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Cost-Effectiveness of Improvements to Stopping-Sight-Distance Safety Problems

TIMOTHY R. NEUMAN AND JOHN C. GLENNON

Stopping-sight distance (SSD) is one of the most significant design features of highways. The treatment of locations that have deficient sight distance is generally costly and difficult because most such deficiencies involve basic problems with horizontal or vertical geometry. An attempt was made to systematically evaluate the cost-effectiveness of spot improvements of SSD-deficient locations. A framework was established for classifying the accident potential of such locations. Countermeasures to treat sight-distance problems on both rural and urban highways were proposed. Their implementation costs and hypothetical safety benefits were evaluated in order to discover any potential cost-effective improvements. Despite conservative assumptions about safety, the research indicated that only relatively inexpensive countermeasures hold the potential for cost-effectiveness. A greater potential for cost-effectiveness was indicated when improvements are made in conjunction with a planned rehabilitation or reconstruction program.

Safe stopping-sight distance (SSD) is one of the most significant design features of highways. Potentially serious safety problems are created by short vertical curves or by roadside obstructions on the inside of sharp horizontal curves. Although it is easy to identify highway sections with deficient SSD, treatment of the problem is difficult. Most sight-distance deficiencies are created by geometric deficiencies that are costly to correct.

A cost-effectiveness analysis for treating existing sight-distance deficiencies is presented in this paper. A rational approach was used that relied on published accident research and knowledge gained from an FHWA research contract, "Effectiveness of Design Criteria for Geometric Elements." A framework was established to classify SSD problems by their potential impacts on safety.

Countermeasures to treat sight-distance problems were developed, and estimates of their effectiveness were made. By comparing the costs of implementing these countermeasures with the safety benefits derived from hypothesized accident reductions, a measure of the potential cost-effectiveness was obtained.

HIGHWAY SAFETY AND SSD: ISSUES AND RELATIONS

A review of highway safety research forms the basis for evaluating the relative safety of SSD restrictions. The results of previous research, which relate accidents to roadway geometry, are summarized in the next paragraph. The findings are useful in estimating the magnitude and severity of accidents attributable to SSD restrictions.

Foody and Long (1) investigated the incremental hazard associated with geometric elements such as grades, curves, intersections, and sight-distance restrictions. One phase of the project focused on single-vehicle accidents on two-lane rural highways. A regression model was derived that included percentage of SSD restrictions as an independent variable. A sensitivity analysis of the SSD variable predicted an increase of about 1 single-vehicle accident per million vehicle miles in going from 0 to 100 percent SSD restrictions.

Kihlberg and Tharp (2) studied the difference in annual accident rates over 0.5-km highway sections with all combinations of four geometric features: grades (4 percent or more), curvature (4° or more), intersections, and structures. Although SSD restrictions were not directly studied, the geometric variables can be used to evaluate the sensitivity of safety to conditions that create SSD deficiencies (such as vertical curves after steep grades and sharp horizontal curves). The study also provided clues on the variability in accident rates created by variable geometry and conditions. The worst conditions resulted in accident rates about 2.5 times higher than the best conditions.

Table 1. Basic accident rates selected for use in SSD analyses.

Facility Type	Representative Accident Rate[a] (per million vehicle kilometers)	Accidents Resulting in Injury or Fatality (%)
Rural freeway	0.50	38
Rural two-lane highway	1.50	42
Urban freeway	1.10	29
Urban arterial	5.30	32

[a] Data from AASHTO (11), although the statewide accident data from Florida and Illinois were obtained from the FHWA contract, "Effectiveness of Design Criteria for Geometric Elements."

Cirillo and others (3) studied the relations of geometry and traffic variables to accident rates on Interstate highways with a series of regression models. One model, which described accident rates along the main line between interchanges, contained minimum SSD as a geometric variable. Its contribution to predicted accident experience was negligible.

Other studies were inconclusive on the safety effects of SSD. Schoppert (4) judged sight distance as insignificant in explaining variations in accident rates. Raff (5), Gupta and Jain (6), and Sparks (7) did not reach any conclusions on sight distance. Agent and Deen (8) reported that a significant portion of accidents on two-lane rural highways were rear-end collisions, which suggested that sight distance may play a role in accident causation. [Other reports that may be of interest are from Dart and Man (9) and Glennon and Weaver (10).]

This review of safety literature reveals three basis conclusions that relate SSD and accident occurrence:

1. Identification of the specific effects of limited SSD on accident rates has not been achieved by previous research,
2. Indications are that limited SSD contributes to safety problems on a range of highway types, and
3. Combinations of geometric problems (including SSD restrictions) generally result in higher accident rates.

