope was limited to two-lane roads with ADTs of fewer than 2,000 vpd. The accident analysis used the data base of approximately 2,400 mi of two-lane roads from seven states from a previous FHWA study (*6*) supplemented with data from about 4,100 mi of similar roads in three other states. In addition, three independent data bases from 3 states totaling more than 54,000 mi of low-volume roads were used to validate the models developed from the 10-state primary data base. Key findings from the analysis are reported below.

Figure D-3 shows the accident rate comparisons of classes of lane width and shoulder width derived from the data bases. Table D-7 shows the accident rates by lane width, shoulder width, and terrain that can be used to determine expected accident reduction in a cost-effectiveness analysis. From these and other data, the researchers drew the following conclusions regarding safety effectiveness of variable lane and shoulder widths:

1. The presence of a shoulder is associated with a significant accident reduction for various lane width categories, particularly for shoulder widths of at least 3 to 4 ft.
2. For 10-ft lanes, a shoulder of 5 ft or wider appears to be needed to affect accident rate significantly.
3. For 11-ft and 12-ft lane widths, shoulders of 3 ft or wider have significantly beneficial effects.
4. Lane widths of 11 ft have substantially lower accident rates than lane widths of 10 ft, particularly where narrow shoulders exist.
5. Little, if any, real accident benefit can be gained from having lane widths wider than 11 ft on *low-volume* roads. [Emphasis added here.]

Researchers also offered the following points regarding appropriate design standards for cross sections:

1. Except in very specific instances, 10-ft lanes are considered the minimum appropriate lane width for rural highways. The exceptions are for local and collector roads with very low volumes and in rolling or mountainous terrain.
2. A minimum shoulder width of 2 ft for drainage, structural support, and traffic operations is considered appropriate.
3. In certain cases, 12-ft lane widths are considered appropriate (higher-speed, higher-class highways) regardless of the lack of a quantitative safety benefit of 12-ft versus 11-ft lanes.

VERTICAL ALIGNMENT ELEMENTS

Only a limited number of studies that have attempted to document the relationship of safety to vertical alignment elements could be identified. A 1953 study (*10*) concluded that grade alone did not have any particular effect on accident rates for tangent sections on any type of rural highway. However, the study found that grade did have an effect on accident rates for curves on two-lane rural highways.

A 1961 study (*11*) of 10,000 accidents on 54 mi of urban freeways in Texas found a concentration of accidents at crest and sag vertical curves. The conclusion of the 1961 study was that the general lack of sight distance contributed to the higher accident rates on the upgrade approaches to crests and the downgrade approaches to sags.

A 1970 study (*12*) investigated the operating characteristics of trucks ascending grades. One of the results of that study, which appears in AASHTO's Green Book (*13*), is the estimated accident involvement rate of trucks as a function of speed reduction. Figure D-4 presents this relationship, which was developed based on simulated speeds and accident prediction equations.

For a 1978 NCHRP study (*14*) accident rates were estimated for long, steep grades. These estimates were based on truck and vehicle speed distributions that were generated from computer simulations and the speed-accident involvement accident rates that were developed in Solomon's 1964 study (*15*). The estimated accident rates increased dramatically as the percentage of recreational vehicles and trucks increased. For example, for long 4- to 8-percent grades with 20 percent low-performance trucks, the predicted accident rates were 175 to 250 percent higher than similar grades with no trucks or recreational vehicles.

As part of their examination of the parameters that affect SSD, Olson et al. (*16*) conducted a limited accident analysis to isolate the effect of available SSD on safety. They used accident data from 10 pairs of sites matched for traffic volume, abutting land use, lane widths, shoulders, and ditches as well as the same algebraic difference in available SSD. They found that 52

TABLE D-5. Accident reduction factors for related accident types for various combinations of lane and shoulder widening (7)

Amount of Lane Widening (in ft)	Shoulder Condition ("Before" Period)		Percent Related Accidents Reduced							
			Shoulder Condition ("After" Period)							
	Shoulder width	Surface Type	2-ft Shoulder		4-ft Shoulder		6-ft Shoulder		8-ft Shoulder	
			P	U	P	U	P	U	P	U
	0	N/A	43	41	52	49	59	56	65	62
	2	Paved	32	--	43	--	52	--	59	--
	2	Unpaved	34	33	44	41	53	49	60	56
	4	Paved	--	--	32	--	43	--	52	--
	4	Unpaved	--	--	36	32	46	41	54	49
	6	Paved	--	--	--	--	32	--	43	--
	6	Unpaved	--	--	--	--	37	32	47	41
	8	Paved	--	--	--	--	--	--	32	--
	8	Unpaved	--	--	--	--	--	--	39	32
2	0	N/A	35	33	45	42	53	50	61	56
	2	Paved	23	--	35	--	45	--	53	--
	2	Unpaved	25	23	37	33	46	42	55	50
	4	Paved	--	--	23	--	35	--	45	--
	4	Unpaved	--	--	27	23	38	33	48	42
	6	Paved	--	--	--	--	23	--	35	--
	6	Unpaved	--	--	--	--	29	23	40	33
	8	Paved	--	--	--	--	--	--	23	--
	8	Unpaved	--	--	--	--	--	--	31	23
1	0	N/A	26	24	37	34	47	43	55	50
	2	Paved	12	--	26	--	37	--	47	--
	2	Unpaved	14	12	28	24	39	34	48	43
	4	Paved	--	--	12	--	26	--	37	--
	4	Unpaved	--	--	17	12	30	24	41	34
	6	Paved	--	--	--	--	12	--	26	--
	6	Unpaved	--	--	--	--	19	12	31	24
	8	Paved	--	--	--	--	--	--	12	--
	8	Unpaved	--	--	--	--	--	--	21	12

Note: Cells were left blank where they correspond to projects that would decrease shoulder width and/or change paved shoulders to unpaved shoulders.

P = paved, U = unpaved

These values are only for two-lane rural roads.

percent more accidents (i.e., 82 versus 54) occurred at crest vertical curve sites with sight restrictions (e.g., available SSD below the 1965 AASHTO standard) compared with control sites (e.g., comparable crest vertical curves having SSDs greater than the 1965 AASHTO standard.) Control sites had available SSDs greater than 700 ft. However, the researchers cautioned that because of the small sample size, the relationship cannot be considered reliable. A 1987 TRB *State-of-the-Art Report* (*17*) examined the relationship between safety and key highway features, including vertical alignment. The report indicated the following:

1. Grade sections have higher accident rates than level sections.
2. Steep grades have higher accident rates than mild grades.
3. Downgrades have higher accident rates than upgrades.

