TRANSPORTATION RESEARCH

RECORD

No. 1512

Highway and Facility Design

Safety Effects of Roadway Design Decisions

A peer-reviewed publication of the Transportation Research Board

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY PRESS
WASHINGTON, D.C. 1995

Transportation Research Record 1512
ISSN 0361-1981
ISBN 0-309-06171-7
Price: $18.00

Subscriber Category
IIA highway and facility design

Printed in the United States of America

Sponsorship of Transportation Research Record 1512

GROUP 3—OPERATION, SAFETY, AND MAINTENANCE OF TRANSPORTATION FACILITIES
Chairman: Jerome W. Hall, University of New Mexico

Facilities and Operation Section
Chairman: Jack L. Kay, JHK & Associates

Committee on Operational Effects of Geometrics
Chairman: Daniel S. Turner, University of Alabama
Secretary: Douglas W. Harwood, Midwest Research Institute
Rahim F. Benekohal, Myung-Soon Chang, John E. Fisher, Kay Fitzpatrick, J. L. Gattis, Don Jay Gripne, Michael F. Hankey, Jeffrey P. Hartman, Warren E. Hughes, Raymond A. Krammes, Ken Lazar, Mark A. Marek, Patrick T. McCoy, John J. Nitzel, K. F. Phillips, Abishai Polus, Justin True, Walter E. Witt, Paul H. Wright

Transportation Research Board Staff
Robert E. Spicher, Director, Technical Activities
Richard A. Cunard, Engineer of Traffic and Operations
Nancy A. Ackerman, Director, Reports and Editorial Services

Sponsorship is indicated by a footnote at the end of each paper. The organizational units, officers, and members are as of December 31, 1994.

Transportation Research Record 1512

Contents

Foreword v

Relationships Between Operational and Safety Considerations in Geometric Design Improvements 1
Douglas W. Harwood

Safety Module for Highway Geometric Design 7
Ruediger Lamm, Artur K. Guenther, and Elias M. Choueiri

Safety Effects of Roadway Design Decisions—Roadside 16
King K. Mak

Effects of Tort Liability on Roadway Design Decisions 22
Daniel S. Turner and Joseph D. Blaschke

Safety Relationships Associated with Cross-Sectional Roadway Elements 29
Charles V. Zegeer and Forrest M. Council

Foreword

The Committee on Operational Effects of Geometrics provides a focus and forum within the Transportation Research Board for issues related to the effects of roadway design decisions on operations and safety. The Committee seeks to promote a better understanding of the effects of these decisions within the transportation profession. It has sponsored, and cosponsored with the Committee on Geometric Design, a number of sessions at TRB Annual Meetings focused on various geometric design issues. The papers in this volume are from the 1992 TRB Annual Meeting and they cover topics related to the safety effects of geometric design decisions.

All papers in this volume are sponsored by the Committee on Operational Effects of Geometrics and have been peer reviewed. The Committee encourages comments and discussion on the issues raised in this volume and encourages suggestions for future discussion topics.

Relationships Between Operational and Safety Considerations in Geometric Design Improvements

DOUGLAS W. HARWOOD

Traffic operations have an important influence on safety. This paper demonstrates that traffic operational improvement projects can have a positive influence on safety under varied highway conditions. Examples of operational improvement projects on two-lane highways and urban arterials that also reduce accidents are cited. The examples address passing lanes on two-lane highways and use of narrower lanes and center two-way left-turn lanes on urban arterials. These examples primarily concern issues related to the highway cross-section. The safety benefits of these types of improvement projects result partly from an improved level of service and partly from smoother traffic operations with fewer vehicle-vehicle conflicts. Relationships between traffic operations and safety are less well understood for other design elements such as horizontal and vertical alignment. The need for flexibility in geometric design standards to obtain both these traffic operational and safety benefits is illustrated. Further research is needed to establish reliable relationships between traffic congestion (volume-capacity, or V-C ratio) and safety for highway sections and intersections.

It has been accepted for many years that traffic operational considerations have an important influence on the safety performance of geometric design improvements. Many engineers have been taught since their school days that "operations and safety go hand in hand." In other words, smooth traffic operations, at an appropriate level of service, provide safe traffic operations. The purpose of this paper is to explore the practical meaning of this concept for geometric designers.

The important role of traffic operations in safety, although generally accepted, has never been well quantified. Indeed, the structure of our highway improvement programs has tended to encourage us to think about traffic operations and safety as separable issues. Some highway improvements are classified as "safety projects," because the projects are constructed at high-accident locations identified by a computerized accident surveillance system and because categorical safety funds are used in their solution. Other projects are thought of as operational improvements, because they are constructed in response to daily congestion patterns and motorist complaints about delay. In fact, many "safety projects" have a strong operational component, and many operational improvements provide opportunities to bring about substantial reductions in accident rates and changes in accident patterns.

There is a strong temptation to assume that traffic operational issues can be addressed completely with the procedures of the *Highway Capacity Manual* (HCM) (*1*) and that safety issues can be addressed completely by providing a design that meets applicable AASHTO policies (*2,3*). However, in the real world of highway design, there is a clear need for safety analysts to understand the existing operational problems at a site, and for operational analysts and geometric designers to be familiar with the existing accident patterns at a site and the likely safety performance of candidate alternative solutions.

The following discussion illustrates the role of traffic operational improvements projects in improving highway safety by means of examples for both rural two-lane highways and urban arterial streets. The paper also focuses on what is known about the relationships of traffic congestion and safety and what future research is required on this important issue. The examples provided here primarily concern issues related to the highway cross-section. Relationships between traffic operations and safety are less well understood for other design elements such as horizontal and vertical alignment.

OPERATIONAL IMPROVEMENTS ON RURAL TWO-LANE HIGHWAYS

Operational problems on two-lane highways arise because drivers of faster vehicles are delayed by drivers of slower vehicles and find themselves unable to pass. There is a variety of vehicle speeds on two-lane highways because some drivers have lower desired travel speeds than others and because the maximum speed of some vehicles is limited by horizontal and vertical alignment restrictions and vehicle performance abilities. The operational analysis procedures in Chapter 8 of HCM base the level of service for two-lane highways on percent time delay, which is defined as the percentage of their time that drivers spend delayed in platoons behind other drivers while traversing a section of highway. Thus, percent time delay is essentially a platooning measure that represents the imbalance between passing demand and passing supply on a particular highway section.

One of the most effective methods for improving the level of service on a two-lane highway is the installation of passing lanes to provide additional passing opportunities (*4–6*). A passing lane is an added lane in one or both directions of travel on a two-lane highway to improve passing opportunities. This definition includes passing lanes in level or rolling terrain, climbing lanes on grades, and short four-lane sections. Figure 1 illustrates a typical passing lane on a two-lane highway.

Analyses of the operational effectiveness of passing lanes have shown them to be very effective in improving traffic operations on two-lane highways (i.e., increasing the level of service). Passing lanes cut traffic platooning essentially in half over the length of the passing lane. Furthermore, this benefit of reduced platooning car-

---

Midwest Research Institute, 425 Volker Boulevard, Kansas City, Mo. 64110.

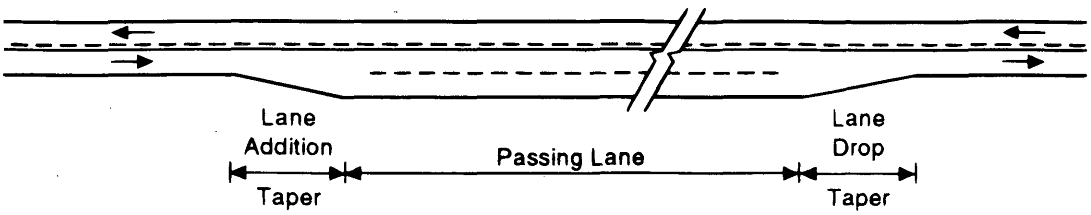


FIGURE 1 Plan view of a typical passing lane section.

ries over onto the downstream roadway and typically persists for 5 to 13 km (3 to 8 mi) downstream of a passing lane (*5,6*).

The key point to be emphasized in this paper is that passing lanes not only have operational benefits, they also have substantial safety benefits. Research has established that installation of a passing lane on a two-lane highway typically reduces total accident rates by 25 percent and fatal and injury accident rates by 30 percent (*4,6*).

The key reason for the substantial reduction in accident experience is the effect of better operations. Passing lanes provide an opportunity for drivers to make passing maneuvers without using the lanes normally reserved for opposing traffic. Passing lanes provide an assured passing opportunity. Drivers know that they will be able to pass in a passing lane whether or not there is traffic present in the opposing direction. If drivers know that passing lanes are provided at intervals, they may be discouraged from making marginal passing maneuvers in the face of opposing traffic on the normal two-lane highway since better passing opportunities will certainly be available in an upcoming passing lane. Advance signing, informing drivers of upcoming passing lanes 3 to 8 km (2 to 5 mi) before they reach the passing lane, may encourage caution in passing.

Passing opportunities on two-lane highways can also be provided by installation of short four-lane sections that function as side-by-side passing lanes. Some engineers have hesitated to use short four-lane sections to provide additional passing opportunities on two-lane highways because four-lane undivided roadways have been considered to have high accident rates. However, the higher accident rate of some four-lane undivided roadways is generally attributable to use at rural or urban sites with substantial roadside development. Where short four-lane sections have been used to provide passing opportunities in relatively undeveloped areas, total accident rates have been reduced by 34 percent and fatal and injury accident rates have been reduced by 43 percent. As in the case of passing lanes, the provision of additional passing opportunities by installation of a short four-lane section has been demonstrated to enhance safety (*4,6*). The accident reduction effectiveness measures cited above include only the passing lane or short four-lane sections themselves plus 0.8 km (0.5 mi) on either side. It is possible that the installation of passing lanes and short four-lane sections may also reduce accident risks by discouraging improper passing at locations remote from the actual passing lane site.

OPERATIONAL IMPROVEMENTS ON URBAN ARTERIALS

Even more dramatic effects of operational improvements on safety can be demonstrated on urban arterials. NCHRP Report 330, "Effective Utilization of Street Width on Urban Arterials" (*7*), provides guidelines for improving traffic operations on urban arterials without changing the total curb-to-curb street width. These guidelines are applicable to streets in developed areas for which geometric alternatives that would require widening of the street are infeasible. Improvement strategies evaluated in the research included projects that involved the use of narrower lanes, median removal, provision of additional through lanes, and installation of a center two-way left-turn lane (TWLTL).

TWLTLs have been found to be a very effective method for improving traffic operations on urban and suburban arterial streets by removing left-turning traffic from the through lanes and eliminating delays to through traffic caused by the turning vehicles at driveways and unsignalized intersections. In addition to their obvious traffic operational benefits, TWLTLs also reduce accidents. In general TWLTLs have been found to reduce accidents on urban and suburban arterials by 35 percent. Even higher accident reductions from TWLTLs have been found on urban and suburban arterials with a high percentage of left-turn and rear-end accidents and on rural two-lane highways (*6,8*).

ACCIDENT REDUCTION EFFECTIVENESS

NCHRP Report 330 found that both operations and safety of urban arterials can be improved by implementing strategies that involve the use of narrower lanes. For example, Table 1 illustrates the accident reduction effectiveness of three improvement strategies:

- Conversion from a four-lane undivided street to a five-lane street with a center TWLTL;
- Conversion from a four-lane divided street with a narrow 1.2-m (4-ft) median to a five-lane street with a center TWLTL; and
- Conversion from a six-lane divided street with a narrow median to a seven-lane street with a center TWLTL.

Figure 2 illustrates each of the cross-sections involved in these strategies. Each of these project types identified above resulted in statistically significant reductions in accident rate with no change in the percentage of fatal and injury accidents, even though through lanes as narrow as 2.7 m (9 ft) were used in some cases to make room for the TWLTL. In other words, any increase in accidents that might be associated with the use of narrower lanes was more than offset by the substantial reduction in accidents associated with the installation of a TWLTL. Since the street cross-section could not be widened, the use of narrower through lanes was the only way to provide space for a TWLTL at these sites.

The lessons to be drawn from this experience are that traffic operational and safety problems are related, and solving traffic operational problems on an arterial highway can lead to safety benefits as well. Furthermore, in situations in which traffic operational prob-

TABLE 1 Accident Reduction Effectiveness of Selected Project Types on Urban Arterials (7)

	Accident rate reduction	
Project type	Expected value (%)	90% Confidence interval (%)
Conversion from a four-lane undivided street to a five-lane street with a TWLTL	44	13-75
Conversion from a four-lane divided street with a narrow median to a five-lane street with TWLTL	53	24-82
Conversion from a six-lane divided street with a narrow median to a seven-lane street with TWLTL	24	11-38

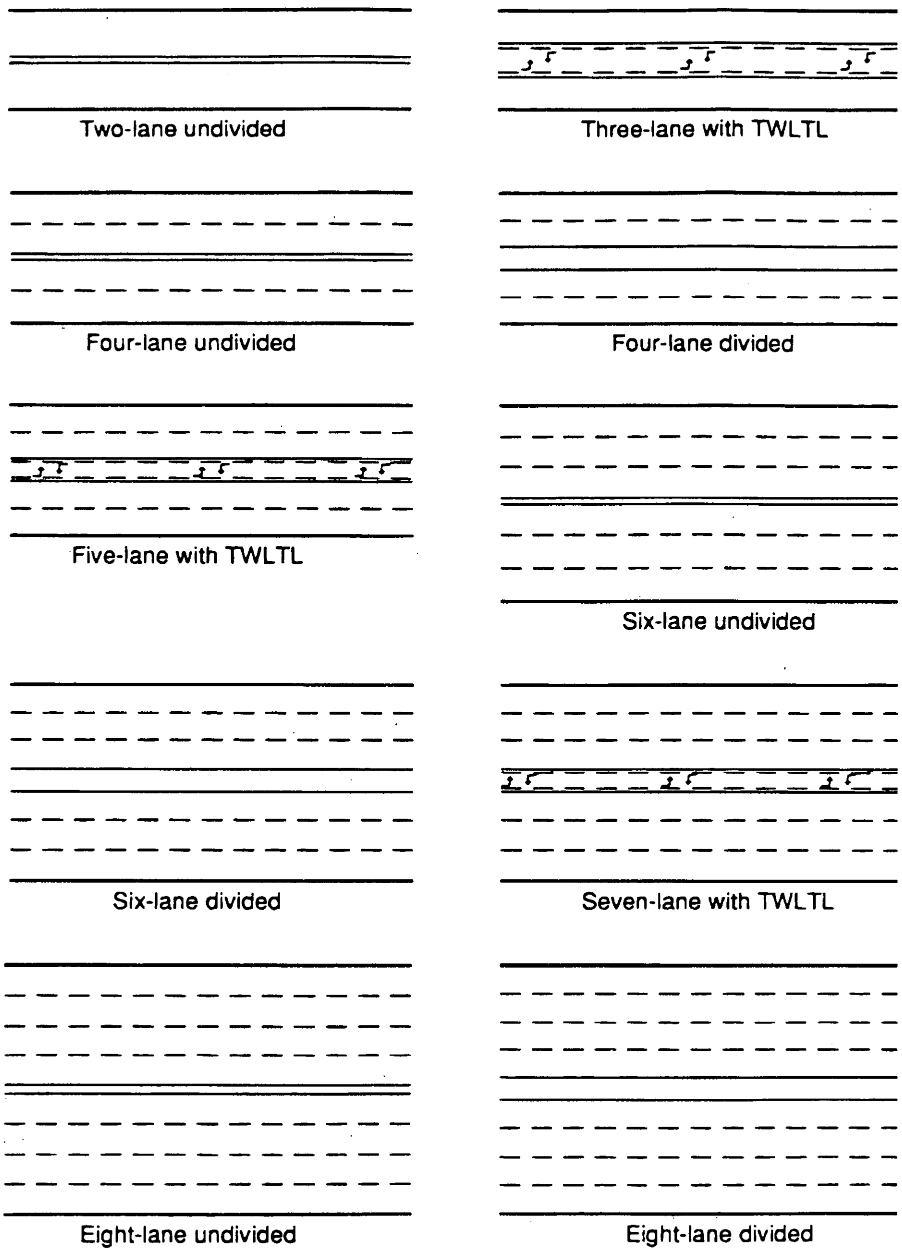
lems exist, solving these problems frequently has a positive effect on safety even when some geometric standards, such as lane width, must be relaxed to do so. Highway agencies should be careful to monitor projects in which narrower lanes are used to make sure that safety problems do not develop and, in doing so, highway agencies should build up experience about what works and what doesn't work in their area.

Nothing said here is intended to encourage indiscriminate use of narrower lanes. However, at the same time, a blanket prohibition against the use of narrower lanes will cause highway agencies to miss opportunities to solve traffic operational problems in a cost-effective manner and to improve safety at the same time. Rational guidelines, based on research and highway agency experience, are needed to guide implementation of such projects. Such guidelines have been developed and are presented in the next section.

GUIDELINES FOR REALLOCATION OF STREET WIDTH ON URBAN ARTERIALS

The following guidelines for projects involving narrower lanes on urban arterials were developed in NCHRP Report 330. These guidelines indicate where geometric design policies can be relaxed without compromising safety in improvements to existing facilities and illustrate the multitude of considerations that affect such decisions:

- Narrower lane widths (less than 3.4 m or 11 ft) can be used effectively in urban arterial street improvement projects in which the additional space provided can be used to relieve traffic congestion or address specific accident patterns. Narrower lanes may result in increases in some specific accident types, such as same-direction sideswipe collisions, but other design features of a project may offset or more than offset that increase.
- Projects involving narrower lanes nearly always reduce accident rates when the project is made to implement a strategy known to reduce accidents, such as installation of a center TWLTL or removal of curb parking. Highway agencies should not hesitate to implement such projects on urban arterial streets.
- Projects involving narrower lanes whose purpose is to reduce traffic congestion by providing additional through lanes may result in a net increase in accident rates, particularly for intersection accidents. Such projects should be evaluated carefully on a case-by-case basis, considering the agency's previous experience with that type of project. Both the traffic operational and traffic safety effects of the project should be evaluated and the feasibility of incorporating geometric improvements at intersections (such as left-turn lanes) to reduce intersection accidents should be considered.
- Lane widths as narrow as 3.1 m (10 ft) are widely regarded by urban traffic engineers as being acceptable for use in urban arterial street improvement projects. Except for one specific project type that is not common (conversion from a two-lane undivided to a four-lane undivided street), all projects evaluated in this study that consisted exclusively of lane widths of 3.1 m (10 ft) or more resulted in accident rates that were either reduced or unchanged. Where streets cannot be widened, highway agencies should give strong consideration to the use of 3.1-m (10-ft) lanes, where they are necessary, as part of a geometric improvement to upgrade traffic operations or alleviate specific accident patterns.
- Lane widths less than 3.1 m (10 ft) should be used cautiously and only in situations in which it can be demonstrated that increases in accident rates are unlikely. For example, numerous project evaluations in this study found that 2.7- and 2.9-m (9- and 9.5-ft) through-traffic lanes can be used effectively in projects to install a center TWLTL on existing four-lane undivided streets. Such projects nearly always result in a net reduction in accident rate. On streets that cannot be widened, highway agencies should consider limiting the use of lane widths less than 3.1 m (10 ft) to (a) project types in which their own experience indicates that they have been used effectively in the past or (b) locations where the agency can establish an evaluation or monitoring program for at least 2 years to identify and correct any safety problems that develop.
- In highly congested corridors, agencies should anticipate that traffic operational improvements on one street, such as provision of additional through lanes, may attract traffic to that street from parallel streets. This may lead to increased traffic volumes and increased accidents on the improved street, but may still reduce delays and accidents in the corridor as a whole.
- Projects that change the geometrics of signalized intersection approaches should be accompanied by adjustments in signal timing (and, in some cases, changes in signal phasing). Traffic volumes on the project (and, possibly, on parallel streets) should be reviewed 1 or 2 months after project implementation to determine if there is a need for further adjustments in a signal timing.
- Truck volumes are an important consideration in the implementation of projects involving narrower lanes. There appears to be general agreement that narrower lanes do not lead to operational problems when truck volumes are less than 5 percent. Sites with truck volumes between 5 and 10 percent should be evaluated care-



Two-lane undivided

Three-lane with TWLTL

Four-lane undivided

Four-lane divided

Five-lane with TWLTL

Six-lane undivided

Six-lane divided

Seven-lane with TWLTL

Eight-lane undivided

Eight-lane divided

FIGURE 2 Design alternatives evaluated for urban arterial streets (*7*).

fully on a case-by-case basis. Use of narrower lanes should be discouraged on streets with more than 10 percent truck traffic.