That previous research has not established a strong link between accident experience and SSD is not surprising. First, highway sections that have unusual or severe SSD restrictions are relatively rare; therefore, the inclusion of such sections in a large data base would dilute the effects of the restrictions. Second, a characteristic of SSD restrictions is their relatively short length. Accident studies that rely on long study sections would dilute any effect of the SSD restriction, which usually affects only a small proportion of the section length. Third, the safety history of limited SSD locations would reflect not only the severity of the restriction, but also the effect of other geometric elements present at or near the restriction, such as intersections, sharp curvature, and narrow structures. No study has quantified SSD restrictions to the extent necessary to identify these effects.

DEVELOPMENT OF A SAFETY EFFECTIVENESS RATIONALE

The relation of SSD to safety is hypothesized as a series of basic elements. These elements relate to the functional and operational aspects of SSD, the other geometric characteristics of the highway, and the basic measures of exposure to the SSD hazard. The framework developed to evaluate the sensitivity of SSD to safety has five basic elements: traffic volume, facility type, severity of SSD restrictions, length of SSD restrictions, and presence of other geometric features.

Traffic Volume

Traffic volume is an obvious determinant of the relative hazard at a location that has limited SSD. The risk of an accident resulting from a critical event (e.g., object in road, head-on encounter) within the SSD restriction is directly proportional to the number of vehicles exposed.

Facility Type

Accident experience varies considerably among facility types. Traffic volumes, patterns, and operating speeds; the character of the roadway alignment; and the presence, number, and nature of conflicts all contribute to variances in the types and number of accidents. For example, head-on encounters and crossing conflicts are potential problems on two-lane rural highways, but not on freeways. Conversely, on urban freeways the proximity of entrances and exits combined with high traffic volumes at locations of limited sight distance can create rear-end incidents. The data in Table 1 give the representative accident rates and severities selected for the analysis of SSD safety for the various highway facilities studied.

Severity of SSD Restriction

The relative hazard at a location that has limited SSD depends partly on the severity of the restriction. Severity refers to the amount of SSD available relative to the operating speed of the highway. This concept recognizes the operational and safety differences presented by the range of SSD-deficient locations. For example, consider two crest vertical curves on a highway with an operating speed of 115 km/h. Curve A has a minimum SSD of 200 m, whereas curve B has a minimum SSD of 240 m. Although both vertical curves are deficient (relative to the AASHTO minimum SSD requirement of 260 m), curve A clearly presents a more hazardous situation. With a 185-m braking distance at 115 km/h, curve A only provides 15 m for perception-reaction time, which amounts to 0.47 sec. Curve B has 55 m and 1.72 sec of perception-reaction time.

The severity of SSD restrictions can be characterized by the differential between the design speed and the operating speed of the highway. Therefore, the locations in this analysis were classified by their SSD severity according to the following table, where the severity of a location is measured against the AASHTO minimum SSD (note that operating speed in this table represents the speed at which free-flowing vehicles travel through the area of restricted SSD):

Severity	Increment of Speed (km/h) Under Highway Operating Speed for which SSD Is Sufficient
Moderate	15
Significant	25
Extreme	35

Length of Sight-Distance Restrictions

Another factor that affects the relative safety of a SSD deficiency is the length of highway over which the restricted sight distance exists. This length is a basic measure of exposure to risk; the longer the restriction, the greater the probability that an event (such as an object falling onto the road) will occur within the restricted area. The length of restriction is determined by a sight-distance profile, as shown in Figure 1.

The relations among length of restriction, severity of the restriction, and A (the algebraic difference in grades) are shown in Figure 2. In general, the more severe the restriction, the shorter the length of highway affected. (For analysis purposes, AASHTO minimum SSD is used as the required SSD for the parameters in Figure 2.)

Relations similar to those of Figure 2 for horizontal SSD restrictions are not as readily developed because of the great variability in conditions that create horizontal SSD restrictions.

Other Geometric Features

The fifth element of SSD-deficient locations is the character of the roadway as defined by all other geometric features within the restricted area. A short crest vertical curve that hides a sharp horizontal curve presents a greater accident potential than if no such condition existed. These locations are rightfully viewed as particularly susceptible to sight-distance-related accidents. The data in Table 2 give a classification of confounding geometric features in terms of their estimated relative hazard when combined with deficient SSD.

SAFETY CHARACTERIZATION OF SITES THAT HAVE SSD DEFICIENCIES

A link between deficient SSD and higher accident rates is only indirectly established by previous research. Incremental safety effects of SSD deficiencies defined by various levels of severity of restriction and situational hazards have not been established. Nevertheless, greater accident rates are expected on highway sections that have large SSD deficiencies and other hazards, such as intersections and curves, within the sight restriction. What must be hypothesized is the magnitude of these accident rates relative to average rates.