Using FHWA's HSIS, researchers recently completed an investigation of the accident experience on 1,424 crest vertical curves (*18*). The analysis involved the merging of accident location data with vertical curvature data. The distance from each accident to the crest of the vertical curve was determined. Figure D-5 illustrates a plot of accident frequency (e.g., number of

TABLE D-6. Factors to convert total accidents to related accidents on two-lane rural roads (7)

ADT (vpd)	Adjustment Factors		
	Flat Terrain	Rolling Terrain	Mountainous Terrain
500	0.58	0.66	0.77
1,000	0.51	0.63	0.75
2,000	0.45	0.57	0.72
4,000	0.38	0.48	0.61
7,000	0.33	0.40	0.50
10,000	0.30	0.33	0.40

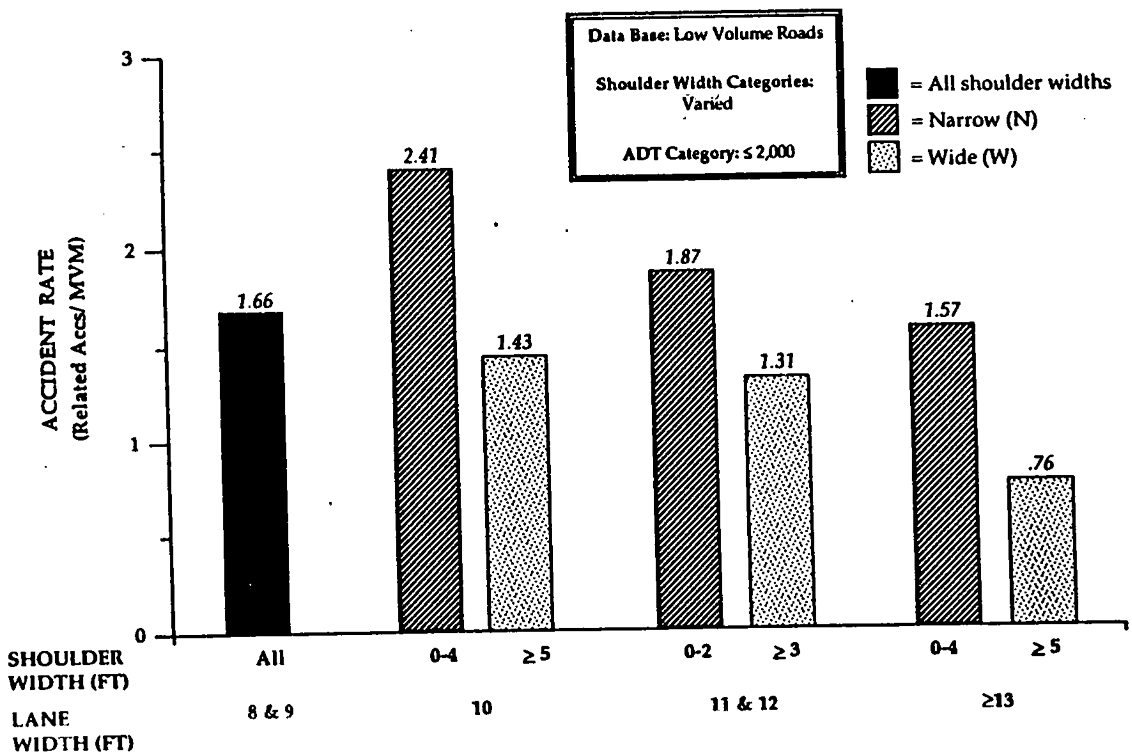


Figure D-3. Accident rates of related accidents by lane and shoulder width from the low-volume roads data base (9).

accidents per crest over a 3-year period) versus distance from the center of the crest for curves with small (i.e., fewer than 6 percent) and large (i.e., greater than 6 percent) grade differential. This figure shows that a greater proportion of accidents are found within 0.02 mi of the crest and that the increased grade differentials show an ever-greater proportion of accidents. More detailed analysis, including the collection of sight distance data, was recommended.

HORIZONTAL ALIGNMENT ELEMENTS

Since the early 1950s, numerous reports have presented findings on the relationship of horizontal alignment to accidents. The major findings of these reports have been grouped and summarized by specific aspects of horizontal alignment, which include degree of curvature/radius, presence of spiral transition curve, and superelevation, among others. It also should be noted that while this section does include some findings related to run-off-road accidents, additional discussion of these accidents is presented later in this appendix under "Roadside Design Elements."

Tangents Versus Horizontal Curves

While the available data clearly indicate that most accidents occur on level tangents, accident research has shown that acci-

TABLE D-7. Accident rates used for analysis of cost-effective widths on low-volume roads (9)

Lane Width (ft)	Shoulder Width (ft)	Accident Rates (Accidents PMVM)		
		Terrain		
		Level	Rolling	Mountainous
10	0-2	2.28	2.41	2.86
	3-4	2.28	2.41	2.86
	>4	1.30	1.43	1.88
11	0-2	1.74	1.87	2.32
	3-4	1.18	1.31	1.76
	>4	1.18	1.31	1.76
12	0-2	1.74	1.87	2.32
	3-4	1.18	1.31	1.76
	>4	1.18	1.31	1.76

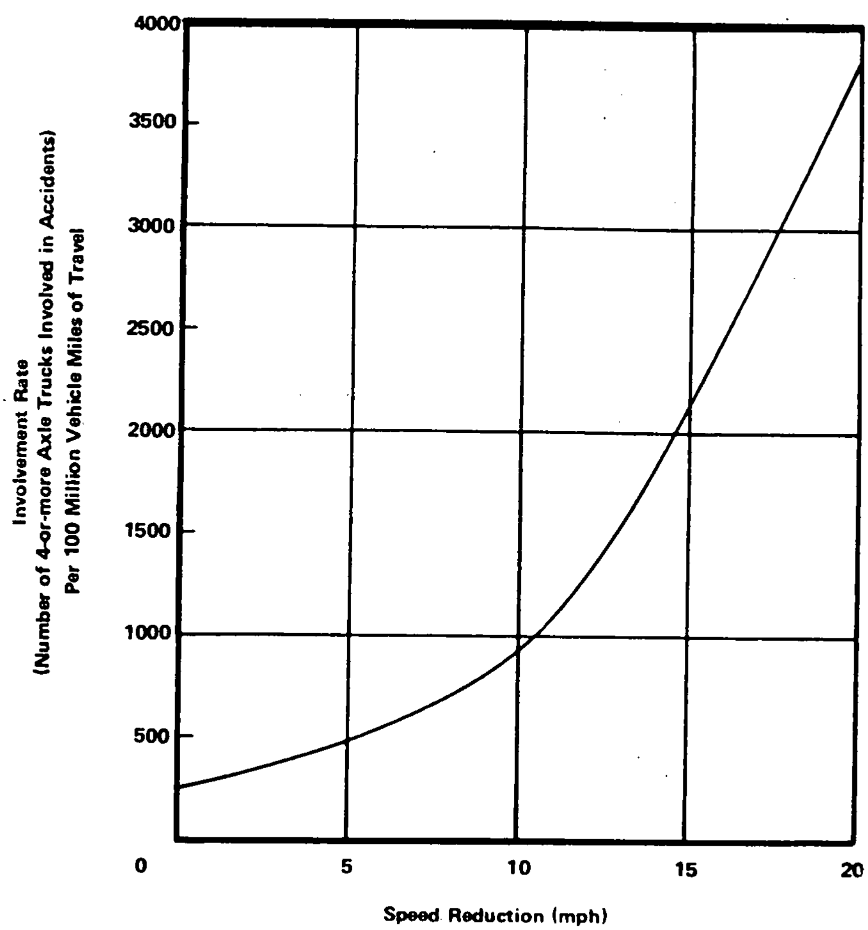


Figure D-4. Accident involvement rate of trucks for which running speeds are reduced below average running speed of all traffic (Reference 12 as presented in Reference 13).