- Higher truck volumes may not cause operational problems on streets with narrower lanes if the trucks travel straight through the site without turning.
- Trucks may be a greater concern on streets with horizontal curves than on tangents.
- Tractor-trailer combination trucks may be more critical than single-unit trucks because of their greater width and their greater offtracking.
- Curb lanes should usually be wider than other lanes by 0.3 to 0.6 m (1 to 2 ft) to provide allowance for a gutter and for greater use of the curb lanes by trucks. Center or left lanes for through traffic and TWLTLs can usually be narrower than the curb lane. One city engineer has pointed out that the left lane for through traffic on an arterial street can be quite narrow if it is adjacent to a center TWLTL, which increases the "effective width" of the through lane. The presence of a TWLTL adjacent to a through lane is obviously less restrictive than the presence of a curb or another through lane.
- Narrow lane projects do not work well if the right lane provides a rough riding surface because of poor pavement conditions or the presence of grates for drainage inlets. Drivers may avoid the right lane if they believe uncomfortable driving will occur over rough drainage inlets. Thus, projects with narrower lanes may be most satisfactory at sites with curb inlets that do not have grates in the roadway.
- The needs of bicyclists should be considered in implementing projects involving narrower lanes. The literature indicates that curb

lane widths of at least 4.6 m (15 ft) are desirable to accommodate the shared operation of bicycles and motor vehicles (*9,10*); thus, it may not be possible to fully accommodate bicyclists even on many existing streets with 3.6-m (12-ft) curb lanes. Decisions concerning implementation of projects with narrower lanes should be made by taking into consideration the volume of bicyclists using the roadway and the availability of other bicycle facilities in the same corridor.

- When lanes are narrow, operational efficiency at some sites may be reduced because of staggering of traffic in adjacent lanes. The capacity per lane may be reduced because drivers are reluctant to travel side by side. However, drivers in adjacent lanes still travel at shorter headways than they could in a single lane, so the overall through traffic capacity of the street should increase, but not by as much as would be possible if wider lanes could be used.
- Projects that can be implemented by remarking only can be implemented very quickly, often in a single day. However, projects that involve construction, such as median removal, require more time to complete.
- A common problem in remarking projects is that it is difficult to remove the existing pavement markings completely. Current removal methods include grinding, sandblasting, and waterblasting. Because of these problems, some agencies implement almost all remarking projects in conjunction with pavement resurfacing.
- Remarking projects may be confusing to drivers if the new lane lines no longer match the pavement join lines (or the reflections of the pavement joint lines). This potential problem is another indication that implementation of remarking projects in conjunction with pavement resurfacing is very desirable.
- Access control regulations concerning driveway location and design are important on all urban arterial streets, but especially for streets that are not wide enough to install a median or center TWLTL. Driveway design and location measures that have been found to be effective are summarized in NCHRP Report 330 (*7*).

ROLE OF TRAFFIC CONGESTION IN SAFETY

The highway community needs broader knowledge about the relationship between traffic congestion and safety so that we can take better advantage of opportunities to improve safety by reducing traffic congestion. Although the examples of two-lane highway and urban arterial improvements presented above illustrate specific instances in which traffic operational improvements also improve safety, we do not have a complete understanding of the relationship between traffic congestion and safety. For example, it would be extremely valuable to know how safety varies with V-C ratio and what V-C ratios provide minimum accident rates.

It would also be valuable to have a better understanding of the role of oversaturated operating conditions, with V-C ratios greater than 1.0, in producing accidents. Freeways in many urban areas operate under oversaturated stop-and-go conditions during peak hours and under more normal free-flow conditions at other times of day. The stop-and-go operations may lead to high accident rates, particularly involving rear-end and lane-changing accidents, although the lower speeds involved suggest that the severity of such accidents may be relatively low. Oversaturated approaches to signalized intersections develop queues that may extend well back from the intersection. Such queues may also be associated with rear-end accidents. The safety implications of oversaturated intersection operations also need to be studied more fully.

Only limited research has been conducted on the variation of safety with V-C ratio. One recent study was reported by Hall and Pendleton (*11*), who studied roadway accident rates in New Mexico as a function of V-C ratio by comparing the hourly patterns of reported accidents to the hourly patterns of traffic volumes from permanent count stations on the same highways. This study took exactly the right approach to this research, but the applicability of the results was limited by the nature of the roadway system in New Mexico, which includes very few highways with high V-C ratios. Another recent study by Hall and Polanco de Hurtado (*12*) has examined the variations of accident experience with traffic volumes at urban intersections. More research of this type is needed, over a greater range of V-C ratios, to establish valid relationships between safety and traffic congestion to provide a basis for maximizing the safety benefits from operational improvement projects.

SUMMARY AND CONCLUSIONS

Traffic operational conditions have a strong influence on the potential for the occurrence of traffic accidents. Many operational improvement projects provide important safety benefits through reductions in traffic congestion. This paper has presented examples of traffic operational improvements that also have positive impacts on safety, including:

- Installation of passing lanes and short four-lane sections to increase passing opportunities on two-lane highways; and
- Reallocation of street width on urban arterials, through use of narrower through lanes and removal of raised medians, to provide room for operational improvements such as center TWLTLs.

The safety benefits of these types of improvement projects result partly from an increased level of service and partly from smoother traffic operations with fewer vehicle-vehicle conflicts.

It is important that geometric design policies recognize that substantial safety benefits can be obtained from traffic operational improvements and that, in some cases, exceptions to geometric design standards may be necessary to obtain both the operational and safety benefits. Further research is needed to establish relationships between traffic congestion (e.g., V-C ratio) and safety as a basis for using traffic operational improvements as a means for reducing accidents.

REFERENCES

1. *Special Report 209: Highway Capacity Manual*, 3rd ed. TRB, National Research Council, Washington, D.C., 1994.
2. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, 1994.
3. American Association of State Highway and Design Officials. *Roadside Design Guide*, 1989.
4. Harwood, D.W., and A.D. St. John. *Passing Lanes and Other Operational Improvements on Two-Lane Highways.* Report FHWA/RD-85/028. FWHA, U.S. Department of Transportation, July 1984.
5. Harwood, D.W., and A.D. St. John. *Operational Effectiveness of Passing Lanes on Two-Lane Highways.* Report FHWA/RD-86/196. FWHA, U.S. Department of Transportation, 1986.
6. Harwood, D.W., and C.J. Hoban. *Low-Cost Methods for Improving Traffic Operations on Two-Lane Roads—Informational Guide.* Report FHWA-IP-87-2. FWHA, U.S. Department of Transportation, 1987.
7. Harwood, D.W. *NCHRP Report 330: Effective Utilization of Street Width on Urban Arterials.* TRB, National Research Council, Washington, D.C., Aug. 1990.
8. Harwood, D.W. *NCHRP Report 282: Multilane Design Alternatives for Improving Suburban Highways.* TRB, National Research Council, Washington, D.C., March 1986.

9. McHenry, S.R., and M.J. Wallace. *Evaluation of Wide Curb Lanes as Shared Lane Bicycle Facilities*. Report FHWA/RD-85/106. Maryland State Highway Administration, Aug. 1985.
10. Feldman, W., *Bicycle Compatible Roadways—Planning and Design Guidelines*. New Jersey Department of Transportation, Dec. 1982.
11. Hall, J.W., and O.J. Pendleton. Rural Accident Rate Variations with Traffic Volume. In *Transportation Research Record 1281*, TRB, National Research Council Washington, D.C., 1990.
12. Hall, J.W., and M. Polanco de Hurtado. Effect of Intersection Congestion on Accident Rates. In *Transportation Research Record 1376*, TRB, National Research Council, Washington, D.C., 1992.

Safety Module for Highway Geometric Design

RUEDIGER LAMM, ARTUR K. GUENTHER, AND ELIAS M. CHOUEIRI

Three safety criteria for evaluating curved roadway sections including transition sections were analyzed in order to address these important target areas for reducing accident frequency and severity. These criteria are (a) achieving consistency between successive design elements; (b) harmonizing design speed and operating speed, especially on wet pavements; and (c) providing adequate dynamic safety of driving. The above safety criteria constitute the core of the overall safety module proposed in this study for classifying road networks or roadway sections (or both), existing or planned, as good, fair, or poor designs. The evaluation process of the safety module, encompassing separate evaluation processes for each of the above safety criteria as well as for the combination of all three criteria, can be done manually by using the Geographic Information System known as "SPANS." By using discriminating colors or symbols with SPANS, the resulting separate or combined design safety levels can be easily recognized by the highway engineer. For the case study in this paper, the actual accident rates for the majority of the investigated roadway sections corresponded with the results of the overall safety module, or the results were at least on the safe side. Generally speaking, the results in this paper appear to be pointing in the right direction for evaluating roadway sections and networks using various safety criteria. The proposed procedure verifies for the first time that the evaluation of roadway sections or networks by an overall safety module is possible for design, redesign, rehabilitation, and restoration strategies.

Comparative analyses and statistical evaluations of accidents in Western Europe and the United States revealed that the rural road network system, which consists mainly of two-lane rural roads, represents between 60 and 70 percent of the total number of fatalities on both continents. It is estimated that half of these fatalities, or at least 30 percent, occur on curved roadway sections, primarily when drivers exceed the critical speed of a curve and thereby loose control. Based on this percent figure, it can be estimated that in 1990 about 13,000 persons in the U.S.A. and about 15,000 in the countries of the European Union lost their lives at curved sites, or in transition sections (*1*).

From the point of view of highway design and traffic safety engineers, it can be said, then, that curved roadway sections, including transition sections, represent one of the most important target areas for reducing accident frequency and severity. It should be noted that curved roadway sections are especially dangerous for young drivers between the ages of 15 to 25 years (*1*).

Based on these fatality figures, the need for a safety module appears to be a necessity. This safety module is defined by a classification system based on three individual safety criteria defined in the following, and should be able to analyze the relationships between highway geometric design, driver behavior, the accident situation, and driving dynamics on road networks or roadway sections, or both. Because of the complexity that exists between these issues, linking this safety module with existing data processing systems for highway engineering or with Geographic Information Systems (GIS), or both, is very significant.

BACKGROUND

During the period from 1940 to 1970, the only direct safety criterion in geometric design guidelines available to highway engineers in most Western European Countries and the U.S.A., was mainly directed toward evaluating the dynamic safety of driving, such as calculating for a given design speed, minimum radii of curves, super-elevation rates, necessary stopping sight distances, minimum radii of crest vertical curves, and so forth (*2,3*).

Since the 1960s, many experts have recognized the fact that abrupt changes in operating speeds lead to accidents on two-lane rural roads, and that these speed inconsistencies may be largely attributed to abrupt changes in horizontal alignment (*4–7*). Since the 1970s, two additional indirect design criteria related to traffic safety have been provided in the geometric design guidelines of some European countries. German, Swedish, and Swiss designers, for instance, are partially provided with design criteria to ensure design consistency between design elements, and to harmonize design speed and operating speed (*8–11*).

Research studies conducted over the past two decades have shown that, in the area of highway geometric design, three safety criteria should be addressed in order to gain direct or indirect safety advantages (*4–6,12–14*). These criteria are (I) achieving consistency between successive design elements; (II) harmonizing design speed and operating speed, especially on wet pavements; and (III) providing adequate dynamic safety of driving.

Criteria I to III were the subject of a number of reports, publications, and presentations by the authors (*11–20*). These investigations included (a) processes for evaluating horizontal design consistency and inconsistency between successive design elements, (b) processes for evaluating design speed and operating speed differences, and (c) processes for evaluating the differences between side friction assumed and side friction demand on curved roadway sections.

The above criteria will constitute the core of the overall safety module proposed in this study for (a) examining consistency or inconsistency between successive design elements, (b) examining the expected operating speed in relation to the design speed, and (c) examining the dynamic safety of driving on curved roadway sections. It is recommended that road networks or roadway sections (or both), existing or planned, be evaluated by the safety module, mainly in relation to good, fair, and poor design practices.

R. Lamm, Dipl. Inform, Heiko Steffen, Institute of Highway and Railroad Engineering, University of Karlsruhe, 76128 Karlsruhe, Kaiserstr. 12, Germany. A. K. Guenther, Director, AKG Software Consulting, 79282 Ballrechten-Dottingen, Franz-Hess-Str. 6, Germany. E. M. Choueiri, Transportation Consultant, P.O. Box 407, Hazmieh, Beirut, Lebanon.

CRITERION I: ACHIEVING CONSISTENCY BETWEEN SUCCESSIVE DESIGN ELEMENTS

Achieving consistency in horizontal alignment, and thereby a consistent operating speed, is an important, safety criterion to be considered in the design and redesign of two-lane rural highways or networks to avoid possible critical driving maneuvers, which may in turn lead to unfavorable accident risks (*17–20*).

In this connection, the 1984 AASHTO Policy on the Geometric Design of Highways and Streets (*21*) recommends the following:

- Consistent alignment always should be sought;
- Sharp curves should not be introduced; and
- Sudden changes from areas of flat curvature to areas of sharp curvature should be avoided.

Therefore, a method for identifying consistencies or inconsistencies between successive design elements is, without a doubt, of great importance for enhancing traffic safety. Research that evaluated the impact of design parameters (degree of curve, length of curve, super-elevation rate, lane width, shoulder width, sight distance, gradient (up to 6 percent), posted speed, and traffic volume on a data base (the present data bases contain road sections with gradients up to 6 percent and traffic volumes between 500 and 10,000 vehicles per day) of 322 two-lane curved highway sections in New York State demonstrated that the most successful parameter in explaining much of the variability in operating speeds (V85) and accident rates (ACCR) was the degree of curve (*12,14,15*). The relationship of operating speed-accident rate and degree of curve are quantified by the regression models presented in Table 1, and schematically shown in Figure 1(*a*) (*14*). Similar results were found in the Federal Republic of Germany (see Table 1 and Figure 1(*b*) (*8,22*). The German data base consisted of 204 two-lane rural curved highway sections.

For a better understanding, the following reading is conducted with respect to Figure 1(*a*) for U.S. conditions. For a curve with a degree of curve (DC) = 10° and a lane width (LW) = 12 ft, an operating speed (V85) = 50 mph, and an accident rate (ACCR) = 10.5, accidents per 106 vehicle miles may be expected.

Note that the relationships in Figure 1, with the exception of those in the upper part of Figure 1(*b*) between operating speed and degree of curve in the Federal Republic of Germany, are linear. Generally speaking, the results of both figures show a certain degree of similarity. It should be noted that the American accident rates are related to all accidents, whereas the German ones are related only to run-off-the-road accidents. This difference may explain the lower accident rate values in Germany. As the figures show, operating speeds decrease with increasing degree of curve, whereas accident rates increase with increasing degree of curve.

Based on a literature review and research experiences gained by the authors in the U.S.A. (*6,11,12,14–16*) and in Europe (*7,13,23*), the changes in operating speeds between successive design elements (Table 2) provide a reasonable and quantifiable classification system for differentiating good, fair, and poor design practices. The classification system is based largely on mean accident rates (*15,17*).

With respect to degree of curve, the 85th-percentile speed can be determined for every curve or independent tangent [for defining and classifying independent tangents, see the work of Lamm et al. (*16*)] by using Figure 1(*a*) for the U.S.A. and Figure 1(*b*) for Germany. By knowing the 85th-percentile speed of every design element, the speed differences between successive design elements (V85) can be calculated, and the observed road section or road network can then be classified as good, fair, or poor design. The speed changes corresponding to Criterion I are listed in Table 2 for different design levels.

TABLE 1 Regression Equations of Operating Speeds and Accident Rates for the FRG and for the U.S.A.

FEDERAL REPUBLIC OF GERMANY

12 ft.: $V85 = 37.50 + 24.81 \cdot e^{(-0.145 \cdot DC)}$ ①
10 ft.: $V85 = 37.50 + 23.03 \cdot e^{(-0.190 \cdot DC)}$ ②
≥11 ft.: $ACCR^{*} = -0.29 + 0.37 \cdot DC; R^2 = 0.33$ ③
<11 ft.: $ACCR^{*} = -0.50 + 0.55 \cdot DC; R^2 = 0.35$ ④
(for ROR* Accidents, only)

UNITED STATES OF AMERICA

12 ft.: $V85 = 59.75 - 1.00 \cdot DC; R^2 = 0.82$ ①
10 ft.: $V85 = 55.65 - 1.02 \cdot DC; R^2 = 0.75$ ②
12 ft.: $ACCR = -0.55 + 1.08 \cdot DC; R^2 = 0.73$ ③
10 ft.: $ACCR = -1.02 + 1.51 \cdot DC; R^2 = 0.30$ ④
(for all Accidents)

Legend:
V85 = Estimate of the operating speed, expressed by the 85th-percentile speed for passenger cars (mph),
DC = Degree of curve (degree/100 ft.), range: 0° to 25°,
R^2 = Coefficient of determination,
ACCR = Estimate of accident rate including all accidents (acc./10^6 vehicle-miles),
$ACCR^{*}$ = Estimate of accident rate including Run-Off-The-Road accidents (acc./10^6 vehicle-miles), only.

Since for this study geographical information on road sections or road networks, such as design elements, operating speeds, and accidents, are available, a GIS appears to be the most suitable method for solving the complex relationships through the safety module proposed here. A Canadian program known as SPANS (*24–26*), developed by TYDAC Technologies, was used in this paper for analysis of the various safety criteria which make up the core of the overall safety module. The benefit of SPANS is that data of different formats and from different origins can be read in, analyzed, and displayed together. In this study, the display is made on a digitized map (see Figure 2) superimposed on the following with the results of the safety criteria. The case study reported in this paper is related to Ehingen County in Southwest Germany. Because of monetary constraints, the authors were unable to conduct similar case studies in the U.S.A.

It should be noted that the safety evaluation process of Criterion I can be performed manually for every two successive design elements. However, this is time consuming, not only with respect to this criterion, but also for Criteria II and III, as well as for the combination of all three criteria. Therefore, it is more efficient to use a GIS.

The results of Safety Criterion I, "Achieving Consistency Between Successive Design Elements," are shown in Figure 2, which was developed by SPANS. Originally, discriminating colors were used to easily recognize good, fair, and poor designs. Since colors cannot be presented in a TRR publication, discriminating

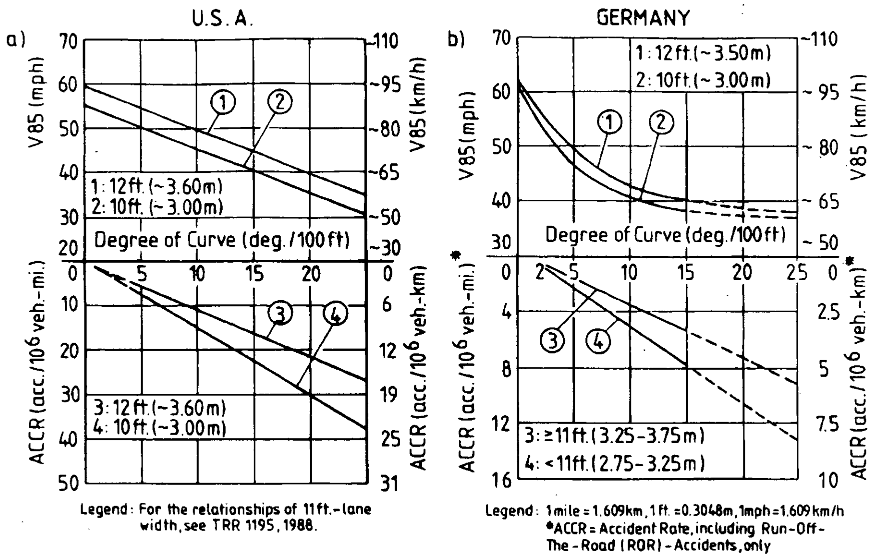


FIGURE 1 Nomogram for evaluating operating speeds and accident rates as related to degree of curve for the U.S.A. and Germany (West).

symbols had to be applied. The roadway sections in Figure 2, graphically not interpreted by symbols, were not included in this investigation.

CRITERION II: HARMONIZING DESIGN SPEED AND OPERATING SPEED

All reviewed highway geometric design guidelines (*8–10,21,27,28*) indicate that the design speed should be constant along longer roadway sections. Research investigations (*4,5,13*) have shown that the driving behavior on curved roadway sections often exceeds by substantial amounts the design speed on which the original design of the road section was based, especially at lower design speed levels. Therefore, harmonizing design speed and operating speed is another important safety criterion that should be considered in the design, redesign, or rehabilitation processes (or all) of two-lane rural highways and networks.