Accident Frequency Distributions

Accident data collected in three states (for the FHWA contract "Effectiveness of Design Criteria for Geometric Elements") for two-lane rural highway curves indicate how accident rates fluctuate. The data in Table 3 give both the mean accident rates and the numbers of sites that have rates significantly higher than the mean. Despite differences among the states, rates of 3 to 5 times the mean are clearly appropriate for worst-case geometry situations.

This distributional characteristic of accident rates allows the quantification of potential accident rates relative to levels of perceived hazard. For example, it can be presumed that the accident rate attributable to deficient SSD is greater than the average rate (considering that most highway mileage has adequate SSD) and less than 5 times the average rate. Furthermore, it can be presumed that the contribution of deficient SSD, expressed as a multiple of the average rate, would depend on the other important elements previously discussed (i.e., severity of the restriction and other geometric hazards).

Accident Rate Reduction Factors

The basic research objective was to identify potentially cost-effective countermeasures to SSD safety problems. With this objective, optimistic assump-

Figure 1. SSD profiles for vertical curves.

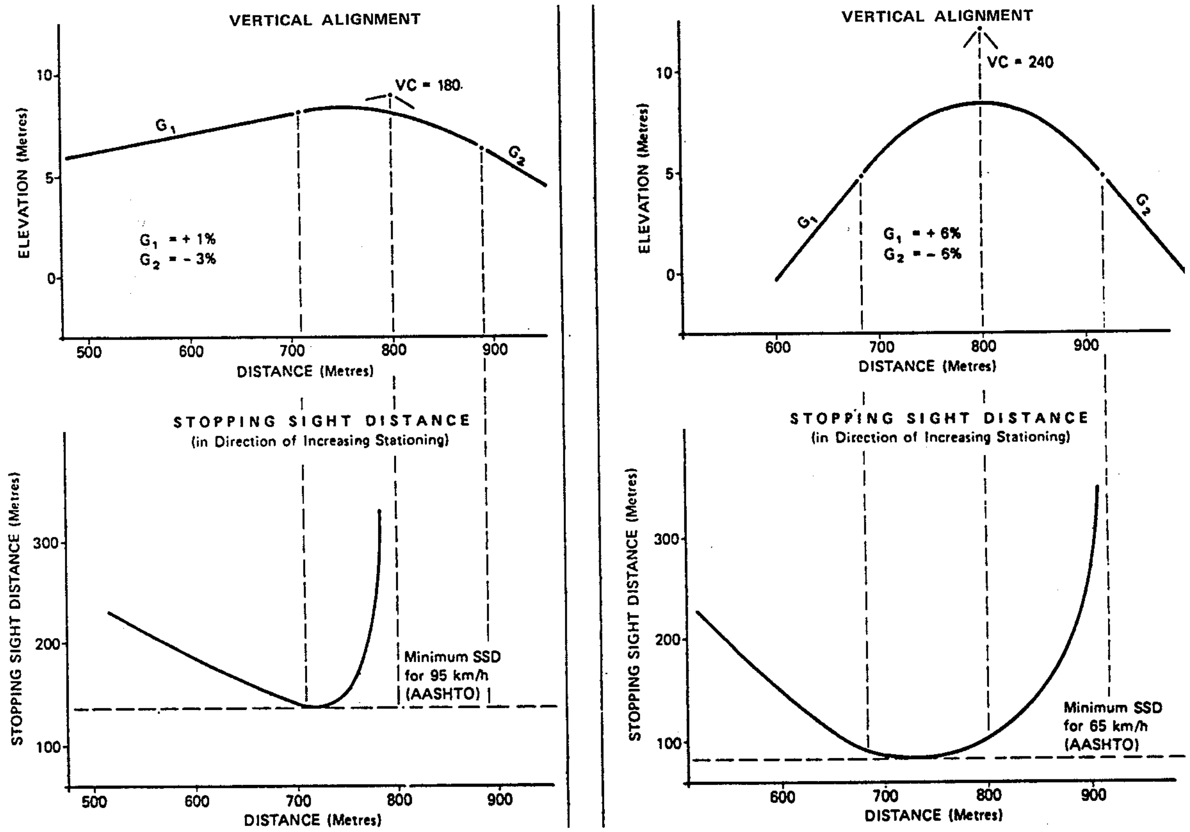

Figure 2. Relations among grades, severity, and length of SSD restrictions on vertical curves.