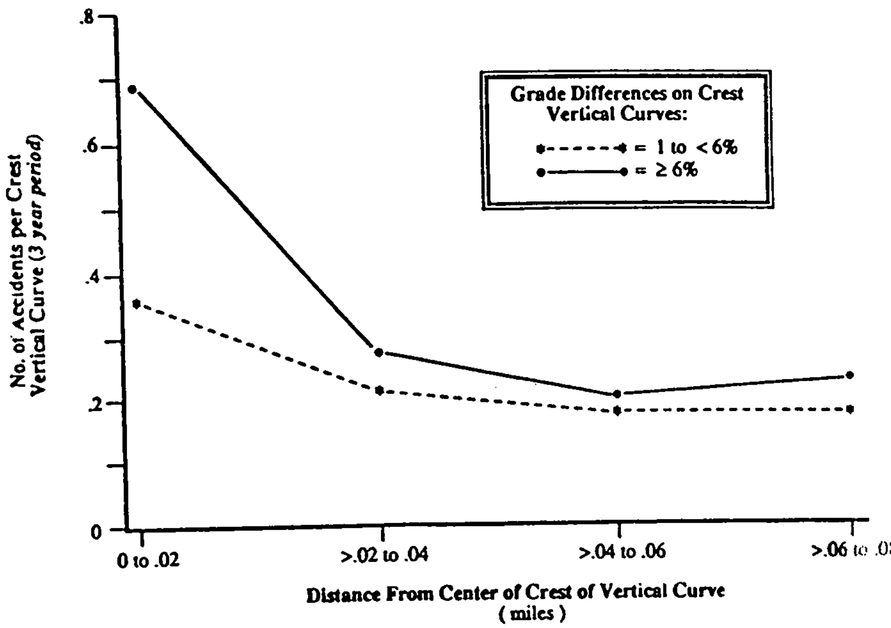


Figure D-5. Accident frequency relative to distance from crest vertical curves (18)

dent rates, expressed as accidents PMVM of travel, for horizontal curves are higher than the accident rates for tangents. In other words, there is greater probability of an accident on a horizontal curve than on a tangent. Accident studies indicate that horizontal curves experience accident rates ranging from one and a half to four times greater than tangent sections (*19*). A 1985 FHWA research study (*20*) concluded the following:

1. The average accident rate for highway curves is about three times the average accident rate for highway tangents.
2. The average single-vehicle, run-off-road accident rate for curves is about four times the average single-vehicle, run-off-road accident rate for highway tangents.
3. Highway curves experience a higher proportion of wet pavement accidents than do highway tangents.
4. Highway curves experience a higher proportion of severe (fatal and injury) accidents than do highway tangents.

A 1991 FHWA study (*21*) also investigated the difference in accident occurrence based on 3,427 curve/tangent pairs in Washington State. The study found that compared with tangents, curves had more severe accidents (i.e., in terms of fatal and A-injury accidents, which are accidents in which one or more persons suffer an incapacitating injury that prevents the person from walking, driving, or normally continuing the activities he/she was capable of performing before the injury occurred). In addition, compared with tangents, curves had a higher percentage of the following accident types:

- Head-on and opposite-direction, sideswipe crashes
- Crashes at night
- Fixed-object and rollover accidents
- Crashes involving drinking drivers.

Degree of Curvature/Radius

Most documented accident studies show that the rate of accidents on individual curves increases as the degree of curvature increases. A 1953 study (*10*) concluded that for all types of roads investigated, the sharper the curve, the higher the accident rate. Table D-8 presents a condensed summary of the results of the 1953 study. The sample of accidents on which these estimates were based was largest for two-lane roads.

A 1978 study (*22*) of single-vehicle accidents found that the distribution of run-off-road accidents differed as a function of degree of curvature. On the basis of a random sample of single-vehicle, run-off-road accidents, it was determined the percentage of accidents running off on the outside of the curve increased with increasing curvature. Table D-9 presents the results from that study.

As part of a 1992 FHWA study (*23*) attempting to develop a conceptual plan for an interactive highway design model (IHDM), an investigation of the HSIS data base revealed a potential relationship between degree of curvature and accident rate for two-lane rural roads. The data, which were from Utah, are summarized in Table D-10. These data indicate that accident rates increase for increasing degrees of curvature. This table also indicates that the run-off-road accident rate, in general, increases with increasing degrees of curvature.

Several studies have investigated the accident reduction consequences of flattening curves (i.e., reconstructing a horizontal curve to make it longer with a lower degree of curvature). For a 1991 FHWA study, (*21*) estimated ARFs that would result from flattening curves were developed. These are shown in Tables D-11 and D-12 for isolated and nonisolated horizontal curves, respectively. An isolated curve is defined as a curve having tangent approaches of 650 ft or more on both ends of the curve. The reduction factors are presented as a function of

TABLE D-8. Accident rates on curves by degree of curvature (Reference *10* as cited in Reference *1*)

Degree of Curvature	Accident Rate (Accidents per Million Vehicle Miles)			
	Two-Lane Roads	Four-Lane, Undivided Roads	Four-Lane, Divided Roads	Four-Lane Roads with Controlled Access
Tangent	2.3	2.7	2.9	1.7
0 - 2.9°	1.6	1.9	1.8	1.6
3 - 5.9°	2.5	2.6	2.4	2.3
6 - 9.9°	2.8	3.3*	3.1*	4.5
10° or more	3.5	1.2*	6.7*	N/A

* Denotes associated number of accidents fewer than 25; estimate subject to error

the central angle, degree of curvature before, and degree of curvature after.

Frequency of Horizontal Curves

Highway safety research indicates that the frequency of horizontal curves does influence accident frequency. The aforementioned 1953 study (*10*) found that for two-lane roads, the accident rates generally increased as a function of curves per mile. The study found, however, that long tangents followed by sharp (i.e., 10 degrees or greater) curves had the highest accident rate. The accident rates that were estimated as a function of both frequency and degree of curvature from that 1953 study are presented in Table D-13.

A 1985 FHWA study (*24*) investigated the effect of frequency of curves on accident rate on two-lane, rural curves using two different data bases. One data base had been developed for an FHWA study of skid reduction; the other had been developed for an FHWA study of delineation treatments. On the basis of the results from analyses of those two data bases, accident rates were estimated for two-lane, rural roads stratified by ADT, intersections per mile, and curves per mile for that 1985 FHWA report. The results are presented in Table D-14.

TABLE D-9. Distribution of run-off-road accidents as a function of degree of curvature (Reference *22* as cited in Reference *17*)

Degree of Curvature	Percentage of Run-off-Road Accidents	
	Outside Curve	Inside Curve
0 - 4°	67	33
4.1 - 8°	74	26
8.1 - 12°	78	22
Above 12°	84	16

Superelevation

Although not an accident-based investigation, a 1980 FHWA study (*25*) used the Highway-Vehicle-Object Simulation Model (HVOSM), a computer simulation program, to analytically relate vehicle dynamics during curve traversal to horizontal curve design criteria. On the basis of the results, it was concluded in a synthesis of the safety effectiveness of highway design features that "superelevation does not appear to play a significant role in affecting transient dynamics on curves, but does influence the steady-state steer characteristics of the vehicle" (*19*).

A 1985 FHWA report (*20*) also documented a study of operational and safety considerations related to the horizontal curve design. The report indicated the following:

> In its present form, AASHTO policy overemphasizes the dynamic effects of superelevation relative to curve radius. This is because the policy establishes superelevation rates assuming all vehicles track the highway curve. Instead, the field studies show vehicle path curvature is significantly sharper than that of the highway curve for a meaningful proportion of the driver population. Therefore, to produce the intended lateral tire accelerations at design speed for a nominally critical driver on an AASHTO highway curve, *more* superelevation is required than is called for by AASHTO policy.