To achieve this goal, the 85th-percentile speed (V85) of every independent tangent or curve must be tuned with the existing or selected design speed (V_d), according to the recommended design speed criteria shown in Table 2.

By calculating the differences between the 85th-percentile speed and the design speed, a curved roadway section design can then be classified as good, fair, and poor. If needed, the results of Safety Criterion II could be shown in a graphical presentation similar to Figure 2.

CRITERION III: PROVIDING ADEQUATE DYNAMIC SAFETY OF DRIVING

Skid resistance research investigations (*19,29–31*) have indicated that sufficient friction supply should be a main safety consideration in designing, redesigning, or resurfacing roadways. Glennon et al. (*32*) indicated that the probability of a highway curve becoming an accident black spot increases with decreasing pavement skid resistance (side friction factor).

Safety Criterion III examines whether or not assumed side friction factors for curve design, as proposed in the geometric design guidelines of the U.S.A. (*21*) and the Federal Republic of Germany (*33*), are sufficient for actual driving behavior on curves or curved sections. In this study, the American data base consists of 197 curved roadway sections located in New York state, and the German data base consists of 204 curved roadway sections located in Ehingen county in Southwest Germany (*22*).

To achieve the objective of Criterion III, a comparative analysis of side friction demand (f_{RD}) and side friction assumed (f_R) was carried out. The results are shown in Figure 3 for the U.S.A. and Germany. The assumed side friction was derived from actual geometric design data collected in the field (U.S.A.) or was obtained from the design data bank of Stuttgart (Germany).

By knowing design speed (or recommended speed), degree of curve, and super-elevation rate in the U.S.A. [refer to Lamm et al. (*20*) and the AASHTO policy (*21*)], or the design speed, radius of curve, and super-elevation rate in Germany [refer to the work of Steffen (*22*) and "Guidelines for the Design of Roads (RAL-L-1)" (*33*)], the assumed side friction factor was determined. Side friction demand was calculated from the same geometric design data, but was related to actual observed operating speeds (V85) on the curves under study (see Figure 1). Side friction assumed and demand were then calculated, based on the fundamental driving dynamic formulas for curve design (*20*):

$$f_{R(D)} = [(V)^2 \times (\mathrm{DC})/85{,}660] - e \qquad \text{(United States)}$$

$$f_{R(D)} = (V^2/15\,R) - e \qquad \text{(Germany)}$$

$$f_R, f_{RD} = \text{side friction assumed/demand } (-)$$

where

V = design speed (V_d) or operating speed (V85) [mph];
DC = degree of curve (degree/100 ft);
R = radius of curve (ft); and
e = super-elevation rate (ft/ft).

$$\text{Conversion: } DC = \frac{360°}{2\pi R} = \frac{5729.6}{R} \text{ (degree/100 ft).}$$

TABLE 2 Recommended Ranges for Design Practices for Criteria I and II for the Federal Republic of Germany and the United States of America

RECOMMENDED CONSISTENCY CRITERIA (FRG and U.S.A.)

CASE 1 (GOOD DESIGN):

Range of change in operating speed: $\Delta V85 \leq 6$ mph (10 km/h).
For these road sections, consistency in horizontal alignment exists between successive design elements, and the horizontal alignment does not create inconsistencies in vehicle operating speed.

CASE 2 (FAIR DESIGN):

Range of change in operating speed: 6 mph $< \Delta V85 \leq 12$ mph (20 km/h).
These road sections may represent at least minor inconsistencies in geometric design between successive design elements. Normally, they would warrant traffic warning devices, but no redesigns.

CASE 3 (POOR DESIGN):

Range of change in operating speed: $\Delta V85 > 12$ mph (20 km/h).
These road sections have strong inconsistencies in horizontal geometric design between successive design elements combined with those breaks in the speed profile that may lead to critical driving maneuvers. Normally, redesigns are recommended.

RECOMMENDED DESIGN SPEED CRITERIA (FRG and U.S.A.)

CASE 1 (GOOD DESIGN):

$V85 - V_d{}^* \leq 6$ mph (10 km/h).
No adaptions or corrections are necessary.

CASE 2 (FAIR DESIGN):

6 mph $< V85 - V_d \leq 12$ mph (20 km/h).
Superelevation rates must be related to V85 to ensure that side friction assumed will accomodate to side friction demand.

CASE 3 (POOR DESIGN):

$V85 - V_d > 12$ mph (20 km/h).
Normally, redesigns are recommended.

$^*V_d$ = Design Speed, V85 = 85th-percentile Speed

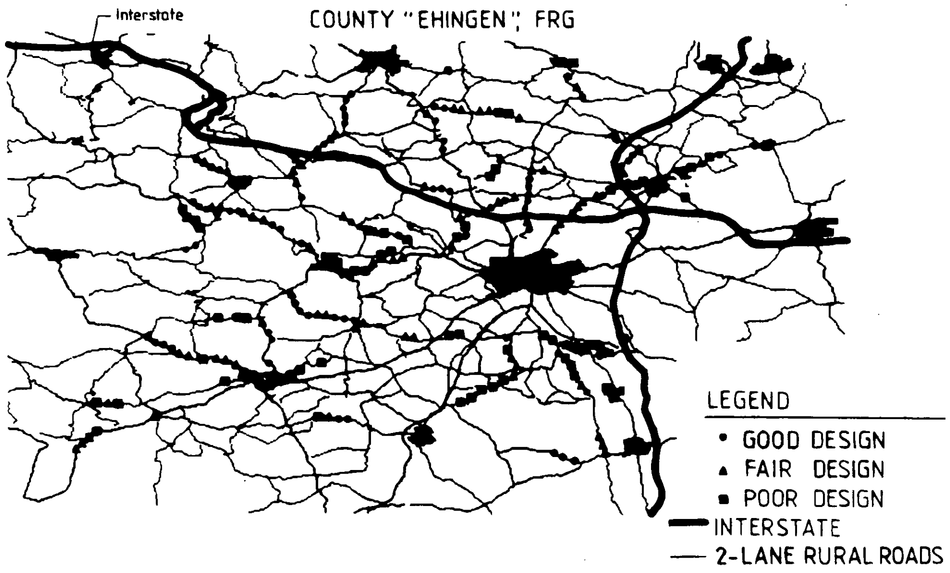


FIGURE 2 Digitized map of the road network of the county "Ehingen," FRG [30] results of criterion I.

The relationships of side friction assumed and demand, and degree of curve are quantified by the regression models shown in Table 3(*a*) and graphically presented in Figure 3.

A comparison of the relationships in the U.S.A. and Germany (Figure 3) clearly indicates that, in both countries, the points at which the curves for side friction assumed and demand intersect fall between 5 and 6 degrees. These values correspond to radii of curve between 290 and 350 m (960 to 1150 ft).

The curves for side friction demand are highly comparable between the U.S.A. and Germany. With respect to side friction assumed, the values in the U.S.A. are higher than in Germany; this is the result of lower friction factors in the German guidelines than in the American guidelines (*19*). Furthermore, the figures show that, in both countries, the side friction assumed is higher than the side friction demand on curves up to 5 degrees (Germany) and up to 6 degrees (U.S.A.). For degrees of curve greater than these values, the figures show that (a) the side friction demand is higher than the side friction assumed, and (b) the gap between side friction demand and assumed increases with increasing degree of curve. That means that, from a driving dynamic safety point of view, beginning with the point at which the two curves intersect between 5 and 6 degrees, the probability of critical driving maneuvers increases with increasing degree of curve.

On the basis of the recommendations for good, fair, and poor design practices, it is clear that the point of intersection should lie in the range of fair design practices. In the case of good design practices, side friction assumed exceeds side friction demand, whereas in the case of poor design practices, side friction demand exceeds side friction assumed.

Again, on the basis of recommendations for good, fair, and poor design practices, it can be said, as a first approximation, that (a) a difference Δf_R of $+0.02$ to -0.02 between side friction assumed and demand lies in the range of fair design practices [(Figure 3(*a*)]; (b) a difference greater than $+0.02$ lies in the range of good designs, and (c) a difference less than -0.02 lies in the range of poor designs [see Table 3(*b*)]. Recent studies conducted in Germany to examine

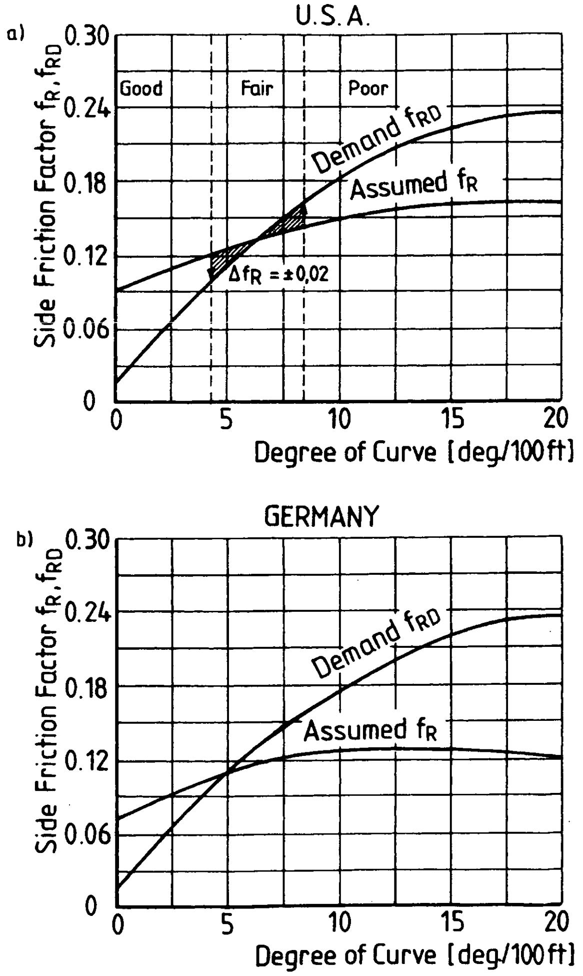


FIGURE 3 Relationship between side friction assumed/demand and degree of curve for the U.S.A. and Germany.

TABLE 3 Regression Equations for Side Friction Assumed/Demand and Recommended Ranges for Good, Fair, and Poor Design Practices (Criterion III)

FEDERAL REPUBLIC OF GERMANY
$f_R = 0.078 + 7.95 \cdot 10^{-3} \cdot DC - 2.9 \cdot 10^{-4} \cdot (DC)^2 \; ; R^2 = 0.408$
$f_{RD} = 0.023 + 2.02 \cdot 10^{-2} \cdot DC - 4.7 \cdot 10^{-4} \cdot (DC)^2 \; ; R^2 = 0.679$
UNITED STATES OF AMERICA
$f_R = 0.092 + 8.10 \cdot 10^{-3} \cdot DC - 2.3 \cdot 10^{-4} \cdot (DC)^2 \; ; R^2 = 0.887$
$f_{RD} = 0.014 + 2.25 \cdot 10^{-2} \cdot DC - 5.7 \cdot 10^{-4} \cdot (DC)^2 \; ; R^2 = 0.864$

Legend:

f_R = assumed Side friction

f_{RD} = demand Side friction

DC = Degree of curve (deg/100 ft.), range: 0° to 20°

R^2 = Coefficient of determination.

RECOMMENDED DRIVING DYNAMICS CRITERIA (FRG and U.S.A.)

CASE 1 (GOOD DESIGN):

$\Delta f_R \geq +\,0{,}02$

No adaptions or corrections are necessary.

CASE 2 (FAIR DESIGN):

$+\,0{,}02 > \Delta f_R \geq -\,0{,}02$

Superelevation rates must be related to V85 to ensure that side friction assumed will accommodate to side friction demand.

CASE 3 (POOR DESIGN):

$\Delta f_R < -\,0{,}02$

Normally, redesigns are recommended.

Δf_R = difference between side friction assumed and side friction demand (see Figure 3a)

in detail the ranges of Safety Criterion III, as based on larger data bases, led to slight changes with respect to the ranges in Table 3 (*34*).

If requested, the results of Safety Criterion III ("Providing Adequate Dynamic Safety of Driving") could be also shown schematically similar to Figure 2.

COMBINATION OF CRITERIA I TO III FOR AN OVERALL SAFETY MODULE

The results of Criteria I to III (see, for example, Figure 2 for Criterion I) and the recommendations provided in Tables 2 and 3(*b*) indicate the existence of roadway sections that exhibit different design safety levels. The reason for this is that each of the discussed safety criteria does represent a separate safety aspect in highway geometric design. It may happen, for example, that the transition section between a tangent and a curve would correspond to poor design, whereas the design speed or the assumed side friction factor, or both, for the observed curve are well in order, or vice versa.

As an overall safety evaluation procedure, the previously discussed three safety criteria will be combined here in an overall safety module. Table 4 shows the classification system of the safety module, as based on Criteria I to III, for good, fair, and poor design levels. All three criteria are weighed equally. With one exception, at least two of the three criteria must correspond in the decision process to assess the design safety level. The developed procedure represents the current state of knowledge. Changes or improvements concerning the boundaries of the safety module may be achieved through the use of larger data bases.

TABLE 4 Classification of the Safety Module for Good, Fair, and Poor Design Levels

CLASSIFICATION	
by Criteria I to III	of the Safety Module
1	2
3 × good 2 × good / 1 × fair 2 × good / 1 × poor	GOOD DESIGN
3 × fair 2 × fair / 1 × good 2 × fair / 1 × poor 1 × good / 1 × fair / 1 × poor	FAIR DESIGN
3 × poor 2 × poor / 1 × good 2 × poor / 1 × fair	POOR DESIGN

Figure 4 schematically shows (using discriminating symbols) the results of the overall safety module for a case study in Ehingen County in Southwest Germany for good, fair, and poor designs. The sections without symbols in the figure were not subject to analysis.

The discussed procedure indicates that the evaluation process of roadway sections or networks by an overall safety module is possible, and that this safety module includes the three discussed quantitative safety criteria in geometric highway design for the first time.

To determine the degree of agreement between the developed safety module and actual accident rates on the observed roadway sections, a 3-year case study was conducted. The results are shown in Figure 5. As can be observed from this figure, the circular symbol, which represents full agreement, and the triangular symbol, which represents a lower accident rate than the safety module would predict, predominate. Thus, it can be concluded that in the majority of investigated road sections the actual accident rate corresponds well with the developed safety module, or the results are at least on the safe side. Only in rare cases of the quadratic symbol is the actual accident rate higher than the predicted one.

Despite the presence of erroneous cases, the developed module does provide sound results. It should be noted that in the field of accident research the relationships are not simple or direct ones, but rather are very often complex, and changes in accidents are often the result of the interplay of many factors besides the investigated three safety criteria. A GIS, such as SPANS, plays a very important role here.

The results of the overall safety module, which includes for the first time the three quantitative safety criteria in geometric highway design, appear to be pointing in the right direction for evaluating roadway sections or networks with respect to design, redesign, rehabilitation, and restoration strategies.

Note that safety strategies, such as the ones developed here, have been known for decades in other civil engineering fields such as structural engineering, water resources engineering, and so forth.

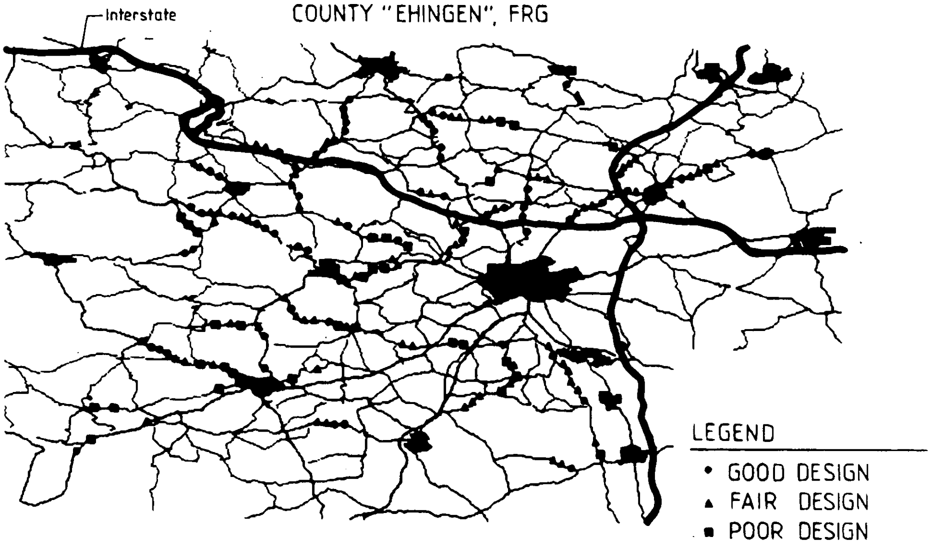


FIGURE 4 Results of the overall safety module.

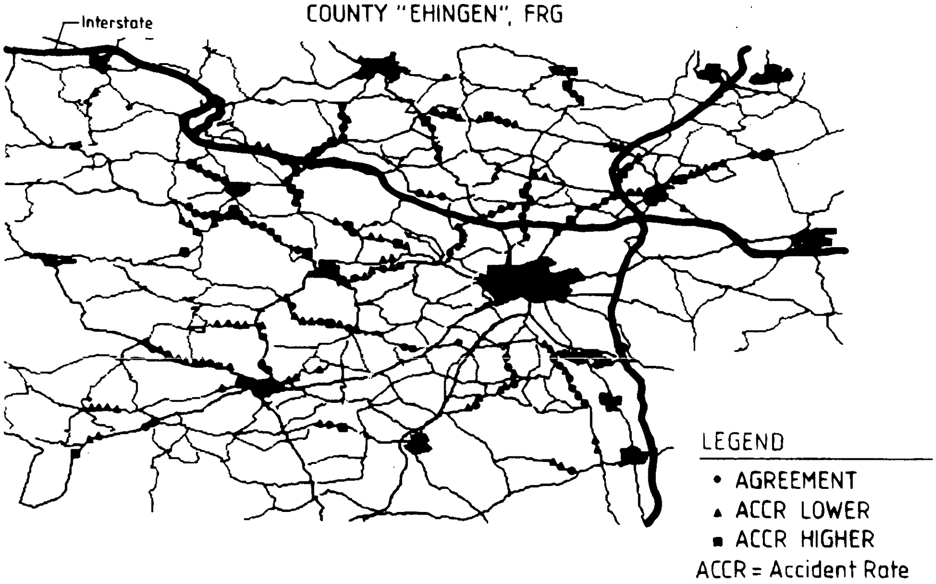


FIGURE 5 Level of agreement between safety module and actual accident rate.

CONCLUSION

Three safety criteria for evaluating curved roadway sections, including transition sections, were analyzed to address these important target areas for reducing accident frequency and severity.

Criterion I: Achieving Consistency in Horizontal Alignment

Research studies conducted in the U.S.A., which evaluated the impact of design parameters and traffic volume, demonstrated that the most successful parameter in explaining much of the variability in operating speeds and accident rates was the degree of curve. Similar results were found in the Federal Republic of Germany. In both countries, operating speeds decrease with an increasing degree of curve, whereas accident rates increase with an increasing degree of curve. Based on these findings, changes in operating speeds between successive elements, based largely on mean accident rates, were developed to classify highway sections, networks, or both.

Criterion II: Harmonizing Design Speed and Operating Speed

To achieve this goal, the 85th-percentile speed of every independent tangent or curve must be tuned with the existing or selected design speed according to the recommended design speed ranges.

Criterion III: Providing Adequate Dynamic Safety of Driving

This criterion examines whether or not the assumed side friction factors for curve design in the highway geometric design guidelines of a given country are sufficient for actual driving behavior in curves or curved sections.

For both the U.S.A. and the Federal Republic of Germany, this study has found that the curves for side friction assumed and demand intersect, and that the point of intersection lies in the range of fair design. In the case of good design practices, side friction assumed exceeds side friction demand, whereas in the case of poor design practices, side friction demand exceeds side friction assumed.

The above safety criteria constituted the core of the overall safety module proposed in this study for classifying road networks and roadway sections–or both–existing or planned, as good, fair, or poor designs. Criteria I to III can be applied manually or by using the GIS known as SPANS. By using discriminating colors or symbols (as in this paper), the designer could easily and immediately recognize different design safety levels for each individual criterion.

For a general evaluation process, the three safety criteria were combined (equally weighed) in an overall safety module.

The developed module represents the current state of knowledge. Changes or improvements concerning the boundaries of the safety module can certainly be achieved through the use of larger data bases. Again, by using discriminating symbols with SPANS, the designer could easily apply the overall safety module and immediately recognize different safety levels, this time representing the combined impact of the three safety criteria.