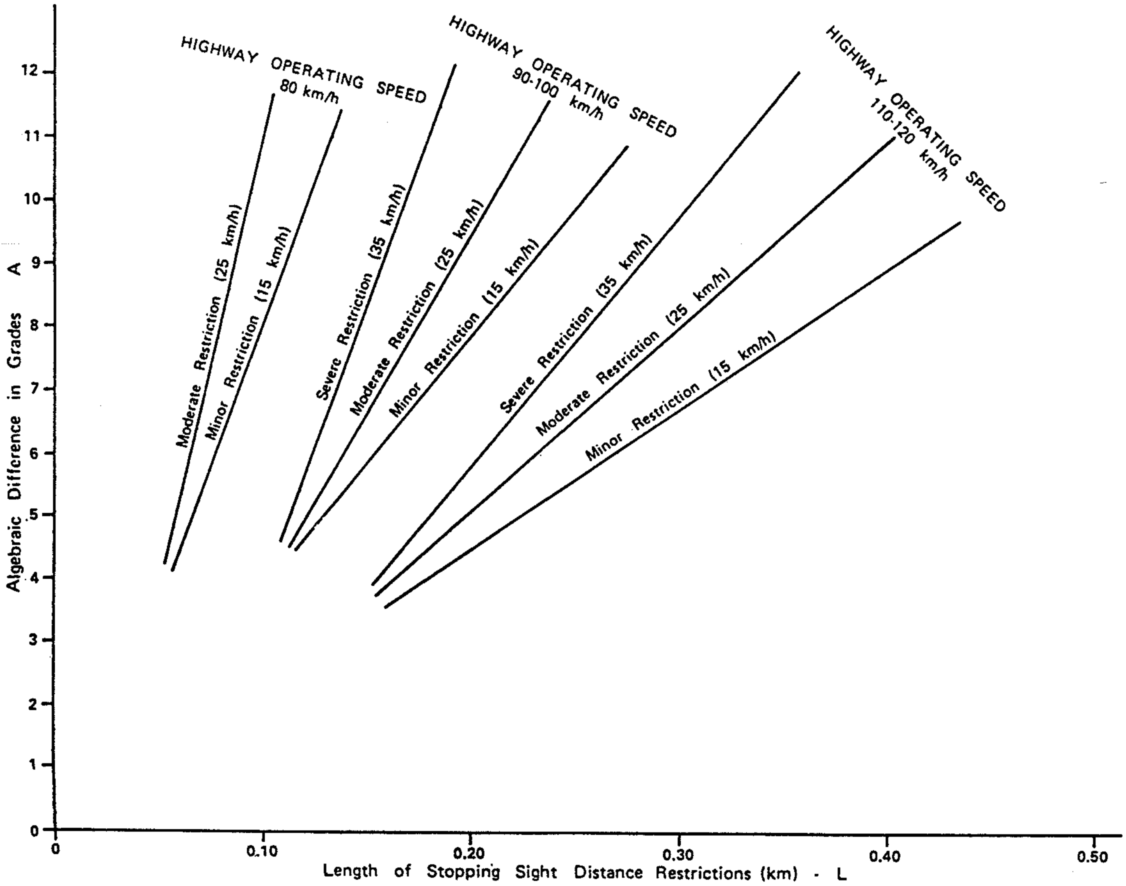

Table 2. Hazard presented by geometric conditions within SSD deficiencies.

Relative Hazard	Geometric Condition
Minor	Tangent horizontal alignment Mild curvature (>600-m radius) Mild downgrade (<3 percent)
Significant	Low-volume intersection Intermediate curvature (300- to 600-m radius) Moderate downgrade (3 to 5 percent) Structure
Major	High-volume intersection Y-diverge on road Sharp curvature (<300-m radius) Steep downgrade (>5 percent) Narrow bridge Narrowed pavement Freeway lane drop Exit or entrance downstream along freeway

tions were built into the framework for evaluating safety benefits, which had the effect of firmly establishing upper limits on countermeasure effectiveness.

With these considerations, a matrix of accident rate reduction factors was developed to describe the hypothesized relations between accident rate and two basic descriptors of SSD conditions: (a) the severity of the restriction, and (b) the presence of other confounding geometric features within the restriction. The factors given in Table 4 for two-lane rural highways represent incremented multiples of the average accident rate for any facility type. These incremental factors were rationally selected to describe the variability in accident rate for all possible combinations of severity of SSD restriction and geometric features.

To illustrate the use of the data in Table 4, note that the greatest factor (4.0) represents a 35 km/h SSD deficiency and includes a major geometric hazard. Such a location is expected to have an accident rate of 5 times the average rate. Full treatment of both aspects (the geometric feature and the severity of SSD restriction) would presumably reduce the rate to the average (1.0). Thus the increment of accident rate attributable to the SSD restriction and the prevailing geometric hazard is 5.0 - 1.0, or 4.0 times the average.