With respect to superelevation on horizontal curves, the report concluded the following:

1. "There is a driver control trade-off between highway curve radius and superelevation rate."
2. "In comparing two different controlling highway curves with the same design speed, the highway curve with the larger

TABLE D-10. Accident rates for curves as a degree of curvature (*23*)

Alignment	No. of Accidents: On-Roadway	No. of Accidents: Off-Roadway	No. of Accidents: Total	Roadway Length (mi)	Travel (MVM)	Total Accident Rate (per MVM)	Run-Off Road Accident Rate (per MVM)
Tangent	1,756	887	2,643	3,500.77	1,583.25	1.67	0.56
Curve <3 deg	38	10	48	59.67	24.87	1.93	0.40
Curve 3-6 deg	119	6	185	212.06	85.86	2.15	0.77
Curve 6-10 deg	62	68	130	131.48	46.76	2.78	1.45
Curve >10 deg	88	116	204	159.20	49.84	4.09	2.33

radius and lower superelevation rate may provide a slightly greater safety margin against loss of control than the highway curve with a smaller radius and higher superelevation rate."

A 1987 article (*26*) documenting a study of fatal accident sites in Georgia and New Mexico noted "deficiencies in available superelevation at fatal accident sites, compared with nearby control sites."

The 1991 FHWA study (*21*) of cost-effective geometric improvements for curves also investigated the relative effects of superelevation on curve accidents. A "small, but significant effect of too little superelevation" was noted. Superelevation data were gathered for 732 curve sites in Washington State. For each site, both the optimal superelevation, which was determined from the AASHTO Green Book (*9*) as a function of degree of curve and terrain type, and the actual superelevation were determined. A variable called superelevation deviation was computed as the difference between the optimal superelevation and the actual superelevation. Using statistical modeling techniques, it was determined that "inadequate superelevation . . . will result in increased curve accidents." Correcting this superelevation deviation was predicted to result in a significant reduction in curve accidents. For example, a 0.02 change in the superelevation deviation was predicted to produce a 10- to 11- percent reduction in curve accidents.

It should be noted that "no evidence was found to support" the hypothesis that "too much superelevation" is associated with higher accident rates. A separate analysis revealed that additional safety benefits could be achieved by providing a more gradual transition of superelevation beginning before the beginning of the curve. On the basis of this analysis, the study produced the estimates of ARFs shown in Table D-15.

Presence of Spiral Transitions

The aforementioned 1980 FHWA report (*25*) documented an investigation of the effects of spiral transitions on vehicle dynamics during curve traversal. On the basis of simulations from the HVOSM, it was concluded that using spiral transition curves would improve traffic operations. The report recommended "that

TABLE D-11. Accident reduction factors for flattening isolated curves on two-lane rural roads (Reference *21* as cited in Reference *19*)

Degree of Curve		Percent Reduction in Related Accident Types				
		Central Angle in Degrees				
Exist	New	10°	20°	30°	40°	50°
30	25	17	17	17	16	16
	20	33	33	33	33	33
	15	50	50	50	50	50
	12	60	60	60	60	60
	10	67	66	66	66	66
	8	73	73	73	73	73
	5	83	83	83	83	83
25	20	20	20	20	20	20
	15	40	40	40	40	40
	12	52	52	52	52	51
	10	60	60	60	59	59
	8	68	68	68	67	67
	5	80	80	79	79	79
20	15	25	25	25	25	24
	12	40	40	40	39	39
	10	50	50	49	49	49
	8	60	60	59	59	59
	5	75	74	74	74	74
15	10	33	33	33	32	32
	8	46	46	46	45	45
	5	66	66	65	65	65
	3	79	79	78	78	78
10	5	49	48	48	47	47
	3	69	68	67	66	66
5	3	37	35	33	32	31

TABLE D-12. Accident reduction factors for flattening nonisolated curves on two-lane rural roads (Reference *22* as cited in Reference *19*)

Degree of Curve		Percent Reduction in Related Accident Types				
		Central Angle in Degrees				
Exist	New	10°	20°	30°	40°	50°
30	25	16	16	16	15	15
	20	33	32	31	31	30
	15	49	48	47	46	46
	12	59	57	56	55	55
	10	65	64	63	62	61
	8	72	70	69	68	68
	5	82	80	79	78	78
25	20	19	19	18	18	17
	15	39	38	36	36	35
	12	50	49	48	46	46
	10	58	56	55	54	53
	8	66	64	62	61	60
	5	77	75	74	72	72
20	15	24	23	22	21	20
	12	38	36	35	34	33
	10	48	45	44	42	41
	8	57	54	52	51	50
	5	71	68	66	64	64
15	10	30	28	26	25	24
	8	43	40	37	35	34
	5	61	56	53	51	50
	3	73	68	64	63	63
10	5	41	36	32	29	28
	3	58	50	45	43	42
5	3	22	15	13	11	11

spiral transitions be used to the greatest extent possible in highway construction."

The 1985 FHWA report (*20*) also found that, on the basis of computer simulation, "adding spiral transitions to highway curves dramatically reduces the friction demands of the critical vehicle traversals." The report also indicated that field studies of driver behavior show drivers "initiate a transitional path on the tangent approach to a circular curve. The observed paths simulate, for all practical purposes, a true 'spiral' curve." The report concluded that spirals produce safety benefits (i.e., providing for spirals on approaches to highway curves should enable drivers of all speeds to naturally perform lower spiraling rates, thereby producing less path overshoot and lower maximum lateral tire acceleration) and that spiral transitions are a "necessary element in design of most highway curves."

The 1991 FHWA curve accident study (*21*) found that there were safety benefits, in terms of accident occurrence, attributable to spiral transitions on high-speed horizontal curves. The model developed for curve accidents revealed that "spiral transitions reduced curve accidents by 2 to 9 percent, depending on degree of curve and central angle." On the basis of this study, it was concluded that "an accident reduction of 5 percent of total accidents was most representative of adding spiral transitions on both ends of a curve on two-lane, rural highways."

Roadway Widening on Curves

Wider lanes and/or shoulders on horizontal curves have also been determined as being associated with a reduction in curve-related accidents. The 1991 FHWA study (*21*) found that widening the lane and/or paved shoulder width would reduce accidents on horizontal curves. The predicted accident reductions in total curve accidents for improvements involving widening lanes and/or shoulders on horizontal curves are presented in Table D-16. It is emphasized that percent reductions are not additive.

Combined Effects of Grade and Curvature

As noted earlier in this chapter on the discussion of safety relationships for vertical alignment elements, a 1953 study (*10*)

TABLE D-13. Accident rates on two-lane curves, by degree of curvature and frequency of curves (Reference *10* as cited in Reference *1*)

Frequency of Curves per Mile	Accident Rates (Accidents per Million Vehicle Miles)			
	Degree of Curvature			
	0 - 2.9°	3 - 5.9°	6 - 9.9°	10° or more
0.0 - 0.9	1.4	2.7	2.0	4.3
1.0 - 2.9	1.4	2.1	2.9	2.6
3.0 - 4.9	1.9	2.5	2.9	3.4
5.0 - 6.9	3.1	2.9	2.6	3.9

TABLE D-14. Approximate mean accident rates for two-lane, rural roads (*24*)