To determine the degree of agreement between the results of the developed safety module and actual accident rates on observed roadway sections, a case study was conducted. For the majority of the investigated roadway sections, the actual accident rate corresponds well with the results of the developed safety module, or the results were at least on the safe side. In very few cases, the actual accident rate was higher than the predicted one.

In closing, the results of the overall safety module, at least based on the investigated case study, appear to be pointing in the right direction for evaluating roadway sections and networks with respect to design, redesign, rehabilitation, and restoration strategies.

Such a safety evaluation process, based on the discussed three individual safety criteria (combined or not combined in a safety module), should be a substantial part of modern highway geometric design guidelines.

But further accident research is needed to establish reliable boundaries for Safety Criterion III, as well as to assign possible individual weights to the three safety criteria for combining them in a safety module.

REFERENCES

1. Lamm, R., E. M. Choueiri, and T. Mailaender. Traffic Safety on Two Continents—A Ten Year Analysis of Human and Vehicular Involvements. *Proc., Strategic Highway Research Program (SHRP) and Traffic Safety on Two Continents*, Swedish Road and Traffic Research Institute, Linkoeping, Sweden, Gothenburg, Sweden, 18–20 Sept. 1991, VTIrapport 372A, Part I, pp. 121–136.
2. *A Policy on Highway Types (Geometric).* Special Committee on Design Policies, AASHO, 1940.
3. *A Policy on the Geometric Design of Rural Highways.* AASHO, 1965.
4. Leisch, J. E., and J. P. Leisch. New Concepts in Design Speed Application. In *Transportation Research Record 631*, TRB, National Research Council, Washington, D.C., 1977.
5. Koeppel, G. Development for the Design of Radii of Curve, Superelevation Rates and Stopping Sight Distances, Depending on Roadway Geometric. *Research Road Construction and Traffic Technique*, Vol. 429, Minister of Transportation, Bonn, Germany, 1984.
6. Hayward, J., R. Lamm, and A. Lyng. Survey of Current Geometric and Pavement Design Practices in Europe, Part: Geometric Design. International Road Federation, 1985.
7. Hiersche, E.-U., R. Lamm, K. Dieterle, and A. Nikpour. Effects of Highway Improvements Designed in Conformity with the RAL-L on Traffic Safety of Two-Lane Highways. *Road Construction Research and Traffic Technique*, Vol. 431, Minister of Transportation, Bonn, Germany, 1984.
8. *Guidelines for the Design of Roads, (RAS-L-1)*, 1984 Ed. German Road and Transportation Research Association, Committee 2.3, Geometric Design Standards.
9. National Swedish Road Administration. *Standard Specifications for Geometric Design of Rural Roads*, 1982 Ed., Sweden.
10. Swiss Association of Road Specialists (VSS), Swiss Norm SN 640080a/b. *Highway Design, Fundamentals, Speed as a Design Element.* 1981 and 1991 Eds.
11. Lamm, R., J. C. Hayward, and J. G. Cargin. Comparison of Different Procedures for Evaluating Speed Consistency. In *Transportation Research Record 1100* TRB, National Research Council, Washington, D.C., 1980, pp. 10–20.
12. Lamm, R., and E. M. Choueiri. *A Design Procedure to Determine Critical Dissimilarities in Horizontal Alignment and Enhance Traffic Safety by Appropriate Low-Cost or High-Cost Projects.* Final Report for the National Science Foundation (Grant No. ECE-8414755), Washington, D.C., March 1987.
13. Lamm, R. *Driving Dynamics and Design Characteristics—A Contribution for Highway Design Under Special Consideration of Operating Speeds.* Vol. 11, Publications of the Institute for Highway and Railroad Engineering, University of Karlsruhe, Karlsruhe, Germany, 1973.
14. Lamm, R., and E. M. Choueiri. *Rural Roads Speeds Inconsistencies Design Methods.* Research Reports for the State University of New York Research Foundation, Contract No.: RF 320-PH72350, Albany, New York. Part I: July 1987, Part II: Oct. 1987.
15. Lamm, R., E. M. Choueiri, J. C. Hayward, and A. Paluri. A Possible Design Procedure to Promote Design Consistency in Highway Geometric Design on Two-Lane Rural Roads. In *Transportation Research Record 1195*, TRB, National Research Council, Washington, D.C., 1988, pp. 111–122.
16. Lamm, R., E. M. Choueiri, and J. C. Hayward. The Tangent as an Independent Design Element. In *Transportation Research Record 1195*, TRB, National Research Council, Washington, D.C., 1988, pp. 123–131.
17. Lamm, R., E. M. Choueiri, and T. Mailaender. Accident Rates on Curves as Influenced by Highway Design Elements—An International Review and an In-Depth Study. *Proc., Road Safety in Europe,* Gothenburg, Sweden, VTIrapport 344 A, pp. 33–54, 1989.
18. Lamm, R., E. M. Choueiri, and T. Mailaender. Comparison of Operating Speeds on Dry and Wet Pavements of Two-Lane Rural Highways. In *Transportation Research Record 1280*, TRB, National Research Council, Washington, D.C., pp. 199–207, 1990.
19. Lamm, R., E. M. Choueiri, P. B. Goyal, and T. Mailaender. Design Friction Factors of Different Countries Versus Actual Pavement Friction Inventories. In *Transportation Research Record 1260*, TRB, National Research Council, Washington, D.C., pp. 135–146, 1990.
20. Lamm, R., E. M. Choueiri, and T. Mailaender. Side Friction Demand Versus Side Friction Assumed for Curve Design on Two-Lane Rural Highways. In *Transportation Research Record 1303*, TRB, National Research Council, Washington, D.C., pp. 11–21, 1991.
21. *A Policy on Geometric Design of Highways and Streets.* AASHTO, 1984, 1990.
22. Steffen, H. *Development of a Safety Module for Examining Highway Geometric Design and the Implementation of Two Complex Data Processing Systems.* M.S. Thesis (Diplomarbeit). Institute for Highway and Railroad Engineering, University of Karlsruhe, Karlsruhe, Germany, 1992.
23. Lamm, R. Safety Evaluation of Highway Design Parameters. *Straßen und Tiefbau* (*Road and Construction*), Vol. 10, Oct. 1980, pp. 14–22.

24. Naess, P. *Environmental Databases in Municipalities.* IBM, Sollentuna, Sweden, 1990.
25. Kollartis, S. *SPANS—Concept and Function of an Innovative GIS.* University of Salzburg, Institute for Geography, TYDAC Technologies, Karlsruhe, Germany, 1990.
26. Anderson, L. D. Applying Geographic Information Systems to Transportation Planning. Federal Highway Administration, U.S. Department of Transportation (paper prepared for TRB, 70th Annual Meeting, Washington, D.C.), 1991.
27. Ministère de l'Equipement et du Logement. *Instruction sur les Conditions Techniques D'Amènagement de Routes Nationales.* 1975 Ed., France.
28. *Highway Link Design, Geometric Alignment Standards.* Department of Transport, Departmental Standard TD9/81, Subject Area, Great Britain, 1981.
29. Mason, J. M., and H. C. Peterson. Survey of States R-R-R Practices and Safety Considerations. In *Transportation Research Record 960*, TRB, National Research Council, Washington, D.C., 1984.
30. Brinkmann, C. P. Safety Studies Related to RRR Projects. *Transportation Journal of ASCE,* Vol. 108, July 1983.
31. Lamm, R. Driving Dynamic Considerations: A Comparison of German and U.S. Friction Coefficients for Highway Design. In *Transportation Research Record 960*, TRB, National Research Council, Washington, D.C., 1984, pp. 13–20.
32. Glennon, J. C., T. R. Neuman, and J. R. Leisch. Safety and Operational Considerations for Design of Rural Highway Curves. Final Report, 1983.
33. *Guidelines for the Design of Roads (RAL-L-1).* 1973 Ed., German Road and Transportation Research Association, Committee 2.3, Geometric Design Standards.
34. Lamm, R., B. Psarianos, and A. K. Guenther. Interrelationships Between Three Safety Criteria, Modern Highway Geometric Design, as well as High Risk Target Locations and Groups. Presented at 3rd International Conference on Safety and the Environment in the 21st Century, Lessons from the Past Shaping the Future, Tel-Aviv, Israel, Proceedings book, 1994, pp. 439–458.

Safety Effects of Roadway Design Decisions—Roadside

KING K. MAK

This paper provides a general overview of roadside safety, covering various aspects from the extent of the problem, to safety improvement priorities, to safety relationships, to cost-effectiveness analysis. The paper is presented as part of a conference session in which different aspects of roadway and roadside safety are covered. The discussions are thus general and brief in nature. The intent is to familiarize highway engineers with the state of art in roadside safety, not to provide detailed discussions on any specific aspect of roadside safety.

Single-vehicle, ran-off-road crashes remain a significant portion of the overall highway accident picture. In 1989, the General Estimate System (*1*) reported that, of the total 6,644,000 motor vehicle crashes nationwide, 1,298,000 (19.5 percent) involved collisions with fixed objects or noncollision (e.g., rollover) as the first harmful event, as indicated in Table 1. The statistics are even more alarming when the severity of the crashes is taken into account. These fixed-object and noncollision crashes accounted for 125,000 (31.7 percent) of the 394,000 crashes involving severe or fatal injury (*1*) and 16,314 (40.1 percent) of the total 40,718 fatal crashes, as indicated in Table 2 (*2*). It is evident that roadside safety is an important issue to be reckoned with in our effort to minimize the carnage on our highways.

There are basically two parts to the solution of this problem: (1) keep the vehicles on the roadway, that is, prevent the crashes from occurring, and (2) mitigate the consequences after the vehicle ran off the roadway, that is, reduce the severity of the crashes. For a long time before the mid-1960s, the efforts had been concentrated on keeping the vehicles on the roadway, for example, by improving the geometrics of the travelway and the frictional properties of the pavement, without giving much attention to roadside safety. The perception was that ran-off-the-road accidents were "the drivers' fault," or the "nut behind the wheel" syndrome.

There has been a change in this perception since the mid-1960s, with the recognition that, despite the best efforts, drivers will continue to run off the road, and a better approach is to modify the roadside environment to mitigate the consequences. Much more attention has since been paid to the safety of the roadside. Numerous roadside safety devices and features have been developed in the intervening years to greatly improve the safety of the roadside, such as crash cushions to shield the errant vehicles from roadside hazards, breakaway luminaire and sign supports to minimize the impact severity, better-performing barriers, end treatment and transition designs to contain and redirect errant vehicles, and safety treatments for drainage structures. The list goes on, and the motoring public has reaped significant benefits from these safety innovations over the years.

The design philosophy as it pertains to roadside safety and the safety effects of roadside safety devices and features are reviewed in this paper. Also, a brief discussion is presented on cost-effectiveness procedures available for evaluating roadside design alternatives.

ROADSIDE SAFETY DESIGN PHILOSOPHY

The general philosophy in roadside safety follows the priorities of (1) remove the hazard, (2) relocate the hazard, (3) make the hazard forgiving, and (4) shield the hazard (*3,4*). The top priorities are to remove or relocate roadside hazards so as to provide a clear recovery area or clear zone along the roadside that provides errant vehicles an opportunity to recover and return to the travelway or to come to a controlled and safe stop. For situations in which fixed objects have to be located in the clear zone, such as luminaries and sign supports that have to be placed close to the travelway, these fixed objects are designed to be forgiving by making them break away or yield on impact to minimize the potential for injury to the vehicle occupants. In situations in which all the above countermeasures are not applicable, for example, bridge piers or trees that cannot be cut down due to aesthetic or environmental concerns, traffic barriers or crash cushions are installed to shield the errant vehicles from these roadside hazards. It should be kept in mind that traffic barriers and crash cushions are hazards in themselves, and their use is limited to situations in which the severity of impacting the traffic barrier or crash cushion is less than that of impacting the hazard the barrier or crash cushion is shielding.

Warrants and guidelines for the use of traffic barriers and other roadside safety appurtenances and features, such as those contained in the 1977 AASHTO Barrier Guide (*3*) and the 1988 AASHTO Roadside Design Guide (*4*), are based on this general philosophy and priority scheme. As an illustration of how this priority scheme is applied to the development of guidelines, Table 3 highlights a set of recommended guidelines for new utility installations developed by Texas Transportation Institute for the Jacksonville Electric Authority (*5*). Again, the priorities are first to provide a clear recovery area. If the desired clear recovery area is not attainable, considerations are then given to eliminating or relocating the utility poles, reducing the potential of errant vehicles striking the utility poles, and minimizing the severity of impact.

This general philosophy certainly makes a lot of sense, is simple to apply, and has worked very well, particularly with new constructions. A look at any recently constructed freeway would indicate the high level of roadside safety built into these highways. However, the application of this general philosophy and the existing warrants and guidelines are not as clear cut when we are dealing with resurfacing, restoration, and rehabilitation (3R), or recon-

---

Texas Transportation Institute, The Texas A & M University System, College Station, Tex. 77843.

TABLE 1 Distribution Of Crashes By First Harmful Event And Crash Severity (1989 General Estimate System)

FIRST HARMFUL EVENT	SEVERE OR FATAL INJURY NUMBER	SEVERE OR FATAL INJURY PERCENT	TOTAL NUMBER	TOTAL PERCENT
COLLISION WITH OBJECT NOT FIXED				
Motor Vehicle in Transport	211,000	53.6	4,435,000	66.8
Parked Motor Vehicle	7,000	1.8	473,000	7.1
Pedestrian or Pedalcyclist	46,000	11.7	197,000	3.0
Other Object Not Fixed (Train, Animal, etc.)	5,000	1.3	241,000	3.6
COLLISION WITH FIXED OBJECT				
Post/Pole	23,000	5.8	264,000	4.0
Culvert/Ditch	15,000	3.8	152,000	2.3
Guardrail, Crash Cushion, or Traffic Barrier	10,000	2.5	142,000	2.1
Tree	20,000	5.1	133,000	2.0
Curb	6,000	1.5	80,000	1.2
Embankment	7,000	1.8	66,000	1.0
Fence	3,000	0.8	62,000	0.9
Other Fixed Object (Bridge, Wall, Bush, etc.)	14,000	3.6	186,000	2.8
NON-COLLISION				
Rollover	20,000	5.1	116,000	1.8
Other Non-Collision	7,000	1.8	97,000	1.5
TOTAL	394,000	100.0	6,644,000	100.0

struction (4R), or both types of projects. There are many instances in which the decisions are not apparent or the specific situations are not covered under existing warrants or guidelines.

For example, consider a project to upgrade an existing two-lane highway with 22-ft pavement width to two 12-ft lanes with 10-ft shoulders. This would undoubtedly improve the safety of the travelway. On the other hand, this would reduce the width of the roadside available for the clear recovery area unless more right-of-way is purchased. The cost of purchasing the additional right-of-way would greatly increase the cost of the project, resulting in fewer projects to be accomplished under a given budget. Yet, without the additional right-of-way, it may be necessary to reduce the width of the clear recovery area or use steeper sideslopes, or to use guardrails extensively, which would be a detriment to roadside safety. These are tough questions to be answered by highway design engineers, who are required to make such difficult decisions on a routine basis.

SAFETY RELATIONSHIPS

What information is available to help the highway engineers make these decisions? Are the safety effects of these roadway and roadside design features, either singly or in combination, known or quantified? The answer is that the state-of-the-knowledge has not yet reached a level to address all these questions and tradeoffs. Much more information on the safety effects of roadside safety features is needed, particularly if tradeoffs between roadway and roadside design features are to be made. The report on the Transportation Research Board (TRB) study on the safety cost-effectiveness of highway geometric standards and recommended minimum standards for resurfacing, restoration, and rehabilitation (3R) projects, states that "In general, relationships between safety and highway features are not well understood quantitatively, and the linkage between these relationships and highway design standards has been neither straightforward nor explicit"(*6*).

FHWA recognizes this gap in the state-of-the-knowledge and has instituted as part of its research program a High Priority National Research Area (HPNRA) in "Highway Safety Design Practices and Criteria." The objective of this FHWA HPNRA is "to develop an integrated design process that systematically considers both the roadway and the roadside in the development of cost-effective highway design alternatives" through a 10-year or less research program.

Although the ability to assess tradeoffs among roadway and roadside design alternatives may be limited, there is considerable information available on the safety effects of individual roadside safety features, for example, traffic barriers, crash cushions, breakaway luminaire and sign supports, and so forth. For example, considerable information is available on collisions involving pole structures, that is, utility poles, luminaires, and sign supports. There have been a number of studies conducted to determine the extent of the pole accident problem, to develop accident prediction models, and to

TABLE 2 Distribution Of Fatal Crashes By First Harmful Event (1989 Fatal Accident Reporting System)

FIRST HARMFUL EVENT		NUMBER	PERCENT
SINGLE VEHICLE CRASHES			
Collision with Fixed Object		11,352	27.9
Tree/Shrubbery	2,947		
Utility Pole/Sign	2,243		
Guardrail	1,049		
Other Fixed Object	5,113		
Other Object Not Fixed		1,434	3.5
Non-Collision (Overturn, etc.)		4,304	10.6
Non-occupant (Pedestrians, etc.)		6,635	16.3
Unknown		7	0.0
Subtotal		3,732	58.3
MULTI-VEHICLE CRASHES			
Collision with Motor Vehicle in Transport		15,916	39.1
Collision with Fixed Object		465	1.1
Tree/Shrubbery	31		
Utility Pole/Sign	47		
Guardrail	114		
Other Fixed Object	181		
Other Object Not Fixed	92		
Non-Collision (Overturn, etc.)		193	0.5
Non-occupant (Pedestrians, etc.)		376	0.9
Collision Type Unknown		36	0.1
Subtotal		16,986	41.7
Total		40,718	100.0

evaluate the effectiveness of the breakaway design (*7–9*). In addition, a wealth of information on the impact performance of the various pole structures is available from pendulum testing and full-scale crash testing, including side impacts.

Information on the safety effects of other roadside safety appurtenances, such as drainage structures, embankments, and so forth, is less well developed, but still available to some extent. From police-reported accident data, the extent of accident problems associated with these roadside features is generally known. There have been various accident studies to assess the effectiveness of these roadside features. For example, there is a recently completed FHWA study to analyze accidents involving longitudinal barriers using in-depth accident data collected under the National Accident Sampling System Longitudinal Barrier Special Study.

Extensive full-scale crash test data are available on these roadside safety appurtenances. However, the data are limited to only the design conditions. For example, for a guardrail, the design test conditions are (1) a 2 401-kg (4,500-lb) vehicle impacting the guardrail at 60 miles per hour (mph) and 25 degrees, and (2) an 816-kg (1,800-lb) vehicle impacting the guardrail at 60 mph and 20 degrees. The impact performance of these roadside safety appurtenances beyond the design test conditions is not known. More information is needed on the impact performance of these safety appurtenances over the entire spectrum of impact conditions as well as their performance limits, that is, the impact conditions under which the safety appurtenance would fail. There is also considerable information on conditions that could adversely affect the performance of these safety appurtenances, for example, placement of a barrier behind a curb or on a sideslope could degrade the performance of the barrier, even resulting in vehicles vaulting over the barrier; a breakaway cable terminal end treatment with less than the required 4-ft flare would significantly reduce the effectiveness of the end treatment, and so forth. This information is useful in selecting and designing the appropriate safety appurtenances.

It should be borne in mind that these safety relationships are not constant values, but would change with the introduction of new designs or products (e.g., the new generation of end treatments for traffic barriers performs significantly better than their older counterparts), change in the vehicle mix (e.g., the introduction of smaller and lighter vehicles or the increasing proportion of pickup trucks and utility vehicles), restraint usage (i.e., mandatory seat belt laws and airbags), and so forth.

COST-EFFECTIVENESS ANALYSIS

Although the state-of-the-knowledge on the safety effects of roadside safety devices and features is somewhat limited, it has allowed development of cost-effectiveness models to help engineers in assessing the relative merits of safety design alternatives. The cost-effectiveness procedures provide a means to compare the safety benefits of alternative improvements in terms of reduced accident costs associated with a safety improvement to the costs associated with that improvement.