The other tabular entries in Table 4 are rationalizations. An average location, i.e., one that does not have a confounding geometric feature but does have adequate SSD, has an incremental factor of 0, which indicates that SSD does not contribute to the accident rate. Similarly, a highway section that does not have SSD deficiencies but does have a major geometric hazard (such as a high-volume intersection) is expected to have an accident rate twice the average (hence the factor 1.0).

The use of the data in Table 4 completes the analysis framework established to evaluate the accident-reduction effectiveness of countermeasures to SSD problem locations. The framework is defined by the following basic steps:

1. Definition of the highway type;
2. Selection of the appropriate average accident rate (R_h) from the data in Table 1;
3. Definition of the geometry at the location by (a) the severity of the SSD restriction from the

Table 3. Distribution of accidents on two-lane rural highways.

State	ADT	Sample Size	Mean Accident Rate, μ (accidents per million vehicle kilometers)	No. of Sites with Accident Rates		
				3μ	4μ	5μ
Florida	1,400-2,099	152	0.81	9	4	2
	2,100-3,099	160	0.75	4	2	1
	3,100-4,899	154	0.76	5	3	2
Ohio	1,400-2,099	251	2.20	1	1	0
	2,100-3,099	224	2.02	5	0	0
	3,100-4,899	181	1.97	1	0	0
Texas	1,400-2,099	328	1.14	13	4	2
	2,100-3,099	458	1.16	23	12	5
	3,100-4,899	274	1.11	9	5	2
Total		2,182		75[a]	31[b]	14[c]

Notes: Data are from an FHWA contract, "Effectiveness of Design Criteria for Geometric Elements."
ADT = average daily traffic.

[a] 3.4 percent. [b] 1.4 percent. [c] 0.6 percent.

Table 4. Hypothesized accident rate factors for evaluation of SSD restrictions.

Character of Geometric Condition within SSD Restriction	Severity of SSD Restriction by Vehicle Speed			
	0 km/h	15 km/h	25 km/h	35 km/h
Minor hazard	0	0.5	1.2	2.0
Significant hazard	0.4	1.1	2.0	3.0
Major hazard	1.0	1.8	2.8	4.0

Note: Factor multiplied by average accident rate is accident rate attributable to the combined effects of the roadway geometry and SSD restriction.

Table 5. Average cost per accident by highway type.

Highway Type	Avg Cost of Accident Resulting in Injury or Fatality[a] ($)	Avg Cost per Accident: All Accidents[a,b] ($)
Rural freeway	28,583	11,263
Rural two-lane highway	25,410	11,048
Urban freeway	14,221	4,584
Other urban	11,922	4,256

[a] Data from FHWA (13). [b] Data from AASHTO (11).

previously discussed in-text table, (b) the length of the SSD (L_r) restriction from the data in Figure 2, and (c) the hazard within the SSD restriction from the data in Table 2;

4. Determination of the accident rate factor (F_{ar}) from the data in Table 4;

5. Calculation of the contribution of the defined situation to the annual accident experience:

Annual number of accidents attributable to the SSD restriction = 365 ADT x (R_h x L_r x F_{ar} x 10^{-6}); and

6. Calculation of the accident-reduction effectiveness for the the various countermeasures.

The framework reveals differences in countermeasures based on their effects on the geometry of the location. Safety benefits achieved by increasing SSD (e.g., by lengthening vertical curves) are determined by reading laterally from right to left in Table 4. Similarly, safety benefits achieved by removing or mitigating the confounding geometric condition (e.g., by moving an intersection or flattening a horizontal curve within the SSD restriction) are determined by reading vertically up in Table 4.

CALCULATION OF SAFETY BENEFITS FROM REDUCTIONS IN ACCIDENT RATES

The basis of many benefit/cost and cost-effectiveness analyses is the dollar value assumed to accrue to society when an accident and injury or fatality is forestalled. In this research the dollar accident benefit from SSD improvements was compared to the costs of implementing these improvements.

The proper cost assignable to traffic accidents has been extensively debated. Given the nature of this study, conservative (high) dollar estimates of safety are appropriate. Therefore, NHTSA (12) societal costs of accidents were used. These costs, updated to 1980, are motor vehicle fatality = $358,408; motor vehicle injury = $3,974; and property-damage collision = $648.

Information from other sources (9) allowed the derivation of average costs per accident for all facility types, which are given in Table 5.

SPOT-IMPROVEMENT COUNTERMEASURES TO SSD SAFETY PROBLEMS

Locations that have SSD deficiencies can be treated with a wide range of countermeasures. These countermeasures may be classified in terms of their intended treatment of the problem. Spot-improvement countermeasures, such as lengthening vertical curves or removing trees or obstructions on the inside of horizontal curves, increase SSD and thereby eliminate the hazard. Considering the basic analysis framework for SSD accidents, it is apparent that other countermeasures are also available. For example, a safer condition can be created by treating a geometric feature within the SSD restriction; i.e., by moving an intersection or flattening a horizontal curve hidden by a crest vertical curve, the accident potential should be reduced.