ADT (Vehicles/Day)	Intersections per Mile	Approximate Mean Accident Rate (Accidents per Million Vehicle Miles)			
		Curves per Mile			
		0.0 - 1.0	1.0-2.5	2.5-4.5	> 4.5
< 400	< 2.5	3.04	3.77	4.44	4.08
	2.5 - 5.0	3.36	4.17	4.92	4.52
	> 5.0	5.69	7.06	8.33	7.64
400 - 1,000	< 2.5	2.22	2.76	3.25	2.98
	2.5-5.0	2.46	3.05	3.60	3.30
	> 5.0	4.16	7.06	8.33	7.64
1,000 - 2,000	< 2.5	2.10	2.60	3.07	2.98
	2.5-5.0	2.32	2.88	3.04	3.12
	> 5.0	3.93	4.88	5.75	5.28
2,000 - 5,000	< 2.5	1.80	2.24	2.64	2.42
	2.5-5.0	2.00	2.48	2.92	2.68
	> 5.0	3.38	4.19	4.94	5.45
5,000 - 10,000	< 2.5	2.00	2.49	2.93	2.69
	2.5-5.0	2.22	2.75	3.25	2.98
	> 5.0	3.76	4.66	5.50	5.04
> 10,000	< 2.5	2.62	3.25	3.83	3.51
	2.5-5.0	2.90	3.60	4.24	3.89
	> 5.0	4.90	6.09	7.17	6.58

TABLE D-15. Accident reduction factors for upgrading superelevation on existing horizontal curves with superelevation rates less than recommended design values (Reference *27* as cited in Reference *19*)

Superelevation Deviation (Recommended AASHTO Superelevation—-Actual Superelevation) ft/ft	Percent Reduction in Total Curve Accidents due to Upgrading Superelevation
.01 to .019	5
> or = .02	10

found that grade alone did not have any particular effect on accident rates for tangent sections on any type of rural highway, but grade did have an effect on accident rates for curves on two-lane rural highways. One study, which was documented in a 1987 *Transportation Research Record* (*26*), investigated the combined effects of horizontal and vertical alignment on the incidence of fatal rollover accidents in New Mexico and Georgia. The results showed that road sections with extreme horizontal and vertical alignment were as much as 50 times more common at fatal crash sites than at comparison sites. Sharp left curves and steep downgrades were determined to be overrepresented in both states.

MEDIAN DESIGN ELEMENTS

For medians without median barriers, median width has been found to be directly related to total accident rate. A 1974 study of 84-ft-wide medians on Interstate highways in Ohio (*28*) found that raised (mound) medians and depressed (swale) medians, which are illustrated in Figure D-6, were comparable in terms of accident experience. However, a significantly lower number of single-vehicle, median-involved accidents were found on sections with depressed medians compared with sections with raised medians.

A 1973 study (*29*) of median on Interstate and turnpike roads in Kentucky found that highways with at least 30-ft-wide medians had lower accident rates than those with narrower median widths. The key results are shown in Figure D-7. For wider medians, a significant reduction was found in the percent of accidents involving a vehicle crossing the median. Median slopes of 4:1 or steeper had abnormally high accident rates for various median widths. Deeply depressed medians with slopes of 4:1 or steeper were found to have more severe accidents. For median widths of 20 to 30 ft, the use of a raised median barrier was associated with a higher number of accidents involving an impact with the median and then loss of control. On the basis of these accident findings, the researchers recommended the following:

- Minimum median widths of 30 to 40 ft
- Slopes of 6:1 or flatter (particularly where median widths are less than 60 ft)
- Paved shoulders 12-ft-wide on roadway sections where guardrail is installed in the median.

A recent safety investigation of medians without barriers using the HSIS found that accident rates decrease with increasing median width for unprotected medians (*30*). Figures D-8 and D-9 illustrate the relationships of median width and the relative rates of serious accidents (i.e., fatal accidents and A-injury accidents), injury accidents (i.e., D-injury, B-injury, A-injury, and fatal accidents) and property-damage-only accidents that were developed using log linear modeling statistical techniques for Utah and Illinois, respectively. Figures D-10 and D-11 illustrate the relationship of median width for four accident types for Utah and Illinois, respectively.

The relative effect shown in Figures D-8 through D-11 represents the ratio of the applicable accident rate divided by the accident rate for a road with no median. Hence, all curves start at 1.0. If the applicable (e.g., accident, injury, property-damage-only, multivehicle, single-vehicle, head-on, or rollover) accident rate for a road with median width of 30 ft, for example, is less than for a similar road with no median, then the relative effect would be less than 1.0. If the rate is higher, then the relative effect would be greater than 1.0. The general finding from these results is that accident rates do decrease with increasing median width for unprotected medians. The researchers further interpreted the results that in constructing new highways, medians need to be at least 30 ft wide to have a positive safety effect. Also, the data suggest that decreasing existing medians to fewer than 20 to 30 ft wide to enhance capacity may decrease safety. However, it is not known from these data how using a median barrier would compensate for this safety decrease.

TABLE D-16. Estimated percent reductions in total curve accidents due to lane and shoulder widening (Reference *21* as cited in Reference *1*)

Total Amount of Lane or Shoulder Widening (ft)		Percent Reduction in Curve Accidents		
Total	Per Side	Lane Widening	Paved Shoulder Widening	Unpaved Shoulder Widening
2	1	5	4	3
4	2	12	8	7
6	3	17	12	10
8	4	21	15	13
10	5	--	19	16
12	6	--	21	18
14	7	--	25	21
16	8	--	28	24
18	9	--	31	26
20	10	--	33	29

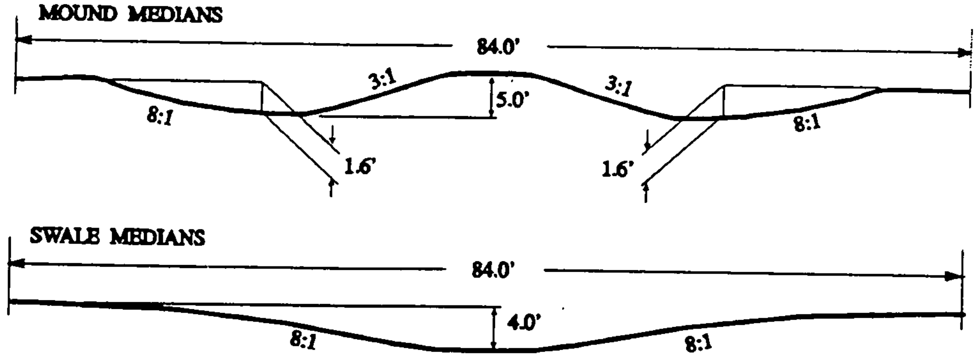
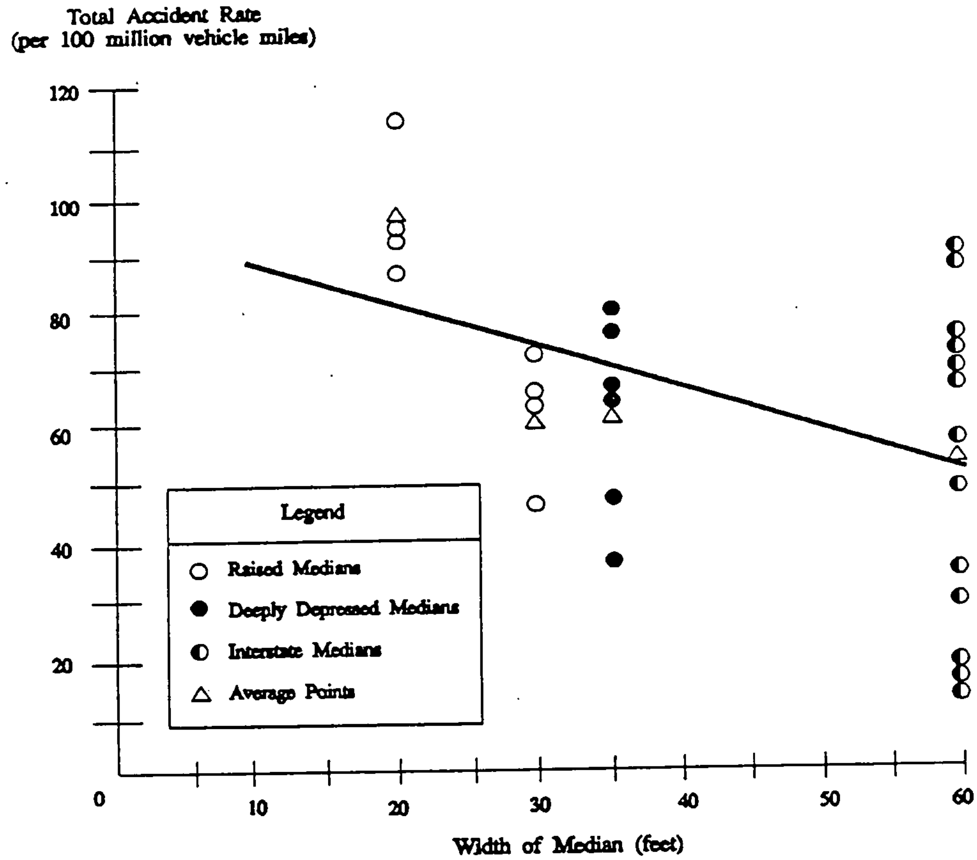