TABLE 3 Recommended Guidelines For New Utility Installations

CLEAR RECOVERY AREA

Roadway Speed Limit (mph)	Lateral Distance To Face of Poles (Feet)
25	5
30	8
35	12
40	15
45	17
50	20
55	24

POLE PLACEMENT

- In situations where the desired clear recovery area is not attainable, consideration should first be given to the feasibility of eliminating the utility poles by undergrounding or selection of alternative locations.
- If elimination or relocation of the utility poles is not feasible, other safety measures should be considered. Safety measures can be divided into two approaches: (1) reduce the probability of a vehicle collision, and (2) reduce the severity of the impact when the utility pole is struck by an errant vehicle.
- Examples of safety measures to reduce the probability of utility poles being struck by errant vehicles:
    - Place utility poles at locations that are less likely to be struck by out-of-control vehicles, e.g., on the inside of curves instead of the outside, on minor streets instead of major roadways, etc. Avoid placing utility poles at vulnerable locations, such as downstream of a lane drop or the area where the roadway narrows, traffic islands, medians, etc.
    - Increase the lateral offset of utility poles to the extent possible, e.g., use of vertical instead of cross-arm construction.
    - Reduce the number of poles through joint use and/or use of largest possible span between poles.
- Examples of safety measures to reduce the severity of the impact:
    - Use of breakaway design for the utility poles.
    - Use guardrail or crash cushion to shield traffic from the utility poles.

Cost-effectiveness analyses have mostly been used to formulate warrants, guidelines and policies, such as the 1989 AASHTO "Guide Specifications on Bridge Railings" (*10*) and the guidelines for pavement edge dropoffs in construction zones adopted by the Texas Department of Transportation (*11*). Cost-effectiveness analysis has also been used in other applications, such as evaluating alternative safety improvement options at specific sites.

Benefit-Cost Methodology

Most of the cost-effectiveness procedures developed today are based on the concept of benefit-cost (B-C) analysis. The principle behind the B-C methodology is that benefits associated with a safety improvement should be greater than the costs associated with that improvement. Benefits are measured in terms of reduced accident frequency, severity, or both. Costs associated with a safety improvement include increases in the cost for initial installation, normal maintenance, and repair of damages from accidents that are attributable to the improvement. The B-C methodology is formulated in terms of incremental benefits and incremental costs, thus allowing for several safety alternatives to be evaluated concurrently. The formulation of the B-C methodology is as follows:

$$BC_{2-1} = (B_2 - B_1/(C_2 - C_1)$$

where

BC_{2-1} = B-C ratio of alternative 2 compared to alternative 1;
B_1 = Annualized safety benefits of alternative 1;
B_2 = Annualized safety benefits of alternative 2;
C_1 = Annualized direct costs of alternative 1; and
C_2 = Annualized direct costs of alternative 2.

A key component of the B-C model is a procedure for predicting the frequency of roadside accidents. Accident frequency predictions are complicated by the large number of factors that contribute to the occurrence of roadside accidents. There are two common approaches for predicting accident frequencies: (1) accident data-based model, and (2) encroachment probability model.

Accident Data-Based Models

Accident data-based models use historical data from reported accidents to develop multiple regression models for predicting roadside accident frequencies as a function of roadway and roadside characteristics. An example of an accident data-based prediction model is a study on cost-effectiveness of countermeasures for utility pole accidents (*7*). Based on accident, roadway, roadside, and traffic data from four states, an accident prediction model for utility pole accidents was developed using the nonlinear regression technique. The model predicts the number of utility pole accidents per mile per year based on average daily traffic, pole density, and pole offset.

Accident data-based models are generally very specific in nature, and of little use for other safety features and appurtenances. Findings of most accident data-based studies are often questioned because of the poor quality of police-level accident data and problems associated with the regression technique. Problems associated with police-level accident data include inaccurate and improper reporting of accidents by the reporting officers and unreported accidents (*12*). Also, the large number of roadway and roadside variables that affect accident frequency greatly complicates the regression analysis.

The location coding of traffic accidents is oftentimes inaccurate and certainly not precise enough for identifying specific roadside appurtenances. For example, the average length of a bridge is approximately 175 ft, whereas accident locations are accurate to only the nearest 0.1 mi or 528 ft. Incorrect use of nomenclature, for example, bridge rail coded as guardrail, is another common occurrence. Also, some accident report forms only have an entry for the first harmful event and thus are not able to report multiple collisions. For example, when a vehicle strikes a bridge approach guardrail near its end and the impact extends onto the bridge railing, the accident may be coded as a simple guardrail accident with no mention of the bridge railing impact.

Estimating the number and severity of unreported accidents becomes important when estimating the performance or effectiveness of safety devices. For example, a safety device may be so effective that most impacts result in unreported accidents, and only those impacts exceeding the designed capacity of the device result in reported accidents with serious consequences. One can reach the erroneous conclusion that the device was not effective if only reported accidents were considered.

Finally, the large number of roadside and roadway variables that could influence the frequency of roadside accidents renders accident data analysis very difficult. Even the best multiple regression model can explain only 60 percent of the variation, that is, R^2 value of 0.6 in accident frequencies with traffic volume accounting for most of the variations, whereas most models have much lower R^2 values.

Encroachment Probability Model

Another approach for predicting accident frequencies is based on encroachments onto the roadside. This approach is unique to roadside safety cost-effectiveness models. The encroachment probability model is based on the assumption that accident frequency can be directly related to encroachment frequency. A probability model is developed to relate encroachment frequency to accident frequency, based on such assumptions as the distribution of lateral encroachment distances, distribution of encroachment speeds and angles, distribution of encroaching vehicle sizes, and relationships between highway geometrics and encroachment frequency.

The primary advantage of encroachment probability models over accident data methods is the versatility of the approach. Unlike accident data techniques, one encroachment model can be used to predict accident frequencies for a wide variety of roadside features. Furthermore, the encroachment model is not based on historical data and is the only method of predicting accident frequency for newly constructed or reconstructed roadways and for unusual hazards that are not commonly found along roadsides.

Another application in which the encroachment probability model is used instead of an accident data-based model is the evaluation of multiple performance levels for roadside safety devices. The multiple performance-level concept allows for the use of different performance-level safety hardware in accordance with the characteristics of the highways, for example, lower performance and lower cost hardware on rural, low-volume, low-speed roadways. Existing accident records are inappropriate since virtually all existing roadside safety appurtenances are designed to a single performance level. Even after the roadside hardware with different performance levels is deployed, police-level accident data will not provide the level of detail needed to distinguish among the various performance levels.

It should be noted that the encroachment probability model also has many limitations and drawbacks. For example, encroachment data were collected by observing tire tracks along the roadside left by encroaching vehicles (*17,18*). There is no objective means to determine whether the sets of tire tracks were left by vehicles encroaching in a controlled or uncontrolled manner. One roadside encroachment study using electronic monitoring equipment and time-lapse video estimated that the ratio between controlled and uncontrolled encroachments may vary from a high of 500 to 1 for urban freeways to 10.5 to 1 for rural two-lane roadways (*19*). These high numbers reflect the large number of drivers that intentionally stop or drive in the shoulder area. Other studies based on observed marks or damages on barriers have indicated that a significant portion of impacts with barriers went unreported (*20*).

Other limitations associated with encroachment probability models include lack of data on encroachment characteristics, such as distributions on encroachment speed and angle, extent of lateral vehicle movement, sizes of encroaching vehicles, and the attitude of encroaching vehicles. Many of these characteristics are correlated, but due to the lack of accurate information regarding the degree of correlation, most encroachment characteristics have been treated as independent factors. Similarly, the accuracy of the model is also hampered by lack of data on other components of the model, such as relationships between injury severity and impact conditions, performance limits on various roadside safety features, and so forth.

Cost-Effectiveness Analysis Procedures

Most of the more recent cost-effectiveness procedures are based on the encroachment probability model, despite its many drawbacks and limitations. The cost-effectiveness procedure contained in the 1977 AASHTO Barrier Guide (*3*) is one of the earlier encroachment probability models. This procedure incorporates the fundamental encroachment probability model with many simplifying assumptions. The procedure does not take into account the shielding of hazards from one another and it cannot distinguish between impacts with tangent and flared barrier sections. Furthermore, the average impact severity used for the hazards are considered excessive.

The Roadside program, mentioned in the 1988 AASHTO "Roadside Design Guide" (*4*), is a close cousin to the procedure in the 1977 AASHTO Barrier Guide. The biggest improvement over the older model is in the method for specifying accident severity. The Roadside model allows users to input different accident severity indices for the upstream end and the face of the hazard. The program also incorporates different average encroachment angles based on the design speed. However, although the Roadside model has a few enhancements over the procedure contained in the 1977 AASHTO Barrier Guide, it still suffers from the same limited range of applicability. Also, users have experienced difficulties in using the program, and some have found the results questionable.

The Benefit-Cost Analysis Program (BCAP) (*13*), used in the development of the performance-level selection table in the 1989 AASHTO Guide Specifications for Bridge Railings (*10*), is a sophisticated encroachment probability model that is capable of analyzing most roadside safety problems. The program incorporates a very fine distribution of vehicles, impact speeds, and impact angles in an attempt to accurately calculate the severity of accidents predicted to occur. This procedure is well suited for development of warrants and guidelines for safety appurtenance implementation. The program also incorporates a sophisticated hazard-imaging procedure that allows the program to analyze barrier runout lengths and flare rates. However, the recently completed validation effort of the program under NCHRP Project 22-8 (*14*) has found significant problems with the recommended barrier performance limits and the algorithm for predicting rollover during barrier impacts. Further, the program's predicted distributions of impact speed and angle were found to be somewhat questionable.

The TTI Benefit/Cost program is another sophisticated encroachment probability model (*15*). This program is the forerunner of the BCAP model and it has undergone significant improvements and limited validation. Primary differences between the BCAP and the TTI Benefit/Cost models include: the barrier penetration algorithm, the impact speed and angle distributions, and the lateral extent of encroachment distributions. This program has been used extensively in recent years for a number of different applications, including development of warrants for replacement of outdated small sign supports, barrier flare rates, and safety treatment of utility poles.

A study is currently underway to develop improved cost-effectiveness procedures for analyzing roadside safety features (*16*). It is anticipated that the new procedures will be based on the encroachment probability model with enhanced features, including a more user-friendly interface. Also, a more comprehensive validation effort is planned for this new cost-effectiveness analysis procedure, which is another area of weakness for the existing procedures.

SUMMARY

This paper provides an overview on roadside safety, covering various aspects from the extent of the problem, to safety improvement priorities, to safety relationships, to cost-effectiveness analysis. The discussions are necessarily general and brief in nature, intended to familiarize highway engineers with the state of art in roadside safety, not detailed discussions on any specific aspect of roadside safety.

REFERENCES

1. *General Estimates System 1989, A Review of Information on Police-Reported Traffic Crashes in the United States.* Report DOT-HS-807-665. NHTSA, U.S. Department of Transportation, Dec. 1990.
2. *Fatal Accident Reporting System 1989, A Decade of Progress.* Report DOT-HS-807-693. NHTSA, U.S. Department of Transportation, March 1991.
3. *Guide for Selecting, Locating, and Designing Traffic Barriers.* AASHTO, Washington, D.C., 1977.
4. *Roadside Design Guide.* AASHTO, Washington, D.C., Oct. 1988.
5. Ivey, D. L., and K. K. Mak. Recommended Guidelines for New Utility Installations. Presented at the 68th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 1989.
6. *Special Report 214: Designing Safer Roads—Practices for Resurfacing, Restoration, and Rehabilitation.* TRB, National Research Council, Washington, D.C., 1987.
7. Zeeger, C. V., and M. R. Parker. *Cost-Effectiveness of Countermeasures for Utility Pole Accidents.* Final Report, Prepared for FHWA, U.S. Department of Transportation, Sept. 1982.
8. Jones, I. S., and A. S. Baum. *An Analysis of the Urban Utility Pole Problem.* Final Report, Prepared for FHWA, U.S. Department of Transportation, Dec. 1980.
9. Mak, K. K., and R. L. Mason. *Accident Analysis—Breakaway and Nonbreakaway Poles Including Sign and Light Standards Along Highways.* Final Report, Prepared for NHTSA, U.S. Department of Transportation, Aug. 1980.
10. *Guide Specifications for Bridge Railings.* AASHTO, Washington, D.C., 1989.
11. Ivey, D. L., and K. K. Mak. *Assuring Appropriate Levels of Safety in Construction Zones Where Pavement Edge Dropoffs Exist.* Policy Development Report 0130-1, prepared for the Texas State Department of Highways and Public Transportation, Austin, Tex., Nov. 1986.
12. Mak, K. K. *Transportation Research Circular No. 256: Problems Associated with Police-Level Accident Data in Evaluation of Roadside Appurtenance Performance.* TRB, National Research Council, Washington, D.C., 1983.
13. *Benefit to Cost Analysis Program, Volumes 1–3.* FHWA, U.S. Department of Transportation, 1988.
14. *Evaluation of Performance Level Selection Criteria for Bridge Railings.* NCHRP Project 22-8, ongoing study conducted by Texas Transportation Institute, Texas A & M University System, College Station, Tex.
15. Sicking, D. L., and H. E. Ross. Benefit-Cost Analysis of Roadside Safety Alternatives. In *Transportation Research Record 1065*, TRB, National Research Council, Washington, D.C., 1986.
16. *Improved Procedures for Cost-Effectiveness Analysis of Roadside Safety Features.* NCHRP Project 22-9, ongoing study conducted by Texas Transportation Institute, Texas A & M University System, College Station, Tex.
17. Hutchinson, J. W., and T. W. Kennedy. Medians of Divided Highways—Frequency and Nature of Vehicle Encroachments. *Engineering Experiment Station Bulletin 487*, University of Illinois, Champagne, Ill., June 1966.
18. Cooper, P. *Analysis of Roadside Encroachments—Single Vehicle Run-Off-Road Accident Data Analysis for Five Provinces.* B.C. Research, Vancouver, British Columbia, Canada, March 1980.
19. Calcote, L. R., et al. *Determination of the Operational Performance Requirements for a Roadside Accident Countermeasure Warranting System.* Final Report on FHWA Contract DOT-FH-11-9523, Southwest Research Institute, San Antonio, Tex., 1985.
20. Galati, J. V. Median Barrier Photographic Study. *Highway Research Record 170*, Highway Research Board, Washington, D.C., 1967.

Effects of Tort Liability on Roadway Design Decisions

DANIEL S. TURNER AND JOSEPH D. BLASCHKE

Tort liability has become a major issue for today's highway designer. The nature of tort liability, current tort trends, and several tort issues that affect highway design are reviewed in this paper. Highway tort claims and losses have grown at a rate of 16 percent per year since 1972. During 1990, an estimated 33,000 to 35,000 claims were filed against state highway agencies. During the same year, state departments of transportation paid out between $200 and $300 million to defend and settle these claims. Government units at all levels probably lost more than one-half billion dollars to tort claims in 1990. Forty-four percent of the states responding to a 1988 AASHTO survey indicated that they had asked their legislatures to adopt or strengthen a "design immunity" statute. Without design immunity, they could be sued for improper roadway design. Thirty-six percent of the states indicated that they had tried to adopt (or strengthen) "economic defense" legislation. States without this defense find that the courts will not allow them to plead that they did not have enough money to fix all the deficient locations on their roadways as the reason that a roadway hazard was allowed to exist. One of the largest areas of current tort concern involves design practices for resurfacing, restoration, and rehabilitation (RRR) projects. Suits in virtually all of the states are helping to determine whether old roads may be partially improved to provide more capacity and safety without bringing them up to current standards.

Yesterday's highway engineer lived in a much simpler environment than the one that exists today. Strong environmental regulations, wetland policies, extensive public involvement, and similar issues have made the design of highways a much more difficult task. Perhaps the most frustrating issue for today's designer is tort liability.

The number of suits against highway agencies is growing at an astonishing rate. Rumors circulate of huge financial judgments against highway agencies. Designers often do not understand the law and dread the possibility of being called into court.

Even when designers understand the law, it changes with time. The body of common law expands each time there is a new ruling on a case. New code is adopted each time the legislature meets. Design decisions made today may have disastrous results 20 years from now if the legal system changes and the design is no longer acceptable.

In light of the current legal climate, designers may tend to become very conservative. If they do not understand the law or are afraid of what might occur in the future, they may retreat behind ancient and conservative design standards. On the other hand, roadway designers who are unskillful, who do not exercise care, or who approach their duties in a haphazard manner, face a good probability of a future court date.

NATURE OF TORT LIABILITY

A tort is a civil wrong. The liability associated with a tort is the responsibility to restore the damaged party. In a highway tort liability case, the court will attempt to determine whether the highway agency committed a wrong, and if so, what action (or what payment) is necessary to restore the damaged party.

Negligence

Usually, the plaintiff alleges that negligence on the part of the highway agency caused or contributed to a traffic accident. Negligence involves the failure to use due care in the treatment of others. The issue is often paraphrased as what a "reasonable man" would have done in the circumstances of the case. The term "reasonable man" is very important, and the jury must decide what would have been reasonable. Legally, the plaintiff must prove the following to establish negligence:

- Defendant had a duty to use reasonable care toward plaintiff,
- Defendant breached that duty,
- Defendant's negligence was the proximate cause of plaintiff's injury, and
- Plaintiff incurred resulting damages.

Depending on the state where the suit is brought, the plaintiff's contributory negligence may bar recovery, or the plaintiff's comparative negligence may limit the amount of recovery.

Standard of Care

In trying to establish negligence, the judge or jury must determine whether the defendant acted reasonably, that is, whether the defendant's actions were appropriate for the circumstances. The actions are measured against the prevailing standard of care. The standard may be a published document, such as an AASHTO design manual. It may also be a previous court ruling on a topic. Where the standard has not been previously established, the court will attempt to determine one.

Both the plaintiff and the defendant will try to establish what standard of care applies to the case. Then both sides will attempt to prove whether the defendant acted within the standard of care.

TORT TRENDS

The Administrative Subcommittee on Legal Affairs of AASHTO addressed their strong concerns about the highway tort situation in the late 1970s. This subcommittee performed a survey and pub-

---

D. Turner, Department of Civil Engineering, The University of Alabama, Box 870205, Tuscaloosa, Ala. 35487-0205. J. D. Blaschke, Transportation Engineering Analysts, 1722 Broadmoor, Suite 212, Bryan, Tex. 77802.

lished the results (*1*). This survey was repeated periodically, and reports were published in 1979, 1981, 1983, 1987, and 1988. The survey dealt exclusively with state-level highway agencies. Local governments were not represented.

AASHTO used a lengthy questionnaire to gather data on sovereign immunity, tort liability, insurance, and other issues from the states. All of this information was self-reported. After 1981, there was wide variability in the number of states that responded to the survey in any given year, and to the completeness and quality of the responses. For two of the surveys, only about one-half of the states responded. To overcome partial or incomplete reporting, the authors developed maximum and minimum estimates for states that did not reply to the survey. This involved extrapolating previously reported values based on the trends of the other states.

The original AASHTO survey asked the states to supply information back to 1972. The subsequent AASHTO surveys provided data through 1987. The University of Alabama supplemented this information with a telephone survey to gather 1988, 1989, and 1990 data.

Number of Claims

Claims and suits filed against state highway agencies have been tabulated in Table 1. The values through 1981 are those reported by the states. After 1981, the values indicated in the table are the midpoints between the author's estimated maximum and minimum values.

Several conclusions may be drawn from the data. In 1990, an estimated 33,000 to 35,000 claims were filed against state highway agencies, for an average of about 675 claims per state. The increase in claims has been rather consistent from 1972 through 1990. In fact, the rate of growth corresponds to a 16 percent compound interest curve. A conservative estimate is that since 1972 at least 310,000 claims have been filed against state highway agencies. The number of claims continues to grow. It definitely has not reached a plateau or a peak. Based on the reported data, state highway agencies will continue to experience more and more suits in the future.

TABLE 1 Number of Tort Claims Against State Highway Agencies

1972	2,168
1973	2,740
1974	3,230
1975	4,053
1976	4,700
1977	5,607
1978	7,104
1979	9,362
1980	13,276
1981	13,195
1982	13,800
1983	18,702
1984	20,960
1985	21,810
1986	24,959
1987	27,313
1988	32,692
1989	28,970
1990	32,948

Source: AASHTO surveys (1972-1987) and the authors' survey (1988-1990).

Settlements and Judgments

Financial amounts spent by the states to pay settlements and judgments from tort claims have been listed in Table 2. The data was treated in the same manner as that for claims. Before 1981, the values are those reported by the states. After that date, the values are the midpoints between the author's maximum and minimum estimates.

The states responding to the author's survey indicated that financial information was more difficult to accumulate than other tort data. Less than 70 percent of the states were able to respond to this portion of the survey, and those that did respond did not always have good data. Consequently, the author's estimate of maximum and minimum values was quite wide (ranging from $134 to $228 million in 1990). In addition, state highway agencies spent well over $60 million defending liability claims and suits in the same year. This means that the total cost for tort activities was between $200 and $300 million for state DOTs in 1990.

It is reasonable to assume that local government highway agencies probably have tort losses equivalent to those of state highway agencies. When state and local government losses are combined, the total highway tort picture becomes $400 to $600 million in 1990.