The data in Table 6 give the countermeasures considered in this research, which represent the geometric and operational improvements available for all basic highway types.

Calculation of Costs of Implementing SSD Countermeasures

Cost-effectiveness evaluations of the countermeasures given in Table 6 required estimates of their cost. Construction cost estimates based on 1980 unit costs were computed for each countermeasure. The data in Tables 7 and 8 summarize the costs of construction for the countermeasures studied. Implementation costs for most of the countermeasures vary with the assumed initial geometric condition and the increment of improvement. Note that the most severe SSD cases (e.g., large A values for

Table 6. Countermeasures to sight-distance safety problems.

	Countermeasures Designed to	
Highway Type	Increase SSD	Reduce Hazard Within SSD Restriction
Rural Interstate	Lengthen vertical curve Increase cut along inside of curve	Move entrance or exit
Rural two-lane highway	Lengthen vertical curve Remove trees; increase cut along inside of horizontal curve Flatten one or more grades	Flatten horizontal curve within SSD restriction Move intersection Move Y-diverge Widen narrow bridge Widen roadway Signing and delineation
Urban Interstate	Flatten horizontal curve Widen median; remove median barrier; or special median design Lengthen vertical curve Increase offset to retaining wall	Move entrance or exit Flatten horizontal curve Variable message signing Marking or signing schemes on median shoulders
Urban arterial	Lengthen vertical curve	Signalize intersection Signing or marking schemes

Table 7. Costs of construction and implementation for SSD countermeasures on two-lane rural highways.

Countermeasure	Cost of Construction and Implementation ($)
Lengthen vertical curve	
Low A	
15 km/h increase in SSD	120,000-170,000
35 km/h increase in SSD	125,000-185,000
Moderate A	
15 km/h increase in SSD	185,000-270,000
35 km/h increase in SSD	200,000-300,000
High A	
15 km/h increase in SSD	270,000-320,000
35 km/h increase in SSD	300,000-350,000
Clear trees or brush from inside horizontal curve	
15 km/h increase in SSD	3,000-6,000
35 km/h increase in SSD	9,500-15,000
Flatten horizontal curve within SSD restriction	150,000-200,000
Move intersection on Y-diverge away from SSD restriction	120,000-220,000
Widen roadway at crest vertical curve	70,000
Widen narrow structure	—[a]

[a] Generally prohibitive.

Table 8. Costs of construction and implementation for SSD countermeasures on urban freeways.

Countermeasure	Cost of Construction and Implementation ($)
Lengthen vertical curve	
Low A	
15 km/h increase in SSD	500,000
35 km/h increase in SSD	820,000
Moderate A	
15 km/h increase in SSD	870,000
35 km/h increase in SSD	1,270,000
High A, 15 km/h increase in SSD	1,300,000
Move entrance or exit ramp	500,000
Remove horizontal obstructions	200,000-300,000
Install real-time variable message signing	20,000
Redesign of median barrier (offset from centerline) or horizontal curve	60,000-100,000
Signing, marking, or delineation	—[a]

[a] Nominal.

vertical curves and 35 km/h deficiency) are the most costly to improve.

Conversion of Costs to Annual Basis

In performing cost-effectiveness analyses based on annual accident benefits, all construction costs must be annualized. This requires an estimate of the useful life for all elements of the highway. For the types of projects considered in this study, earthwork and roadbed construction were assigned a 40-yr life. The useful life of pavements was assumed to be 20 yr. Thus all current annual construction costs represent complete construction, with reconstruction of the pavement after 20 yr.

If a discount rate of 10 percent is used, the following factors apply:

Present worth (PW) of amount 20 yr hence = PW at 10 percent, 20 yr = 0.148644.

Annual share [capital recovery (CR)] of present amount over 40 yr = CR at 10 percent, 40 yr = 0.102259.

RESULTS OF COST-EFFECTIVENESS ANALYSES OF SSD SPOT-IMPROVEMENT COUNTERMEASURES

Application of the cost-effectiveness framework and all cost estimates yields a complete picture on the nature of countermeasures to SSD safety problems. One basic conclusion is apparent, regardless of facility type:

> Only countermeasures that are relatively inexpensive to implement as spot improvements hold the potential for cost-effectiveness for typical traffic volumes on each type of highway.