Figure D-6. Typical median cross-sections from the 1974 Ohio study (Reference 28 as cited in Reference 7).



NOTE: Figure based on multilane interstate and turnpike roads in rural areas

Figure D-7. Relationship of accident rate to median width from a Kentucky study (Reference 29 as cited in Reference 7).

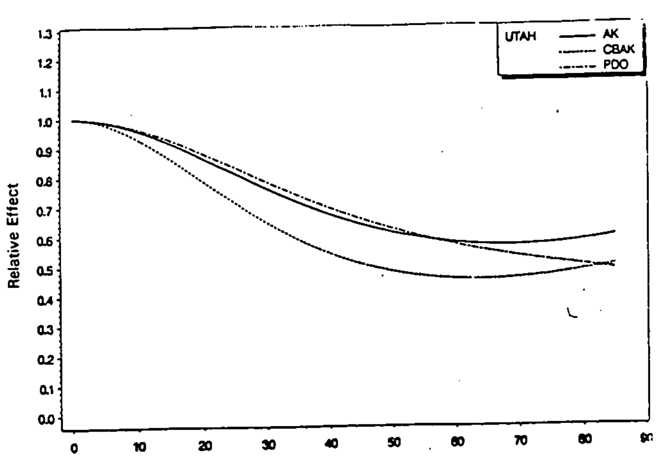


Figure D-8. Estimated relative effects of median width on serious, injury, and property-damage-only accident rates for Utah four-lane, two-way sections (30).

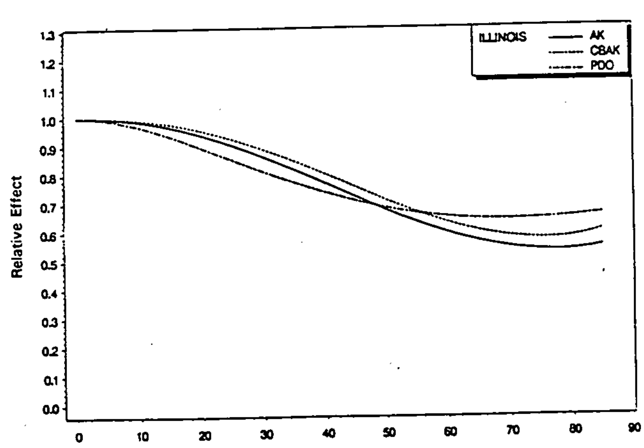


Figure D-9. Estimated relative effects of median width on serious, injury, and property-damage-only accident rates for Illinois four-lane, two-way sections (30).

ROADSIDE DESIGN ELEMENTS

A substantial amount of research has been conducted on accidents and roadside design elements, fixed objects, roadside features, and medians. On the basis of the available literature, the following represents a summary of the key findings related to roadside design.

Clear Zones and Roadside Obstacles

Clear zone policies enhance safety. Research reported in 1982 has shown that roads constructed with adherence to a clear zone policy had significantly lower accident rates compared with roads constructed without clear zones (*31*). The use of clear zones of 30 ft with 6:1 foreslopes results in fewer accidents than clear zones with the same width with 4:1 foreslopes. Table D-17 presents the adjusted mean single-vehicle run-off-road accident rate per 100 million vehicle miles by highway type and roadside policy. Figure D-12 presents a relationship between ADT and single-vehicle, run-off-road accidents per mile per year for two-lane highways with the following roadside designs:

- No clear recovery zone specified outside a variable width shoulder
- A 30-ft clear zone with typically 4:1 or flatter slopes
- A 30-ft clear zone with typically 6:1 or flatter slopes.

According to research by Zegeer et al. (*32*) removing or relocating isolated fixed objects (e.g., cutting down trees, relocating utility poles) close to the edge of the travelway will result in a percent reduction in accidents as shown in Table D-18. The percent reductions apply no matter what the base or "before" condition was. However, because roads with little or no roadside recovery distance are likely to have higher accidents than roads with a wider distance, the absolute reduction in accidents will be larger for these types of roads.

Accident frequency is affected by the density of and lateral clearance to utility poles. A 1983 study (*33*) of utility poles accidents for 2,500 mi of two-lane and multilane roads in urban and rural areas developed the relationship shown in Figure D-13. On the basis of those findings, a procedure was developed to predict changes in the frequency of utility pole accidents. Depicted in Figure D-14 is the nomograph that shows utility pole accident frequency as a function of ADT, pole density (number of poles per mile), and pole offset (average distance of the utility poles from the edge line).

As part of a 1990 FHWA study by Zegeer et al. (*21*), accident reduction estimates were developed for clearing or relocating obstacles such as trees, mailboxes, guardrails, and fences farther from the roadway. Table D-19 presents the estimated percent reductions as a function of increased lateral offset from the edge of the travelway to the obstacle. These estimates of accident reduction apply only to obstacles within 30 ft from the outside edge line. The same observation about the absolute accident reduction that was made for the ARFs in Table D-18 applies here as well.

The severity of a run-off-road, hit-fixed-object accident depends on the crashworthiness of the object, the speed at impact, the angle at impact, whether the vehicle was tracking or not tracking (e.g., spinning about its axis), whether the driver and

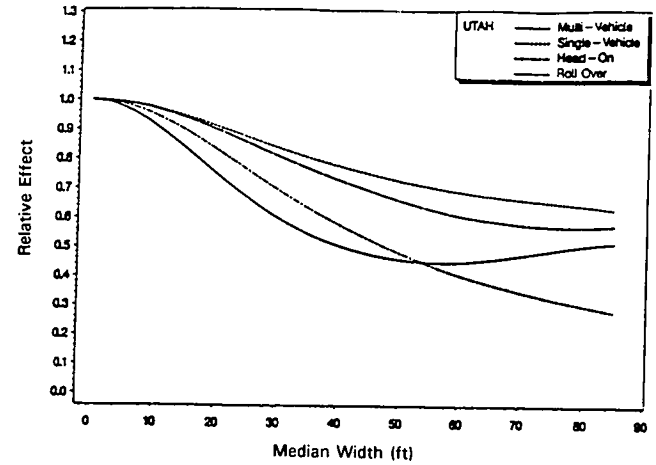


Figure D-10. Estimated relative effects of median width on multivehicle, single-vehicle, head-on, and sideswipe opposite-direction and single-vehicle rollover accident rates for Utah four-lane, two-way sections (30).

passenger(s) were wearing seatbelts, and numerous other factors. Research has found that accidents tend to be more severe when the object hit is nonyielding. Table D-20 presents accident severity data from a 1978 study (*22*) of run-off-road accidents. A 1981 study (*34*) of single-vehicle collisions with roadway appurtenances in Texas found that collisions with culverts were, by far, the most severe accidents with 55 percent of collisions resulting in minor injury or greater, 46 percent resulting in moderate injury or greater, and 19 percent resulting in serious injury or death.