Since 1972, the states have devoted $1.2 to $1.7 billion to tort issues. Local government agencies have probably devoted an equivalent amount.

Summary of Tort Situation

Tort claims and tort losses continue to grow rapidly. Since 1972, the number of claims has increased 16 percent per year. No end is in sight, and highway agencies should plan for tort liability to become an even bigger issue in the future.

TABLE 2 Costs of Tort Settlements and Judgments

1974	$ 9,847,000
1975	$ 6,297,000
1976	$12,416,000
1977	$11,123,000
1978	$15,052,000
1979	$15,996,000
1980	$36,026,000
1981	$39,015,000
1982	$49,262,000
1983	$111,029,000
1984	$139,997,000
1985	$205,824,000
1986	$162,420,000
1987	$180,449,000
1988	$130,540,000
1989	$167,242,000
1990	$190,654,000

Source: AASHTO surveys (1972-1987) and authors' survey (1988-90).

One simple observation may place the tort picture in perspective. At the end of 1990, the states had somewhere between $12.3 and $14.1 billion worth of suits pending in the legal system. Interestingly, this is about the same amount as the total FHWA budget for the same year. Of those states that have closely tabulated and monitored tort claim data, estimates range from 10 percent to 30 percent for the payout compared to face value. This means that $1.3 to $4.2 billion will be needed to pay off pending suits, or that 10 to 30 percent of next year's FHWA funding has already been spent.

Concerted management efforts will be necessary to slow the liability juggernaut. Larger and larger portions of state transportation agency budgets will be devoted to paying liability claims. Designers at all levels of government need to be aware of the consequences of their decisions and of the impact that they might have on their agency's future liability situation.

TORT ISSUES AFFECTING DESIGN

Several current issues will be introduced to indicate how the changing highway tort environment can affect design. These are not the only prominent tort issues, but they provide good illustrations of the problems faced by designers.

Loss of Design Immunity

At one time highway engineers enjoyed unparalleled authority. Their decisions could not be challenged when it came to selecting the location of a roadway, choosing the criteria for the design, or making the detailed design decisions. Roadway design was a special category of decision making protected by the discretionary immunity of government officials. The highway engineer was thought to be in a unique position, to possess special knowledge, and to have all the data with which to make an important decision. As the designer had the authority and responsibility to make a discretionary design decision, he or she was immune to suit. This discretionary immunity was a matter of the judicial branch of government not wishing to interfere with the function of the administrative branch of government. The courts felt that if they overturned the individual decisions made by designers, the designers would quit making them, and society would be left in a worse position.

This has changed, and in some states it has changed drastically. In many locations, design immunity has eroded. In other states, it has been completely removed, usually through a court decision. The most recent survey by AASHTO (*2*) had attempted to have their state legislatures adopt (or strengthen) design immunity legislation. Table 3 indicates that of the 25 states responding to the 1988 AASHTO survey, 11 had tried to adopt design immunity legislation. This is 44 percent of the states that answered the questionnaire in 1988.

Example of a "Design Suit"

A rural highway in a southern state was designed and built in the early 1950s. The roadway was constructed to follow the topography of the area, and there were several vertical curves in the rolling terrain. At one particular location on the roadway, the minimum criteria for the "K" value of a vertical curve was used for the selected design speed of 50 mph.

TABLE 3 Responses to AASHTO Question About Whether States Attempted Legislation Related to Design

State	Design Immunity		Economic Defense	
	Yes	No	Yes	No
Arizona	x			x
California	x		x	
Florida		x		x
Hawaii	x		x	
Idaho		x		x
Indiana		x		x
Iowa	x			x
Kentucky		x		x
Louisiana		x		x
Maine		x		x
Minnesota	x		x	
Mississippi	x		x	
Missouri	x			x
Nevada		x		x
New Jersey	x		x	
New Mexico	x		x	
Ohio		x		x
Oklahoma		x		x
Oregon		x	x	
Pennsylvania	x		x	
Texas		x	x	
Utah		x		x
Vermont		x		x
Wisconsin		x		x
Wyoming	x			x

By the early 1980s, a large city had extended its boundaries and incorporated a portion of the roadway within its city limits, including the particular vertical curve mentioned above. Significant urban development had occurred in the area and the old two-lane rural highway was widened to a six-lane divided urban roadway. The original alignment of the roadway was maintained.

A large apartment complex was located adjacent to the six-lane roadway near the crest of the subject vertical curve. One night, the driver of a vehicle who was attempting to turn left into the apartment complex was hit broadside by a vehicle that approached over the crest of the vertical curve. The driver of the turning vehicle was killed. His wife sued the state and the city claiming that the roadway was improperly designed and that an improper speed limit was posted.

The plaintiff argued that inadequate sight distance caused by the "improperly designed" vertical curve was the primary cause of this accident. The plaintiff alleged that the state's design engineer should have known that minimum design criteria should only be used when better design conditions could not be provided. The plaintiff stated that the terrain was not so rugged that a longer vertical curve was impossible to provide, that a longer vertical curve should have been provided, and that the longer vertical curve would have provided additional sight distance.

The city was sued for posting a speed limit that was "improper." The speed limit was posted at 45 mph based on the measured 85th-percentile speed of traffic. However, the current state design standards (which were based on AASHTO Green Book design guidelines) indicated that the "K" value for the vertical curve was only appropriate for design speeds below 45 mph.

The state and the city were also sued for not bringing the roadway up to current design standards when the roadway was widened. The plaintiff claimed that the state and city should have been required to flatten the curve to increase sight distance when the roadway was reconstructed.

The plaintiff's claims in this case seriously challenged the discretionary decision making of the design engineers. However, the state and city argued that the design decisions were discretionary in nature and exempt from liability, a position that was supported by the state's torts claims act. The judge did not accept this argument and did not grant the defendant's request for summary judgment based on the claim of discretionary immunity. The state and city continued their defense by switching to other issues.

Even though the sight distance at the location of the accident was less than desirable, it was sufficient for typical operating conditions. The accident that led to this case occurred at night on dry pavement. The defense argued that the "glow" from the approaching vehicle could have been observed by the deceased driver before the headlights could be observed, that the dry pavement conditions afforded shorter stopping sight distances than what was selected for design, that the deceased was under the influence of alcohol (which was documented), and that the primary reason for this accident was the speed of the ramming vehicle. Accident reconstructionists estimated the speed of the ramming vehicle from 80 to 90 mph. The jury agreed with the defense and did not assign any negligence to either the state or the city.

Economic Defense

Another interesting observation may be drawn from Table 3. Thirty-six percent of the states that answered the 1988 AASHTO questionnaire had attempted to have economic defense legislation adopted (or strengthened). This defense is when a government agency pleads lack of resources as the reason it did not correct a roadway hazard. Even when the agency knew that the condition existed and did not fix it, if the government can establish that it was reasonable in using its funds, the defense can be adopted. Usually, the government attempts to prove that it was doing a reasonable job of using its budget by indicating that: (a) it was aware of the sites that needed treatment, (b) it had developed a program of corrective treatments for these sites, and (c) it was correcting the sites as funds became available using a priority scheme that treated the most hazardous sites first. This procedure is reasonable because it provides the greatest safety improvement per public dollar spent.

The concept is deeper than the simple example cited here. In a specific suit, the agency might have enough money to pay the plaintiff's claim and to fix the location that was the basis of the suit. However, it would not have enough resources to pay all similar claims and to fix all similar locations on its highways. Even if the agency could shift its funds so that it could pay off all of these claims, some other facet of its activities would suffer. For example, there might not be enough funds left to conduct the pavement overlay program. The quality of existing roads would suffer and accident rates would go up.

The economic or budgetary defense is often used to explain why the highway agency should not have to bring all of its roads up to the most recent standards. If AASHTO were to publish a new standard tomorrow, the agency would not have enough funds to instantly upgrade all of its roads. Even if it could accomplish such an upgrade, AASHTO might publish a new standard again next year (the "pink" book?), and another round of upgrades would be required.

The prevailing rule used to be that if a road was designed and constructed according to the accepted standards of its day, then it did not have to be upgraded if the standard later changed. However, if conditions of the road changed (such as a large increase in traffic volume), then it might be necessary to upgrade the road.

Several states lost their economic defense because they failed to demonstrate to the court that they were reasonable in expending their funds. For whatever the reason, loss of economic defense poses a serious handicap for a highway agency.

RRR Practices of the States

History of the Federal RRR Program

When the Federal-Aid Road Act was passed in 1916, it signaled the first time that the federal government became directly involved with highway design standards. Before that time, the federal government only collected and distributed information relative to roadway design practices. After 1916, the federal government provided funds to states for construction of new highways or reconstruction of existing highways. Specific design standards were not developed or even sought at that time (*4*).

Through trial and error and research efforts, roadway design policies and guidelines were developed and selected by AASHTO, and then adopted as standards by the federal government for federal aid projects. These AASHTO policies and guidelines were documented in the late 1930s and early 1940s. AASHTO eventually developed recommended design criteria and published the same in policy manuals (Blue, Red, and Green Books). Because these early standards selected by the federal government could not be incorporated in every roadway project in every state, design exceptions were constantly requested by the states during the federal aid requesting process.

In 1956, the federal government passed the Federal-Aid and Highway Revenue Act to accelerate construction of the Interstate and Defense Highway System and to provide funds for other federal aid systems. Similar to previous federal funding acts, this legislation provided federal funds for new roadway construction and for reconstruction of existing roadways.

In the mid-1970s, concern arose over the condition of the country's roadway system, and the emphasis shifted from new roadway construction to preservation of existing roadways. As a result of this growing concern, the Federal-Aid Highway Act of 1976 was passed to authorize the use of federal funds for major roadway repair work on the federal aid highway system, classifying this work as RRR. The type of improvements contained in the RRR Program included resurfacing, pavement structural and joint repair, minor lane and shoulder widening, alterations to vertical and horizontal alignments, bridge repair, and roadside hazard elimination.

Initially, states and local governments were totally responsible for RRR-type projects. Minimal standards were set for these types of projects, and specific and unique designs were often selected as well. When the 1976 Act was passed, there were no federal RRR design standards or guidelines in place. AASHTO developed a policy on geometric design for RRR projects which was published in 1977. It was called the "Purple" Book and was immediately controversial because its recommended design values were considerably less stringent than AASHTO design policies for new roadway construction.

Safety Versus Cost-Effectiveness

Roadways initially designed in the 1920s and 1930s were often selected for improvements under the RRR Program. Many of these roadways had narrow rights-of-way, narrow lanes and shoulders, and relatively severe horizontal and vertical alignments. They frequently had large volumes of traffic. Also, many of these roadways were located in places where considerable development had taken place and where additional right-of-way was virtually impossible or very difficult (and expensive) to obtain. Expansion of these types of facilities to meet "current" recommended design guidelines or standards was usually excessively expensive or just plain impossible. However, the RRR Program provided lesser improvements on such roadways, which made them safer and more efficient. Some individuals felt that the lower level of improvements were unsatisfactory and that more extensive improvements should have been made.

Members of various safety organizations and safety-oriented transportation engineers generally opposed the policies of the RRR Program from the beginning. These individuals favored federal funding for work on "deficient" roadways only when these roadways could be reconstructed to meet current recommended guidelines and standards. Other transportation engineers favored making minor improvements, where possible, to make roadways safer and more efficient, even though less than desirable geometric conditions might remain in place.

Safety-oriented individuals concentrated on the safety benefits that would be derived from spending considerable funds to upgrade individual projects. This attitude conflicted with those individuals who preferred to spend funds on a larger number of projects that made less significant roadway improvements but normally had higher cost-benefit ratios. States generally supported AASHTO's lenient RRR design guidelines. Safety organizations generally supported more stringent RRR standards developed by the FHWA. After much discussion, a decision was made to allow states to develop their own standards for RRR projects, with the standards subject to approval by the FHWA.

The argument that safety is sacrificed in some RRR projects still exists. Although it is accepted that the current geometric design criteria adopted by AASHTO provides the safest possible roadway and roadside environment, this concept contains the assumption that there is a direct relationship between safety and roadway features. Even though numerous research studies have been performed, these relationships are not always clearly identified. For example, it is obvious that widening a 9.5-ft-wide travel lane to 12 ft should result in improved safety and operational conditions. However, how much safety is gained from realigning a horizontal curve from a 4° curve to a 3.5° curve? Researchers probably never will be able to develop definitive safety relationships for all of the various roadway features because of the numerous factors that influence infrequent accident occurrences, including driver behavior, vehicle characteristics, traffic regulations, and enforcement policies.

States Seek Categorical Design Exceptions

In general, states have attempted to use cost-effectiveness as the primary factor when selecting and prioritizing RRR projects. Upgrading older roadways to current design standards, as suggested by safety proponents, normally requires substantial funding to obtain the necessary right-of-way and to make substantial geometric changes. State engineers often prefer to make some lesser level of roadway modifications to improve safety and operational capacity at a much lower cost. Because RRR funds are usually limited, states prefer to spend smaller amounts of money on several projects instead of spending a considerable amount of money on only a few projects. This procedure normally results in a more cost-effective use of public funds, even though the completed projects may contain several locations that do not meet currently recommended design standards.

To implement these projects, the states frequently request that FHWA grant exceptions to design standards when applying for RRR funds. If the proposed project results in an operational or safety improvement, the funds often are approved even though the project will not bring the roadway's geometric features up to desirable values or correct all deficiencies. The state and FHWA apparently believe that some improvement is better than no improvement at all.

Example RRR Suit

An example suit will illustrate the problem faced in the design of RRR projects. A southeastern state rehabilitated a low-volume, two-lane, rural highway. There was a restricted amount of right-of-way and a very restricted budget. The RRR project involved widening the highway surface by expanding it onto the existing shoulders. The net effect was a wider paved surface with narrower shoulders.

The plaintiff ran off the roadway, his vehicle overturned, and he was seriously injured. In the resulting suit, he contended that his accident would have been prevented if the shoulders had been reestablished at their original width and that the RRR project resulted in a road less safe than before the project.

The state's defense was supplied by the designer who handled the project. His decision on the width of pavement and width of shoulder had been based on information contained in an FHWA report on accident rates and roadway elements. He had found a table in a research report (*3*) that indicated that wider pavements decreased accidents, whereas narrower shoulders increased accidents. The designer was able to demonstrate his previous calculations, based on the table, to select the pavement width and shoulder width that would produce the least amount of accidents for his site. The defense was effective because of the restricted right-of-way, the limited budget, and the designer's use of authoritative information to make critical decisions while considering the safety of the public.

Additional Design Considerations

Standard or Guideline?

Design-related tort cases have become more common in the United States in recent years. In many states, design immunity has eroded or is no longer an acceptable defense. In tort cases, plaintiff experts generally state that the AASHTO design manuals are national design standards even though these manuals clearly indicate that they are guidelines. Even the word "standard" is often misunderstood. To the legal profession, a standard is some minimum requirement that must always be satisfied. To the engineering profession, a standard is generally considered as an ideal condition that engineers try to obtain. When the standard cannot be obtained, a good design may still result if engineers compensate to offset any deficiencies. For example, extra signs, markings, or other warning devices may alert the driver and compensate for a sharp curve that must be left in place.

Reconstruction or RRR?

Many design-related court cases pertain to older roadways that have been improved to some degree but not brought up to current recommended design criteria. In one southern state, the travel lanes of a roadway were widened from 10 to 12 ft, whereas the shoulders remained at a width that was less than desirable. A lawsuit resulted from an accident on the improved roadway. The plaintiff argued that the roadway-widening improvement was a major reconstruction project and that the state was required to bring the roadway up to current design standards because it was a reconstruction project, not an RRR project. The plaintiff claimed that a wider shoulder would have prevented his accident. The state argued that it was not a reconstruction project and that the state was not required to bring the roadway up to current state standards. The court agreed with the state's argument.

Example Suit Involving a 40-Year-Old Design

Another southern state was sued for failing to provide a median on a divided roadway at a width in accordance with the state's 1950 standards. The state designed a four-lane divided roadway with a minimal median width because there was an existing road bed available for use. The construction of a roadway with a wider median would have required additional right-of-way, considerable drainage improvements, and much higher roadway construction costs. However, no documents existed that explained the decision making process that took place over 40 years before trial. No engineers who worked on the project were alive to testify.

The plaintiff argued that the standards approved by the state should have been used. The state argued that the 1950 decisions must have been based on cost-effective measures and other factors that were unknown to anybody in 1991. The definition of standard as previously described was an issue in this case. Did the state engineers in 1950 view a standard as a minimum requirement or as a desirable condition? Did they even recognize the safety benefits associated with medians? The desire to separate high-speed traffic with wide medians was not much of a design issue until safety research studies were conducted in the 1960s and 1970s. These are tough questions, made even tougher 60 years after the fact. At the time of preparation of this paper, the court had not reached a decision on this case.

Are Older Standards Unsafe?

If a lawsuit results from an accident that occurred on any roadway that does not meet current recommended design criteria or current state standards, the plaintiff may be able to argue that the roadway was deficient. The AASHTO policy manuals clearly indicate that roadways designed in accordance with previous recommended design criteria or older standards are not unsafe. Undesirable features do not necessarily make a roadway unsafe. Each condition is different and requires an analysis of operating conditions, accident history, and compensating elements (such as a curve warning sign with advisory speed on a relatively "sharp" curve).

DOES TORT LIABILITY STIFLE DESIGN INNOVATION?

A Perceived Threat

The threat of a tort lawsuit has caused many transportation engineers to become very cautious and careful when selecting roadway design features and when making traffic engineering or operational improvements. Actually, this fear has caused many engineers to do their job more thoroughly and deliberately, which is good. However, this same fear has sometimes produced an excessive amount of caution, which is not good. Designers have sometimes reverted to using the same very conservative methods over and over again. They tend to hide behind their (archaic) standard drawings instead of diligently searching for the best design for every roadway site and every traffic situation. Design based on fear of doing something wrong is not the answer.

Engineers should use their abilities to solve problems. Sometimes the best solutions to a problem may not be what is conventional or typical. Innovation encourages better methods and technological advancements, which usually benefit society. Because of the fear of litigation, some transportation engineers are no longer willing to "risk" new innovations. They believe that if a future traffic accident could somehow be related to a new engineering concept that is being tested, a lawsuit could result. Plaintiffs' attorneys might claim that the innovative concept had not been proven to be effective and should not have been tested on their clients. Because of this perceived threat of litigation, many transportation engineers are tempted to keep applying conservative and proven methods even though innovative and unique solutions might be better for certain situations.

Innovation Is Still Possible

The perceived threat of future litigation should not be a barrier to thoughtful design. In normal circumstances, the designer gathers and interprets data to determine which "standard of care" is applicable and what type of design best fits the situation. In the majority of all roadway design and operational improvement situations, the tried and true procedures will be applicable and will best handle the situation. In situations in which the engineer possesses the education and skills and uses due care in executing the design, the chances of being involved in a suit are minimal. Thus, highway designers may proceed with confidence in conducting their daily business.

When the designer's evaluation reveals some unique aspect at the site, or when some new or innovative technology appears to offer the promise of a better way to accomplish this design, some method other than the tried and true traditional design may be more appropriate.

The fear of litigation does not have to pose a threat to the development of innovative engineering practices simply because such innovation might result in tort liability. Design engineers may turn to agency attorneys to provide preventative legal advice and subsequent legal defenses that allow the use of innovative techniques. The legal services provided to transportation agencies must be of the quality and have the foresight that allow advances within acceptable tort liability management. Attorneys for state agencies must avoid placing themselves in the policy making arena and restrict themselves to advising and defending their agencies.

Importance of Documenting the Design

Innovations should not be adopted and used indiscriminately. They should be adopted when the designer (by virtue of education, experience, or other expertise) has a firm reason to believe that the new procedure or new technology will do a better job of moving the public safely and efficiently. Deciding when and where to try a new design procedure is difficult. Only the designer has all of the applicable data and is aware of all of the implications of his or her decisions. When the designer concludes that the normal design practice or agency standard is not the appropriate design, it becomes very important that documentation be preserved to indicate why something different was selected. The important factors in making the decision may not be obvious to a jury several years after the design was executed. If the agency is sued, it is important that the defense attorney have access to the designer's thoughts and to the reasons for the particular design. If the suit occurs 40 years after the project was completed, the designer may not be available to testify to a jury. In this instance, the design file may contain the only evidence to indicate that the project was conceived in a thoughtful manner and that the designer used due care in selecting the innovative procedure or design.

SUMMARY AND CONCLUSIONS

Tort liability has become an issue of major concern for today's highway designer. Some of the reasons for this trend have been discussed in this paper.