The reasons for this basic conclusion are apparent when all the aspects of SSD safety are considered. First, deficient SSD is generally the result of a basic geometric deficiency, which is usually costly to correct. Second, the length of highway over which the deficiency affects operations is in most cases relatively short (for vertical SSD restrictions, the worse the deficiency, the shorter the length of highway affected). Such situations would therefore not have a large number of annual accidents, despite having a large incremental rate attributable to the deficiency.

The data in Tables 9 and 10 summarize the cost-effectiveness analyses of spot improvements to SSD problems. The potential cost-effectiveness of SSD safety countermeasures was determined by comparing the hypothesized dollar accident benefits with the annualized construction costs. A benefit/cost ratio of 1.0 or greater indicated potential cost-effectiveness. Because accident benefits are a function of accident rate and traffic volume, the analyses identified traffic volume levels at which cost-effectiveness was achieved.

A number of significant points should be considered when reviewing the data in Tables 9 and 10. It is important to retain a perspective on the concept of cost-effectiveness as it is applied to decision making. In this study countermeasures whose potential annual benefits exceeded annual costs were identified as cost effective. However, this does not necessarily identify them as economically feasible or even desirable. The implementation of projects or programs also depends on other factors, such as available funding and the economic returns provided by competing projects. The net result may be that benefit/cost ratios much greater than 1.0 are required for implementation of certain countermeasures.

Table 9. Cost-effectiveness of spot-improvement countermeasures to SSD safety problems on rural highways.

Countermeasure	ADT Level Required for Potential Cost-Effectiveness	Geometric, Operational, and Traffic Conditions	Notes
Two-lane highways			
Lengthen vertical curve with a 25 km/h deficiency in SSD	13,000-15,000 17,000-19,000	Significant hazard within SSD restriction Minor hazard within SSD restriction	
Lengthen vertical curve with a 35 km/h deficiency in SSD	10,000-14,000 13,000-17,000	Significant hazard within SSD restriction Minor hazard within SSD restriction	
Flatten sharp horizontal curve within a SSD deficiency	11,000-12,000	Design speed of curve at least 25 km/h lower than design speed of highway	
Clear trees or minor obstructions from inside of horizontal curves	200-400	At least 25 km/h SSD deficiency	
Cut earth from inside of horizontal curve	500-1,000	At least 25 km/h SSD deficiency	
Move intersection or Y-diverge away from SSD restriction			Not cost effective under typical geometric, operational, or traffic conditions
Widen roadway at very short crest vertical curve		Very narrow, low-volume minor roads	Not cost effective
Widen narrow bridge within SSD deficiency			Not cost effective under typical geometric, operational, or traffic conditions
Warning signs, delineation, and pavement-marking schemes	Any level	Minor hazard within 25 to 35 km/h SSD restriction; significant or major hazard within 15 to 35 km/h SSD restriction	
Freeways			
Lengthen vertical curve			Not cost effective under typical geometric, operational, or traffic conditions
Cut earth or rock from inside of horizontal curve			Not cost-effective under typical geometric, operational, or traffic conditions
Move entrance or exit ramp away from SSD			Not cost-effective under typical geometric, operational, or traffic conditions

Table 10. Cost-effectiveness of spot-improvement countermeasures to SSD safety problems on urban freeways.

Countermeasure	ADT Level Required for Potential Cost-Effectiveness	Geometric, Operational, and Traffic Conditions	Notes
Arterial streets			
Lengthen vertical curve			Not cost effective under typical geometric, operational, or traffic conditions
Warning signs, delineation, and pavement-marking schemes			Probably cost effective under all typical geometric, operational, or traffic conditions
Signalization			Cost-effectiveness analysis not performed; Manual on Uniform Traffic Control Devices warrants apply
Freeways			
Lengthen vertical curve with a 15 km/h deficiency in SSD	150,000-175,000	Significant hazard within SSD restriction	
Move entrance or exit ramps away from SSD deficiency of 15 to 35 km/h	200,000-225,000		
Rebuild retaining wall to increase horizonal SSD			Not cost effective under typical geometric, operational, or traffic conditions
Flatten sharp horizontal curve within a SSD deficiency			Not cost effective under typical geometric, operational, or traffic conditions
Widen median at controlling curves with narrow medians and barriers			Not cost effective under typical geometric, operational, or traffic conditions
Variable message signing (real time) near SSD deficiencies			Probably cost effective under all typical geometric, operational, or traffic conditions
Marking and signing schemes on median shoulders in horizontal curves			Probably cost effective under all typical geometric, operational, or traffic conditions
Shift median barrier at controlling curves within existing median width	30,000 0	Typical lengths of controlling horizontal curves	

The final determination of potential cost-effectiveness must be tempered by several other considerations, which include costs and benefits not directly included in the analysis but are presumed to apply. In this study only readily identifiable construction costs and accident benefits were applied. Other costs that would be significant on high-volume roadways include the delay to traffic during construction and the direct costs of maintaining traffic. Additional benefits also accrue to those alternatives where significant alignment changes are made. Reductions in vehicle operating costs are expected on flatter grades, longer vertical curves, and milder horizontal curves.