Roadside and Horizontal Curves

There is a higher rate of run-off-road accidents at or near horizontal curves. A 1976 study (*35*) of 300 fatal accidents that involved roadside objects in Georgia found that over one-half of the collisions occurred at or near horizontal curves of greater than 6 degrees.

On horizontal curves on undivided highways, run-off-road right accidents on left curves appear to occur most frequently. The results of a 1978 study (*22*) with respect to the frequency of run-off-road accidents on undivided roads are summarized in Table D-21. The study also found that the proportion of run-off-road accidents to the outside of curves increased with degree of curvature. This same study also found a higher incidence of run-off-road right accidents on tangents compared with run-off-road left accidents on tangents on undivided roads. The overall mean departure angle for right and left departures were 13.5 degrees and 18.6 degrees, respectively. Left-side departures involved larger proportions of nontracking vehicles compared with right-side departures.

Ditches and Sideslopes

Injury rates are affected by ditch depth and slope. A 1978 study (*22*) found that deep ditches had a 20 percent higher injury

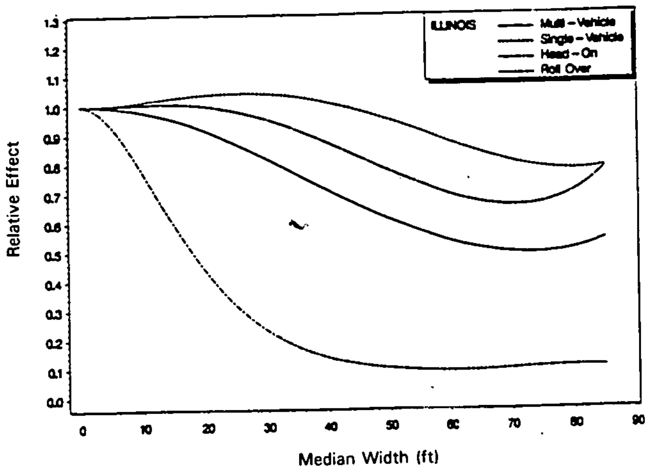


Figure D-11. Estimated relative effects of median width on multivehicle, single-vehicle, head-on, and sideswipe opposite-direction and single-vehicle rollover accident rates for Illinois four-lane, two-way sections (30).

TABLE D-17. Single-vehicle accident rate by highway type and roadside design policy (*31*)

Highway Type	Single-Vehicle Accident Rate (Accidents/100 Million Vehicle Miles)		
	No Clear Zone Policy	Clear Zone Policy with 4:1 Slopes	Clear Zone Policy with 6:1 Slopes
Two-Lane	68.0	40.3	25.4
Freeway	40.7 (est)	28.9	18.2
Four-Lane, Divided (Nonfreeway)	60.7	31.9	15.5

rate. Ditches more than 2 ft deep were struck more often and resulted in greater injury severity. The authors found that 61 percent of accidents with ditches that were at least 3 ft deep resulted in personal injury, compared with 54 percent for accident involving ditches 1 to 2 ft deep. (Part of the increased

TABLE D-18. Accident reduction factors due to increasing roadside recovery distance (*32*)

Amount of Increased Roadside Recovery Distance (ft)	Percent Reduction in Related Accident Types
5	13
8	21
10	25
12	29
15	35
20	44

injury rate was attributed to higher impact speeds, though.) On fill sections, as the slope became steeper or the fill higher, injury rate increased.

Injury rates are much higher for run-off-road, rollover accidents compared with run-off-road, nonrollover, hit-fixed-object accidents. Rollover accidents are more likely to occur on roads built on fill than in cuts. The 1978 study (*22*) found that rollover rates begin to increase when fill exceeds 2 ft and reach a plateau for fills greater or equal to 4 ft. Rollover rates jump markedly for ditches 4 to 5 ft deep; beyond 5 ft depth, rollovers decrease as nonroll impacts with ditches increase.

Rounding the hinge point and ditch bottom will further enhance safety by affording an errant motorist more control in steering and reduces the chance that an errant vehicle will become airborne.

The steepness of the foreslope affects the rate of single-vehicle accidents. A 1987 study (*32*) estimated the ratio of single-vehicle accident rates for two-lane rural roads. Adjustments were made for ADT, lane width, shoulder width, and recovery distance. Figure D-15 shows the estimated ratios relative to the single-vehicle accident rate for 7:1 or flatter foreslopes.

Using the available data, researchers estimated ARFs for flattening foreslopes on two-lane rural roads. These reductions assume that the roadside foreslope to be flattened is relatively clear of rigid obstacles. Table D-22 presents the ARFs.

The steepness of the foreslope also affects the likelihood that a vehicle that has run off the road will roll over. A recent FHWA study (*7*) found that sideslopes of 5:1 (not 4:1) or flatter were needed to significantly reduce the incidence of rollover accidents.