In 1990, there were between 33,000 and 35,000 claims and suits against highway agencies. In the same year, these agencies paid at least $400 to $600 million to defend suits and to pay off claims and judgments. The problem is getting worse, not better. The number of claims has been growing at the rate of 16 percent per year since 1972.

In light of these tort trends, the authors have drawn some simple conclusions about the effects of tort liability on roadway design decisions.

1. Tort liability is here to stay. Instead of fearing or ignoring it, the highway engineer must learn to accept it and deal with it in a professional manner.
2. The highway designer needs to become aware of the consequences of his or her decisions, and of the impact of these decisions on the agency's future liability situation.
3. The highway designer should learn more about tort liability through activities such as attending seminars, reading, and developing an inquisitive attitude. The designer needs to understand the basic concepts of the legal system, become aware of the grounds on which a suit may be brought, know the reasons for each step in processing a claim or conducting a trial, and master good techniques for giving testimony.
4. The engineer must remember that tort liability is more likely to become a reality in situations in which he or she failed to conduct assigned duties and responsibilities in accordance with sound engineering principles.
5. At the same time, there is a (small) chance of involvement in a tort liability suit even when all activities performed by the engineer were in conformance with sound engineering practices and principles.
6. It is becoming essential to document engineering design decisions, especially when a unique or nonstandard design is selected for implementation or when a nonstandard design is adopted for an RRR project. Such documentation is more important in the distant future than in the present.
7. The "best" roadway design for the specific conditions at each site should be the goal of all construction and reconstruction projects. The best design possible may not be the "standard" design adopted by the responsible agency. RRR projects should not be scrapped simply because "standard" roadway design is impossible, impractical, or prohibitively expensive for the roadway segment in question.
8. The engineer should not sacrifice the safety of the motoring public for cheaper but inferior design. However, low-cost improvements that result in good but less than standard designs may be a better alternative than a specific and very costly reconstruction project that results in a single "standardized" roadway. The engineer's discretion should be used to select the best alternatives for each project.
9. Design immunity has been weakened or removed in many states. Even where it still exists, there may be future changes in the laws that affect the immunity issue. Plus, design discretion may be challenged in court as discretionary abuse.

Engineers may be well advised to pursue their designs as though design immunity did not exist. This calls for actions such as careful consideration of options and alternative designs, using the agency "standard design" when it is appropriate but not being afraid to use alternative or innovative designs if they are more appropriate, and preparing documentation to support design decisions.

10. Economic defenses have been removed by the courts in many jurisdictions. Where they still exist, they may be difficult to present and explain in a courtroom. Until a better, more rational basis is found for making design decisions, economic (cost-benefit) analyses remain the most logical procedure for selecting roadway improvement projects.
11. Engineers should not let tort liability stifle innovations. The transportation engineering profession could become stagnant or die without innovation, improvement, and growth. An engineer is still allowed to investigate and experiment with new concepts to determine whether "better" methods exist. As long as the innovation is credible, there is a rational basis for it, safety has been adequately considered, and the design does not place the motoring public in danger, the experiment should be supported.

The growing number of suits and continuing changes in the legal system may intimidate some highway engineers and may stifle design innovation. This does not have to be the case. When the highway engineer possesses the education and skill, and uses due care in executing the design, the chances of being involved in a suit are minimal. When the designer has a firm reason to believe that an innovative or new design will best serve the public, it may be used. In this situation, it is a good idea for the designer to leave proper documentation in the design file.

REFERENCES

1. *A Survey of the Status of Sovereign Immunity Among the States.* AASHTO, Washington, D.C., 1978.
2. *A Survey of the Status of Sovereign Immunity Among the States.* AASHTO, Washington, D.C., 1988.
3. *Synthesis of Safety Research Related to Traffic Control and Roadway Elements.* FHWA, U.S. Department of Transportation, 1981.
4. *Special Report 214: Practices for Resurfacing, Restoration, and Rehabilitation.* TRB, National Research Council, Washington, D.C., 1987.

Safety Relationships Associated with Cross-Sectional Roadway Elements

CHARLES V. ZEGEER AND FORREST M. COUNCIL

This study was conducted to summarize the known relationships between accident experience and cross-sectional roadway elements, along with accident reductions expected because of related roadway safety improvements. Such elements include lane width, shoulder width, shoulder type, roadside features, bridge width, median design, and others. A detailed review of literature and available safety research revealed that accident types related to cross-sectional elements on two-lane roads include run-off-road (including fixed-object and rollovers), head-on, opposite direction sideswipe, and same direction sideswipe. Lane widening can reduce these related crashes by up to 40 percent, whereas shoulder widening can reduce related accidents by up to 49 percent [for the addition of 8-ft (2.4-m) paved shoulders]. Improving roadsides can also contribute to the reduction of as much as 44 percent [for a 20-ft (6.1-m) increase in clear zone], whereas sideslope flattening can reduce single-vehicle crashes up to 27 percent (for flattening a 2:1 sideslope to 7:1 or flatter). Bridge widening can reduce total bridge crashes by as much as 80 percent, depending on the width before and after widening. On multilane roads, wider and flatter medians are associated with a reduced rate of total crashes. Lower-cost multilane design alternatives found to reduce crashes compared to two-lane roadways include two-way left-turn lanes, passing lanes, and turnout lanes. Suburban and rural multilane designs found to significantly reduce crashes compared to two-lane roads include those roads having two-way left-turn lanes with three or more total lanes.

Past studies have revealed that of more than 50 roadway-related features which can significantly affect crash experience, cross-sectional elements are among the most important (*1,2*). Such elements include lane width, shoulder width, shoulder type, roadside features (e.g., sideslope, clear zone), bridge width, and median width, among others. These elements can be modified to reduce accident rates. For example, lanes and shoulders can be widened, and sideslopes can be flattened.

In addition to modifying these elements, multilane design alternatives may also be considered where basic two-lane roads are not adequate. Such alternatives include the addition of through lanes, passing lanes, various median designs (e.g., raised medians), left-turn lanes (two-way, alternating), and others. Such design alternatives can affect traffic operations, as well as safety, along a highway section.

The purpose of this article is to discuss known relationships between cross-sectional elements and accident experience, along with the accident reductions expected because of related roadway safety improvements. All of the information on crash relationships for lanes, shoulders, and bridges (and corresponding effectiveness information for countermeasures) are for two-lane, rural roads only. Most of the discussion on roadside conditions relates to rural two-lane roads. The discussion of median design includes only multilane Interstate and parkway roads in rural areas.

University of North Carolina, Highway Safety Research Center, 134 1/2 E. Franklin Street, Chapel Hill, N.C. 27599.

SUMMARY OF RESEARCH

Figure 1 illustrates the many cross-sectional roadway elements typically found on two-lane roads. Illustrations of cross-sectional features and design alternatives for multilane roads are presented later. Following is a discussion of such roadway features and their known safety effects.

Lanes and Shoulders

Travel lanes are that portion of the highway intended for use by general traffic. The lane width of a two-lane road is measured from the centerline of the highway to the edgeline, or to the joint separating the lane from the shoulder. Shoulders are that portion of the highway immediately adjacent to, and outside of, the lanes. Shoulders are typically designed and intended to accommodate occasional use by vehicles, but not continual travel. Part or all of the shoulder may be paved. The combination of lane and shoulder widths plus median, if any, comprises the roadway width. Total roadway width is among the most important cross-section considerations in the safety performance of a two-lane highway. Generally, wider lanes or shoulders, or both, will result in fewer accidents.

Numerous studies have been conducted in recent years to determine the effects of lane width, shoulder width, and shoulder type on accident experience. However, few of them were able to control for roadside condition (e.g., clear zone, sideslope), roadway alignment, and other factors which, together with lane and shoulder width, influence accident experience. Also, since lane and shoulder width logically affect some accident types (e.g., run-off-road, head-on) but not necessarily other accident types (e.g., angle, rear-end), there is a need to express accident effects as a function of those accident types affected by lane and shoulder width.

A 1987 FHWA study by Zegeer et al. quantified the effects of lane width, shoulder width, and shoulder type on highway crash experience based on an analysis of data for nearly 8 050 km (5,000 miles) of two-lane highway from seven states (*3*). The study controlled for many roadway and traffic features, including roadside hazard, terrain, and average daily traffic (ADT). Accident types found to be related to lane and shoulder width, shoulder type, and roadside condition include run-off-road (fixed object, rollover, and other run-off-road accidents), head-on, and opposite- and same-direction sideswipe accidents, which together were termed as "related accidents." An accident prediction model was developed and used to determine the expected effects of lane- and shoulder-widening improvements on related accidents.

The study found that lane widening of 1 ft (0.3 m) [e.g., from 10-ft (3.0-m) to 11-ft (3.4-m) lanes] will be expected to reduce related accidents by 12 percent. Widening lanes by 2 ft (0.6 m), 3 ft (0.9

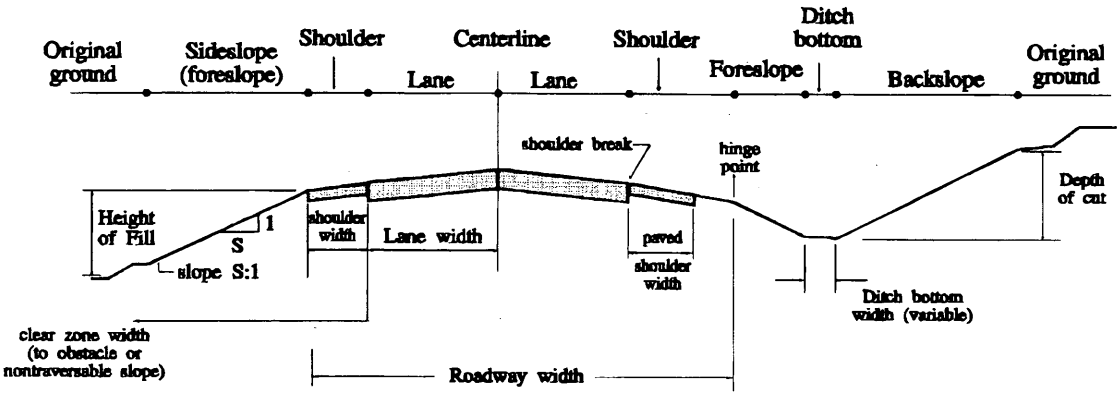


FIGURE 1 Elements of rural two-lane highway cross sections.

m), and 4 ft (1.2 m) will reduce related accident types by 23 percent, 32 percent, and 40 percent, respectively. It is important to mention that the predictive model only applies to two-lane, rural roadways with lane widths of 8 to 12 ft (2.4 to 3.7 m), shoulder widths of zero to 12 ft (3.7 m) (paved or unpaved), and traffic volumes of 100 to 10,000. One should not assume that these accident reductions apply to conditions outside these ranges (*3*).

According to the model, the same percentage of accidents will be reduced for a given amount of lane or shoulder widening, regardless of the lane width or shoulder width in the base (before) condition. For example, adding a 4-ft (1.2-m) paved shoulder to a road with a 10-ft (3.0-m) lane and no shoulder would result in the same accident reduction percentage as adding 4 ft (1.2 m) of shoulder to a 12-ft (3.7-m) lane with an existing 6-ft (1.8-m) paved shoulder. However, the actual number of related accidents eliminated per mile, per year would be greater for adding the 4-ft (1.2-m) paved shoulder to the 10-ft (3.0-m) lane, since the model would also predict a greater number of accidents for the section with the narrower 10-ft (3.0-m) lane. Greater overall benefits would result, then, from adding the 4-ft (1.2-m) shoulder to the 10-ft (3.0-m) lane, compared to adding a 4-ft (1.2-m) shoulder to a 12-ft (3.7-m) lane (*3*).

Reductions in related accidents because of widening paved or unpaved shoulders were also found in that same study. Widening paved shoulders by 2 ft (0.6 m), 4 ft (1.2 m), 6 ft (1.8 m), and 8 ft (2.4 m) will reduce related accidents by 16 percent, 29 percent, 40 percent, and 49 percent, respectively. Similar amounts of widening of unpaved shoulders will reduce related accidents by 13 percent, 25 percent, 35 percent, and 43 percent. Thus, for example, adding 8-ft (2.4-m) paved shoulders to a road with no shoulders will reduce approximately 49 percent of the related accidents (*3*). It should be noted that the predicted accident reductions given above are valid only when the roadside characteristics (sideslope and clear zone) are reestablished as before the lane or shoulder widening.

In general, when two or more roadway improvements are proposed simultaneously, the accident effects are not additive. For example, implementing two different improvements having accident reductions of 20 and 30 percent will not result in a combined 50 percent accident reduction.

Table 1 provides accident reduction factors for projects involving various combinations of lane widening, shoulder widening, and shoulder surfacing. For example, assume a roadway section currently has 10-ft (3.0-m) lane widths and 4-ft (1.2-m) unpaved shoulders, and the proposed improvement will result in 12-ft (3.7-m) lanes with 6-ft (1.8-m) paved shoulders. To determine the combined accident reduction of this improvement project, find the value in Table 1 corresponding to 2 ft (0.6 m) of lane widening (left column), and 4 ft (1.2 m) of unpaved shoulder in the existing condition. Go across horizontally to the column indicating a 6-ft (1.8-m) paved shoulder and read the 38 percent reduction in related accidents. If additional improvements are also considered at the same location (e.g., roadside improvements), accident reduction factors must be combined (not added) as described in a related user guide (*4*).

The results from this study, as given in Table 1, are recommended for use in estimating accident reduction effects of lane and shoulder improvements. These factors are appropriate for two-lane roads with ADTs of 100 to 10,000 vehicles per day (vpd), lane widths of 8 to 12 ft (2.4 to 3.7 m), and 0- to 12-ft (0- to 3.7-m) shoulders that are paved or unpaved (or partly paved and unpaved) (*3*).

A 1989 study by Griffin and Mak quantified accident effects of roadway widening on rural, farm-to-market roads in Texas (*5*). Single-vehicle accident rates decreased for wider road widths for various ADT groupings. The accident reductions matched closely those found in the Zegeer et al. study (*3*). The authors also found that roadway widening is not generally cost-effective for farm-to-market roads with ADTs below 1,000 vpd.

Numerous other studies in recent years have also analyzed large state data bases to determine accident effects of lane and shoulder width. These include studies by Foody and Long in Ohio (*6*); Zegeer, Mayes, and Deen in Kentucky (*7*); Shannon and Stanley in Idaho (*8*); and an NCHRP study by Jorgensen using data from Washington and Maryland, among others (*1*). Although these studies used a wide range of sample sizes and analysis techniques, all basically found that accident rates decrease because of wider lanes or shoulders, or both, even though there was considerable variation in the exact amount of crash reduction.

Although the studies reported above involved developing relationships between roadway width and accident experience from state data files and estimating crash reduction because of the accident relationship, studies by Rinde (in California) (*9*) and Turner et al. (in Texas) (*10*) involved evaluating actual pavement-widening projects. A 1974 study by Heimbach, Hunter, and Chao in North Carolina also found that paving 3 to 4 ft (0.9 to 1.2 m) of unpaved shoulders will result in significant reductions in accident frequency and severity (*11*).

TABLE 1 Accident Reduction Factors for Related Accident Types for Various Combinations of Lane and Shoulder Widening

Amount of Lane Widening (in feet)	Existing shoulder condition (Before period)		Percent Related Accidents Reduced Shoulder Condition in After Period							
			2 ft. Shoulder		4 ft. Shoulder		6 ft. Shoulder		8 ft. Shoulder	
	Shoulder width	Surface type	P	U	P	U	P	U	P	U
3	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	20	24	41	34
	6	Paved	--	--	--	--	12	--	26	--
	6	Unpaved	--	--	--	--	19	12	31	24
	8	Paved	--	--	--	--	--	--	12	--
	8	Unpaved	--	--	--	--	--	--	21	12

Notes:

Cells were left blank where they correspond to projects which 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

1 ft = 0.3048 m

Roadside Condition

Roadside condition is another cross-sectional element that often affects crash frequency and severity. This is because of the high percentage of crashes, particularly on rural two-lane roads, that involve a run-off-road vehicle.

Providing a more "forgiving" roadside relatively free of steep slopes and rigid objects will allow many of these off-road vehicles to recover without having a serious crash.

The relative hazard of the roadside may be described in terms of roadside recovery distance (or roadside clear zone), and sideslope (foreslope). Both the severity of crashes and crash frequency are affected by such roadside features. Following is a discussion of these roadside characteristics.

Roadside Recovery Distance and Clear Zone

The roadside recovery distance is a relatively flat, unobstructed area adjacent to the travel lane (i.e., edgeline) where there is a reasonable chance for an off-road vehicle to safely recover (*3*). Therefore, it is the distance from the outside edge of the travel lane to the nearest rigid obstacle (e.g., bridge rail, tree, culvert, utility pole), steep slope, nontraversable ditch, or other threat (e.g., cliff, lake) to errant motor vehicles. This is similar to the clear zone definition, except that the recovery distance includes a recoverable slope, whereas according to the definition in the new AASHTO "Roadside Design Guide," a clear zone also includes a nontraversable slope (*12*).

Along a roadway section, the roadside recovery distance may vary considerably. The recovery distance for a roadway section can be determined by taking an average of measurements (e.g., three to five measurements per mile (1.6 km) on each side of the road). Roadside recovery distances of 0 to 30 ft (0 to 9.1 m) are generally recorded.

For roadways with limited recovery distances [particularly less than 10 or 15 ft (3.0 to 4.6 m) from the roadway edgeline] where roadside improvements are proposed, accident reduction factors may be found. These factors are again based on the previously cited Zegeer et al. study (*3*). As with lane and shoulder width, the accident model predicts that accident rates will be reduced by a specific percentage for a given increase in roadside recovery distance. Increasing the roadside recovery distance by 5 ft (1.5 m) (e.g., from 12 to 17 ft) (3.7 to 5.2 m) will reduce "related" accidents (as defined earlier) by an estimated 13 percent. Further, increasing the roadside recovery distance by 10 ft (3.0 m), 15 ft (4.6 m), and 20 ft (6.1 m), will reduce related accidents by 25 percent, 35 percent, and 44 percent, respectively. Examples of roadside improvements that can increase the recovery distance include cutting trees near the roadway, relocating utility poles further from the road, and using sideslopes of about 4:1 or flatter. For an improvement involving only sideslope flattening, see the discussion on sideslope given later.

A 1982 study by Graham and Harwood determined the effect of clear zone policy on the single-vehicle accident rate (*13*). Single-vehicle accidents per mile per year are highest for roads with a nonclear zone, next highest for a 4:1 clear zone policy (i.e., same clear area with a 4:1 sideslope), and lowest for a 6:1 clear zone policy for various ADTs. This study also indicates a high potential for safety benefits resulting from increased roadside clear zones.

Sideslope

The steepness of the roadside slope or sideslope, also termed foreslope, is a cross-sectional feature that affects the likelihood of an off-road vehicle rolling over or recovering back into the travel lane. Existing guidelines for acceptable sideslopes have historically been based on computer simulations and observations of controlled vehicle test runs on various slopes, as well as on "informed" judgments. Until recently, little was known about true accident relationships with sideslopes.

As part of their 1987 study, Zegeer et al. developed relationships between single-vehicle crashes and field-measured side-slopes from 1:1 to 7:1 or steeper for 1,776 mi of roadway in three states: Michigan, Alabama, and Washington (*3*). Single-vehicle accidents (as a ratio of accidents on a 7:1 slope) are highest for slopes of 2:1 or steeper, and drop only slightly for 3:1 slopes. Single-vehicle accidents then drop linearly (and significantly) for flatter slopes. This plot represents the effect of sideslope after controlling for ADT and roadway features (*3*).

The accident relationship was used to develop accident reductions matching various sideslope-flattening projects. The percent reductions are given in Table 2 for single-vehicle and total accidents. For example, flattening an existing 2:1 sideslope to 6:1 should result in a reduction of approximately 21 percent and 12 percent of single-vehicle and total accidents, respectively (*3*). These reductions rest on the assumption that the roadside slope to be flattened is relatively clear of rigid obstacles.

The use of flatter slopes not only reduces the accident rate, but it may also reduce rollover accidents, which are typically quite severe. In fact, injury data from three states reveals that 55 percent of run-off-road rollover accidents result in occupant injury and 1 to 3 percent end in death. Of all other accident types, only pedestrian accidents and head-on crashes result in higher injury percentages (*3*). The recent FHWA study found that sideslopes of 5:1 or flatter were needed to significantly reduce the incidence of rollover accidents (i.e., not 4:1, as is often assumed) (*3*). Additional details of accident effects of specific roadside obstacles (e.g., utility poles, culverts, guardrail) are given elsewhere (*14–17*).

TABLE 2 Effects of Sideslope Flattening on Single-Vehicle and Total Accidents

	Sideslope in After Condition							
	4:1		5:1		6:1		7:1 or Flatter	
Sideslope in Before Condition	Single Vehicle Accs	Total Accs	Single Vehicle Accs	Total Accs	Single Vehicle Accs	Total Accs	Single Vehicle Accs	Total Accs
2:1	10	6	15	9	21	12	27	15
3:1	8	5	14	8	19	11	26	15
4:1	0	-	6	3	12	7	19	11
5:1	-	-	0	-	6	3	14	8
6:1	-	-	-	-	0	-	8	5

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

Crash Severity of Obstacles

In addition to crash frequency, the severity of crashes involving specific roadside obstacles is also important. A 1978 FHWA study by Perchonok et al. analyzed accident characteristics of single-vehicle crashes, including crash severity related to types of objects struck (*18*). For nonrollover fixed-object crashes, the obstacles associated with the highest percent of injury occurrences are, in order: bridge or overpass entrances, trees, field approaches (i.e., ditches created by driveways), culverts, embankments, and wooden utility poles. Obstacle types with the lowest crash severity include small sign posts, fences, and guardrails (*18*).

A separate analysis was also conducted for severity of crashes involving ditches. The authors found that ditches that were 3 ft (0.9 m) or deeper were associated with a higher percent of injury accidents (61 percent) when compared to crashes involving ditches 1 to 2 ft (0.3 to 0.6 m) deep (54 percent injury). Percent fatal accidents were about the same for each depth category (i.e., about 5 percent for both the 1- to 2-ft (0.3- to 0.6-m) and 3-ft (0.9-m) plus groups).

Bridges

Highway bridges are sometimes associated with accident problems, particularly rural highway bridges with narrow width, poor sight distance (e.g., just past a sharp horizontal curve), unprotected bridge end, or with poor signing and delineation. Numerous studies have analyzed the effects of various traffic control devices (e.g., signs and markings) on crashes and on vehicle operations such as vehicle placement on the bridge. However, research is scarce on the effects of bridge geometrics on crash experience.

The features that are of most importance with respect to affecting the bridge accident rate are the bridge width, or the width of the bridge in relation to the approach width, or both. The best known accident relationship with bridge width was developed in a 1984 study by Turner (*19*). Based on accidents at 2,087 bridges on two-lane roads in Texas, an accident model was developed as a function of "relative bridge width," which is defined as the bridge width minus the width of the traveled way.

According to Turner's accident model, and as indicated in Figure 2, the number of accidents per million vehicles decreases as the relative bridge width increases (*19,20*). This relationship indicates that it is desirable to have bridge widths at least 6 ft (1.8 m) wider than the travelled way. In other words, shoulders of 3 ft (0.9 m) or more should be provided on each side of the bridge.

Based on Turner's model, the percent reduction in total accidents because of reconstructing narrow bridges to make them wider can be determined. Accident reduction factors given in Table 3 provide percent reductions in the total crash rate expected because of widening shoulders on bridges. For example, assume that a bridge width is 24 ft (7.3 m) wide with 10-ft (3.0-m) lanes and 2-ft (0.6-m) shoulders on each side. According to Table 3, widening the bridge to 32 ft (9.8 m) [i.e., two 10-ft (3.0-m) lanes with two 6-ft (1.8-m) shoulders] would reduce the total bridge accident rate by 62 percent.

Note that values in Table 3 assume that the lane width stays constant in the before and after condition. When the bridge lane width is increased, a conservative estimate of accident reduction would be to use Table 3 and only include the amount of increased shoulder width. For example, when widening a 20-ft (6.1-m) bridge [two 10-ft (3.0-m) lanes and no shoulder] to a 30-ft (9.1-m) bridge [two 12-ft (3.7-m) lanes and two 3-ft (0.9-m) shoulders], assume an increase in shoulder width from 0 to 3 ft (0 to 0.9 m), for at least a 42 percent "minimum" accident reduction.

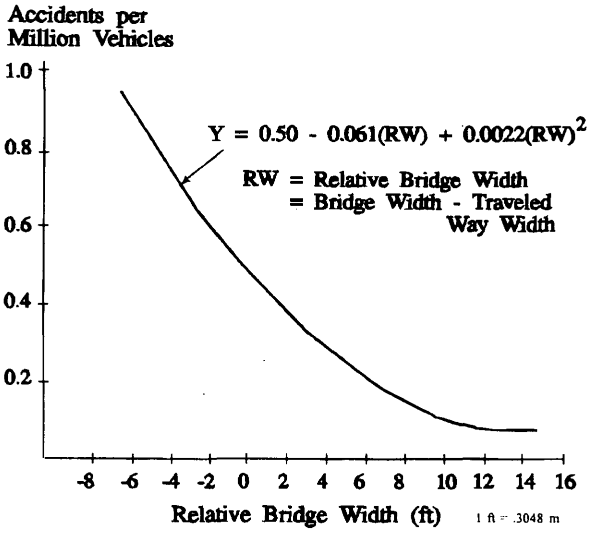


FIGURE 2 Accident rate by relative bridge width.

Median Design

Elements of median design that may influence accident frequency or severity include median width, median slope, median type (raised or depressed), and the presence or absence of a median barrier. Wide medians are considered desirable in that they reduce the likelihood of head-on crashes between vehicles in opposing directions. Median slope and design can affect rollover accidents and also other single-vehicle crashes (fixed object) and head-on crashes with opposing traffic. The installation of median barriers typically increases overall accident frequency because of the increased number of hits to the barrier, but reduces crash severity resulting from a reduction or elimination of head-on impacts with opposing traffic. A controlling factor in median width is often the limited amount of highway right-of-way available.

A comparison was made of the safety of a raised (mound) median design versus depressed (swale) medians in the 1974 Ohio study by Foody and Culp (*21*). Using a sample of rural interstates, all having 84-ft (25.6-m) wide medians and other similar geometrics, accident experience was compared between the two median designs. No differences were found in the number of injury accidents, rollover accident occurrence, or overall accident severity between the raised and depressed median designs. However, a significantly lower number of single-vehicle median-involved crashes were found on sections with depressed medians compared to raised medians. The authors concluded that this may indicate that mildly depressed medians provide more opportunity for encroaching vehicles to return safely to the roadway.

A 1973 study by Garner and Deen in Kentucky compared the crash experience of various median widths, median types (raised versus depressed), and slopes on Interstate and turnpike roads in Kentucky (*22*). Highways with at least 30-ft (9.1-m) wide medians had lower accident rates than those with narrower median widths. For wider medians, a significant reduction was also found in the percent of accidents involving a vehicle crossing the median. Median

TABLE 3 Summary of Accident Reduction Factors Associated with Widening Shoulders on Bridges

Bridge Shoulder Width Before Widening (ft)		Bridge Shoulder Width (ft) After Widening Each Side (total of Both Sides in Parenthesis)						
Each Side	Total of Both Sides	2(4)	3(6)	4(10)	5(8)	6(12)	7(14)	8(16)
0	0	23	42	57	69	78	83	85
1	2	--	25	45	60	72	78	80
2	4	--	--	27	47	62	71	74
3	6	--	--	--	28	48	60	64
4	8	--	--	--	--	28	44	50

1 ft = .3048 m

[a] Assumes that the width of lanes on the bridge remain constant. Values in the table were derived based on the accident model developed by Turner on rural, two-lane roads.[20]

slopes of 4:1 or steeper had abnormally high accident rates for various median widths, whereas a higher crash severity and higher proportion of vehicle overturn accidents were found for medians that were deeply depressed. For median widths of 20 to 30 ft (6.1 to 9.1 m), the use of a raised median barrier was associated with a higher number of accidents involving hitting the median and losing control (*22*).

The authors recommended minimum median widths of 30 to 40 ft (9.1 to 12.2 m), slopes of 6:1 or flatter [particularly when median widths are less than 60 ft (18.3 m)], and 12-ft (3.7-m) paved shoulders on roadway sections where guardrail is installed in the median. Raised medians were found to be undesirable based both on accident experience and on less than ideal surface drainage.

Taken together, the two median studies indicate that when a wide median width can be provided [e.g., 84 ft (25.6 m)], a mildly depressed median [depressed by 4 ft (1.2 m) with 8:1 down-slopes] and mound median (3:1 upslope) provide about the same crash experience. However, in cases with narrower medians [e.g., 20 to 40 ft (6.1 to 12.2 m)], slopes of 6:1 or flatter are particularly important. Deeply depressed medians with slopes of 4:1 or steeper are clearly associated with a greater occurrence of overturn crashes. Although accident relationships are unclear for median widths of less than 20 ft (6.1 m), wider medians in general are better, and median widths in the range of 60 to 80 ft (18.3 to 24.4 m) or more with flat slopes appear to be desirable, where feasible.

Multilane Design Alternatives

A majority of two-lane highways carry relatively low traffic volumes and experience few operational problems. However, considerable safety and operational problems exist on some higher-volume two-lane highways, particularly in suburban and commercial areas. Such problems are often caused by inadequate geometry (steep grades, poor sight distance), the lack of passing opportunities (because of heavy oncoming traffic or poor sight distance, or both), or turns at intersections and driveways. Although a major reconstruction project may be used to reduce the problem (e.g., widening to a four-lane facility or major alignment changes), other lower-cost alternatives have been used successfully to reduce accident operational problems (*23*).

A 1985 study by Harwood and St. John (*24*) evaluated the following five different operational and safety treatments as alternatives to basic two-lane highways:

1. Passing lanes;
2. Short four-lane sections;
3. Shoulder-use sections (i.e., shoulders used as driving lanes);
4. Turnout lanes (a widened, unobstructed area on a two-lane highway allowing slow vehicles to pull off through a lane to allow other vehicles to pass); and
5. Two-way left-turn lanes (TWLTLs).

In addition to an operational analysis, the accident effects of these design alternatives were evaluated for 138 treated sites, compared to adjacent "untreated" two-lane highway sections. The results were used along with some related past studies to determine expected accident reductions caused by making such design improvements on two-lane roads (*25,26*). Note that these reductions are based on sites that carried predominantly higher traffic volumes than average two-lane sections. Thus, the reductions indicated in Table 4 may not apply to low-volume two-lane roads.

As indicated in Table 4, TWLTLs were found to reduce accidents by approximately 35 percent in urban fringe areas and from 70 to 85 percent in rural areas. Accident reductions of 25 to 40 percent were reported for passing lanes, short four-lane sections, and turnout lanes. No known accident effects were found for shoulder-use sections, although sample sizes were quite small (*24,25*).

The reader should use caution regarding the accident effects of these design alternatives, since accident experience may vary widely depending on the specific traffic and site characteristics. In addition, not all of these alternatives are even appropriate for all possible roadway sections. Also, although such alternatives may reduce some safety and operational problems, other problems may be created in some cases. For example, at rural locations where passing zones exist, using TWLTLs can create operational problems with respect to same-direction passing maneuvers. More detailed guidelines are given in an informational guide by Harwood and Hoban for optimal use of these design alternatives (*25*).

A 1986 NCHRP study by Harwood investigated the safety, operational, and cost characteristics of multilane designs for suburban areas (*23*). These designs generally involve adding one or more

TABLE 4 Accident Reductions Related to Five Multilane Design Alternatives, as Compared to a Basic Two-Lane Road Design

Multilane Design Alternative	Type of Area	Percent Reduction in Accidents: Total Accs	Percent Reduction in Accidents: F + I Accs
Passing lanes	Rural	25	30
Short four-lane section	Rural	35	40
Turnout lanes	Rural	30	40
Two-way, left-turn lane	Suburban	35	35
Two-way, left-turn lane	Rural	70-85	70-85
Shoulder use section	Rural	no known significant effect	

Notes:
F + I = fatal plus injury accidents
These values are only for two-lane roads, in rural or suburban areas.

lanes to a two-lane road design and generally are more extensive than the two-lane undivided road alternatives (termed the 2U design "base" conditions) mentioned for the other study above. These multilane designs include (*23*):

- Three-lane divided, with two-way, left-turn lane in the median (3T design);
- Four-lane undivided (4U design);
- Four-lane divided with one-way left-turn lanes in the median (4D design); and
- Five-lane divided with two-way left-turn lane in the median (5T design).

In addition to these five alternatives, a less detailed analysis was also conducted for three other design alternatives, namely:

- Five-lane divided roads with continuous alternating left-turn lane in the median;
- Six-lane divided highways with a raised median; and
- Seven-lane highways with TWLTLs in the median.

An analysis was conducted of accident, operational traffic, and roadway data for sample sections from California and Michigan. Average accident rates were computed for each of the five basic design alternatives for commercial and residential areas. The 3T design had a safety advantage over standard two-lane (2U) highways, and requires only a minor amount of increase in road width. Four-lane undivided (4U) highways had generally higher accident rates than other multilane design alternatives, in part because of the lack of special provisions for left-turn vehicles. Installation of a five-lane highway with a TWLTL (5T design) was associated with reduced accident rates compared to other four-lane design options (*24*).

Other Cross-Sectional Features

In addition to lane and shoulder, roadside features, bridge width, and other features discussed above, there are a multitude of other cross-sectional variables that can affect crash frequency and severity. For example, the cross slope along a highway section normally is characterized on tangent sections by the crown of the road (for drainage purposes) and on horizontal curves by the super-elevation (and super-elevation transition). The effect of cross slope on tangent sections is difficult to quantify because (1) cross slopes may vary within a given section, and (2) the cross slope may be altered somewhat each time a section is repaved (whether intentional or not).

Studies have also found that characteristics of roadside ditches play a role in crash severity, frequency, or both. Ditch shape (e.g., V-ditch, trapezoidal) can influence the vehicle direction and the likelihood of a rollover and the type of impact. Specific crash effects, however, have not been fully quantified.

Relationships also exist between cross-sectional elements and roadway alignment. For example, the effects of lane and shoulder width reported above involve rural roads with all types of alignment. However, if one analyzes accident effects of roadway width on horizontal curves, different relationships are found.

CONCLUSIONS

In the past 20 years, much has been learned about the safety impacts of cross-sectional roadway features. For example, widening lanes can reduce "related" accidents (i.e., run-off-road, head-on, opposite-direction sideswipe, and same-direction sideswipe) by as much as 40 percent. Shoulder widening can reduce related accidents by up to 49 percent, for the addition of 8-ft (2.4-m) paved shoulders. Increasing the roadside clear zone, flattening roadside slopes, or both, are associated with major reductions in fixed object and rollover crashes. Bridge widening on two-lane rural roads can reduce total bridge crashes by as much as 80 percent, depending on the width before and after widening.

On multilane roads, wider and flatter medians are associated with reduced accident rates. Lower-cost multilane design alternatives that reduce crashes compared to two-lane roads include two-way left-turn lanes, passing lanes, and turnout lanes. Suburban and rural multilane designs found to significantly reduce crashes include those roads having two-way left-turn lanes and also those with three or more lanes.

REFERENCES

1. Jorgensen, R., and Associates. *NCHRP Report No. 197: Cost and Safety Effectiveness of Highway Design Elements.* TRB, National Research Council, Washington, D.C., 1978.
2. Zegeer, C. V., and J. A. Deacon. Effects of Lane Width, Shoulder Width, and Shoulder Type on Highway Safety. In *State of the Art Report 6: Relationship Between Safety and Key Highway Features—A Synthesis of Prior Research.* TRB, National Research Council, Washington, D.C., 1987.
3. Zegeer, C. V., J. Hummer, D. Reinfurt, L. Herf, and W. Hunter. *Safety Effects of Cross-Section Design for Two-Lane Roads.* Volumes I and II. Report No. FHWA-RD-87-008. FHWA, U.S. Department of Transportation, 1987.
4. Zegeer, C. V., J. Hummer, L. Herf, D. Reinfurt, and W. Hunter. *Safety Cost-Effectiveness of Incremental Changes in Cross-Section Design—Informational Guide.* Report No. FHWA-RD-87-094. FHWA, U.S. Department of Transportation, 1987.
5. Griffin, L. I., and K. K. Mak. Benefits to be Achieved from Widening Rural, Two-Lane, Farm-to-Market Roads in Texas. Presented at the 1989 Annual Meeting of the Transportation Research Board, Washington, D.C., 1989.
6. Foody T. J., and M. D. Long. *The Identification of Relationships Between Safety and Roadway Obstructions.* Ohio Department of Transportation, Columbus, Ohio, 1974.
7. Zegeer, C. V., J. Mayes, and R. Deen. Effect of Lane and Shoulder Width on Accident Reduction on Rural, Two-Lane Roads. In *Transportation Research Record 806,* TRB, National Research Council, Washington, D.C., 1981, pp. 33–43 (also Kentucky DOT Research Report 524, July 1979).
8. Shannon, P., and A. Stanley. *Pavement Width Standards for Rural, Two-Lane Highways.* The Pacific Northwest Regional Commission, Idaho Transportation Department, Boise, Idaho, Dec. 1976.
9. Rinde, E. *Accident Rates vs. Shoulder Widths.* Report CA-DOT-RT-3147-1-77-01. FHWA, California Department of Transportation, Sacramento, Calif., 1977.
10. Turner, D. S., D. B. Fambro, and R. O. Rogness. Effects of Paved Shoulders on Accident Rates for Rural Texas Highways. In *Transportation Research Record No. 819,* TRB, National Research Council, Washington, D.C., 1981, pp. 30–37.
11. Heimbach, C. L., W. W. Hunter, and G.C. Chao. Paved Highway Shoulders and Accident Experience. *Transportation Engineering Journal Proceedings,* ASCE, Vol. 100, No. TE4, Nov. 1974, pp. 887–908.
12. *Roadside Design Guide.* AASHTO, Washington, D.C., 1988.
13. Graham, J. L., and D. W. Harwood. *NCHRP Report No. 247: Effectiveness of Clear Recovery Zones.* TRB, National Research Council, Washington, D.C., 1982.
14. Zegeer, C. V., and M. R. Parker. *Cost-Effectiveness of Countermeasures for Utility Pole Accidents.* Report FHWA/RD-83-063, FHWA, U.S. Department of Transportation, Sept. 1983.
15. Zegeer, C. V., and M. J. Cynecki. *Selection of Cost-Effective Countermeasures for Utility Pole Accidents: Users Manual.* Report FHWA-IP-84-13, FHWA, U.S. Department of Transportation, July 1984.
16. Zegeer, C. V., R. Stewart, D. Reinfurt, F.M. Council, T. Newman, E. Hamilton, T. Miller, and W. Hunter. *Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves.* Report FHWA-RD-90-021. FHWA, U.S. Department of Transportation, 1990.
17. Ross, H. E., K. C. Walker, and W. J. Lindsay. *The Rural Mailbox—A Little Known Hazard.* Texas Transportation Institute, College Station, Tex., 1980.
18. Perchonok, K., T. Ranney, S. Baum, D. Morris, and J. Eppich. *Hazardous Effects of Highway Features and Roadside Objects, Volume I: Literature Review and Methodology and Volume II: Findings.* Reports FHWA-RD-78-201 & 202. FHWA, U.S. Department of Transportation, Sept. 1978.
19. Turner, D. S. Prediction of Bridge Accident Rates. *Journal of Transportation Engineering,* Vol. 110, No. 1, American Society of Civil Engineers, New York, Jan. 1984, pp. 45–54.
20. Mak, K. K. Effect of Bridge Width on Highway Safety. In *State-of-the-Art Report 6, Relationship Between Safety and Key Highway Features.* TRB, National Research Council, Washington, D.C., 1987.
21. Foody, T. J., and T. B. Culp. A Comparison of the Safety Potential of the Raised vs. Depressed Median Design. Paper presented at the 1974 Annual Meeting of the Transportation Research Board, Washington, D.C., 1974.
22. Garner, G. R., and R. C. Deen. Elements of Median Design in Relation to Accident Occurrence. Paper prepared for Transportation Research Board Annual Meeting, Washington, D.C., Jan. 1973.
23. Harwood, D. W. *NCHRP Report No. 282: Multilane Design Alternatives for Improving Suburban Highways.* TRB, National Research Council, Washington, D.C., March 1986.
24. Harwood, D. W., and A. D. St. John. *Passing Lanes and Other Operational Improvements on Two-Lane Highways.* Report FHWA-RD-85-028, FHWA, U.S. Department of Transportation, Dec. 1985.
25. Harwood, D. W., and C. J. Hoban. *Low-Cost Methods for Improving Traffic Operations on Two-Lane Roads: Informational Guide.* Report FHWA-IP-87-2, FHWA, U.S. Department of Transportation, Jan. 1987.