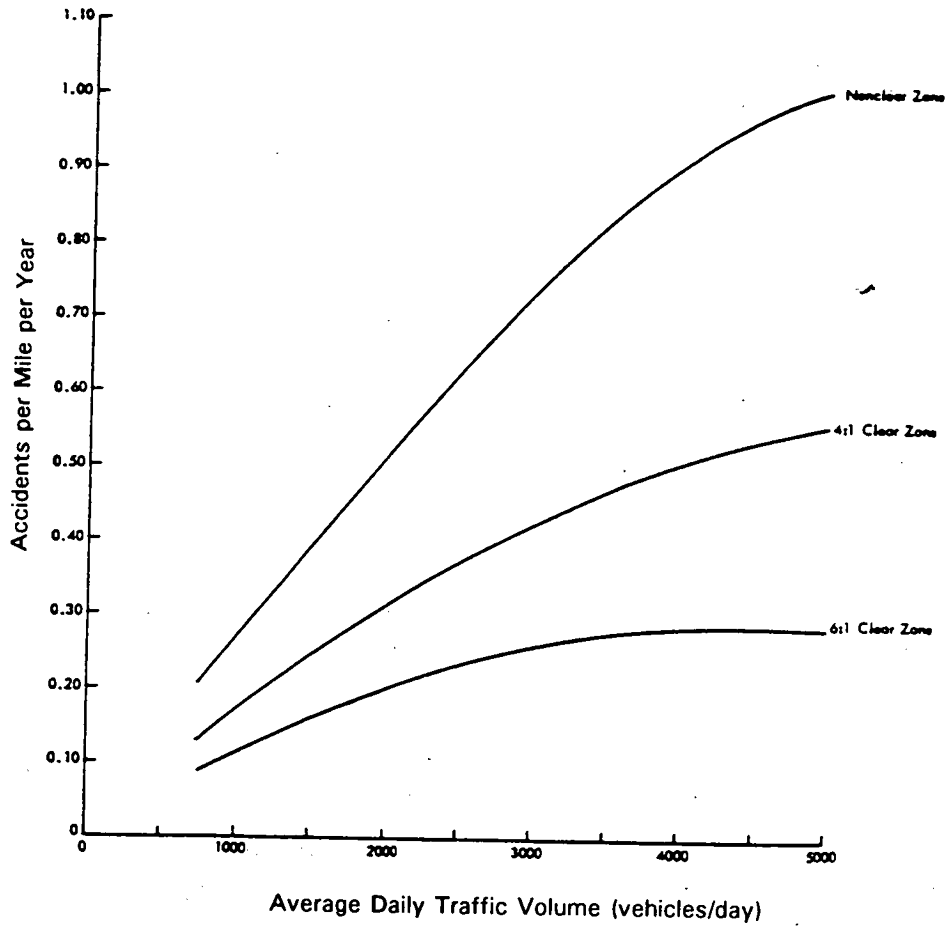


Figure D-12. Single-vehicle accident frequency as a function of clear zone policy and ADT for two-lane rural highways (31).

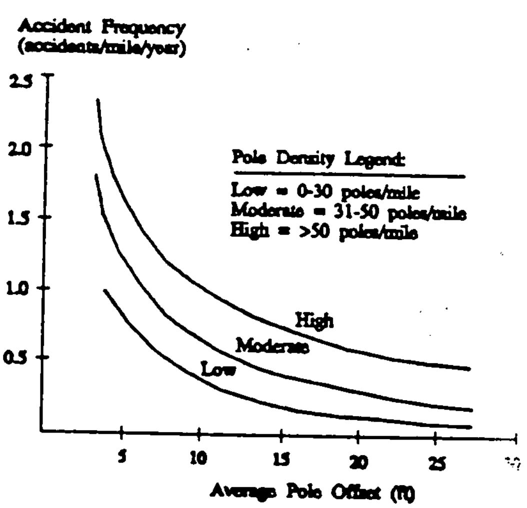


Figure D-13. Annual average frequency of utility pole accidents as a function of pole density and lateral offset to the utility pole (7).

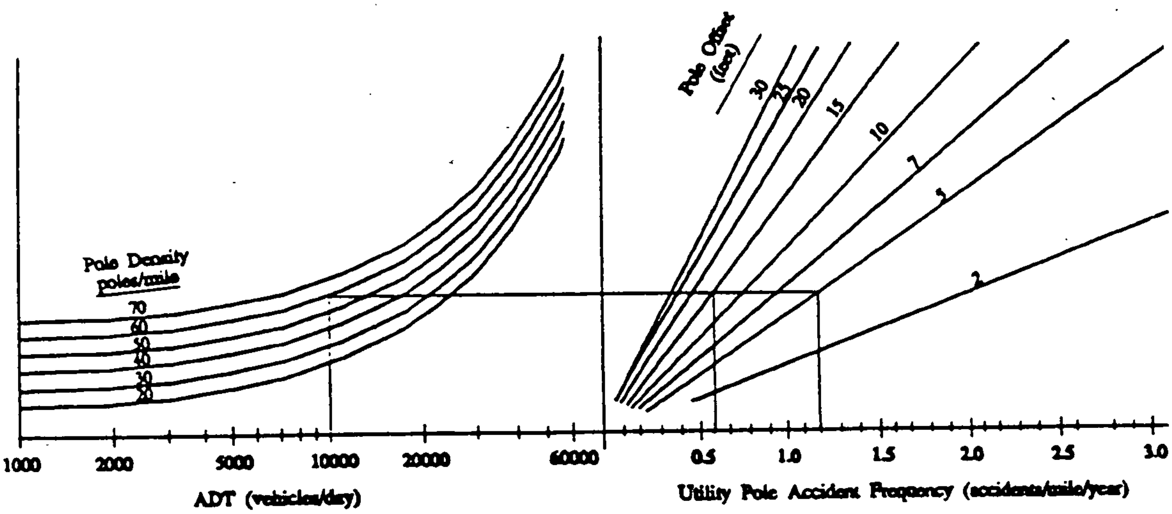


Figure D-14. Nomograph for predicting utility pole accident frequency (7).

TABLE D-19. Accident reduction factors for removing or relocating roadside obstacles on two-lane rural roads (*32*)

Amount of Increase in the Lateral Offset to Obstacle (ft)	Percent Reduction in Obstacle Accidents by Obstacle Type			
	Trees	Mailboxes, Culverts, & Signs	Guardrails	Fences &/or Gates
3	22	14	36	20
5	34	23	53	30
8	49	34	70	44
10	57	40	78	52
13	66	*	*	*
15	71	*	*	*

* Relocation of obstacle to specified distance is generally not feasible.

TABLE D-20. Severest injury by object struck in nonrollover accidents (*22*)

Object	Number of Accidents	Percent Injured	Percent Killed
Bridge or overpass entrance	88	75.0	15.9
Tree	667	67.9	7.2
Field approach	75	66.7	1.3
Culvert	231	62.3	6.1
Embankment	406	57.6	4.4
Wood utility pole	598	51.2	2.3
Bridge or overpass siderail	82	51.2	2.4
Rock(s)	73	49.3	1.4
Ditch	368	48.9	1.1
Ground	153	48.4	3.3
Trees/bush	255	38.4	2.0
Guardrail	284	31.7	1.8
Fence	325	24.3	0.3
Small sign post	76	22.4	1.3
TOTAL	3,681	50.8	3.6

TABLE D-21. Relative distribution of single-vehicle run-off-road accidents on curves of undivided highways (*22*)

Side of Road	Curve Direction	Number of Single-Vehicle Accidents	Relative Percentage	Relative % (Outside vs. Inside)
Right Side	Left Curve	1,415	50.4%	72.7% (Outside Curve)
Left Side	Right Curve	627	22.3%	
Right Side	Right Curve	446	15.9%	27.3% (Inside Curve)
Left Side	Left Curve	320	11.4%	

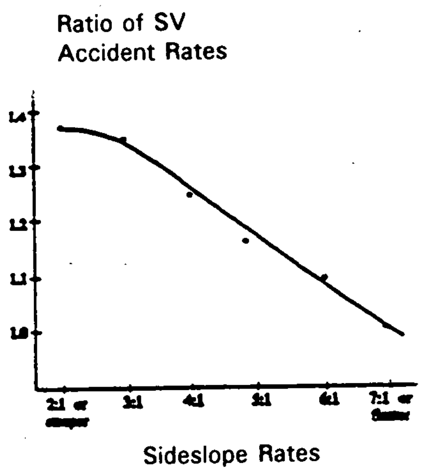


Figure D-15. The ratio of single-vehicle accident rates as a function of steepness of slope (32).

TABLE D-22. Estimated reduction in single-vehicle and total accidents on two-lane rural roads due to flattening of foreslopes (derived from data presented in Reference 7)

Sideslope BEFORE Flattening	Sideslope AFTER Flattening	Percent Reduction in Single-Vehicle Accidents	Percent Reduction in Total Accidents
2:1	4:1	10	6
	5:1	15	9
	6:1	21	12
	7:1	27	15
3:1	4:1	8	5
	5:1	14	8
	6:1	19	11
	7:1	26	15
4:1	5:1	6	3
	6:1	12	7
	7:1	19	11
5:1	6:1	6	3
	7:1	14	8
6:1	7:1	8	5

APPENDIX D
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