OTHER CONSIDERATIONS IN SAFETY DESIGN OF SSD

Two other aspects of SSD safety problems are also of interest. The first concerns the general issue of rehabilitation or reconstruction and its effect on decision making toward treatment of SSD safety problems. The second aspect concerns new designs and construction.

Implementation of SSD Countermeasures During Rehabilitation or Reconstruction

The scheduling of a rehabilitation project for a highway produces an opportunity to identify and treat SSD-deficient locations. In such cases the concept of cost-effectiveness results in quite different answers when compared with the analysis of SSD countermeasures as spot improvements. This is true because the separate decision to invest in reconstruction may result in a reduced incremental cost required to simultaneously treat a SSD problem.

An analysis was performed of the cost-effectiveness of implementing SSD safety countermeasures within a planned rehabilitation project. In such cases certain cost items required for rehabilitation need not be included as costs of treating the SSD problem. (One example is the cost of replacing the pavement, assuming the entire roadway is to be rebuilt.) These implications are important; countermeasures that are not cost effective as spot improvements may be so when incorporated into a planned rehabilitation effort. As an example, consider the basic question of lengthening a vertical curve to increase SSD on a two-lane rural highway. If only earthwork and a portion of drainage and engineering costs are assumed to apply, the percentage of full costs to perform the SSD improvement is estimated as shown in the following table:

Difference in Grades, A	Percentage of Full Cost Applicable under Rehabilitation Project
4	20
6	30
8	40

(Note that for this table that the full-cost basis includes all pavement removal, earthwork, new pavement, and shoulder, drainage, signing, and engineering; and that the cost basis as a part of rehabilitation includes some pavement removal, earthwork, and a portion of drainage and engineering.)

Consequently, the ADT levels required to justify treatments such as lengthening vertical curves are significantly lower within the context of a planned rehabilitation project.

The data in Tables 11 and 12 summarize the estimated cost-effectiveness of countermeasures implemented during a planned rehabilitation project. In some cases the ADT level required to justify a countermeasure is identical to that given in Tables 9 and 10. This reflects the judgment that none of the costs of construction and implementation of the SSD countermeasure would be incurred if the SSD deficiency is not treated. In other cases ADT levels are somewhat lower for implementation within a rehabilitation project. This results from the assignment of significant costs (for example, new pavement) to the necessary rehabilitation, which thereby lowers the marginal cost of treating the SSD deficiency.

SSD Safety in Planning and Design for New Highways

Although many of the countermeasures studied did not offer potential cost-effectiveness as spot improvements or within a rehabilitation context, their application is recommended wherever possible during the planning and design phase of new construction. The operational framework for SSD presented in this paper affords the highway designer the opportunity to rationally plan and design for special situations not explicitly covered by AASHTO design policy (14-16). Provision for additional SSD at critical locations, special design values for highways with high truck volumes, and consideration of all geometry in the design of SSD are all indicated by the research. The important point is that such design sensitivity to the varying requirements and criticality of SSD can result in a better design at no incremental cost when it is applied in the initial design stage.

CONCLUSIONS

An analysis of the potential cost-effectiveness of treating deficient SSD has been presented. A rational framework was established that described the accident potential of SSD-deficient locations. The elements of the framework included (a) type of highway, (b) traffic volumes, (c) severity of the SSD deficiency, (d) presence of other conditions or confounding geometry within the area of deficient SSD, and (e) length of highway with less-than-adequate SSD.

Table 11. Cost-effectiveness of countermeasures to SSD safety problems incorporated within planned rehabilitation projects on rural highways.

Countermeasure	ADT Level Required for Potential Cost-Effectiveness	Geometric, Operational, and Traffic Conditions	Notes
Two-lane highways			
Lengthen vertical curve with a 35 km/h deficiency in SSD	4,000-5,000	Significant hazard within SSD restriction	
Lengthen vertical curve with a 25 km/h deficiency in SSD	5,000-6,000 6,000-7,000	Significant hazard within SSD restriction Minor hazard within SSD restriction	
Flatten sharp horizontal curve within a SSD deficiency	11,000-12,000	Design speed of curve at least 25 km/h lower than design speed of highway	
Clear trees or minor obstructions from inside of horizontal curves	200-400	At least 25 km/h SSD deficiency	
Cut earth from inside of horizontal curve	500-1,000	At least 25 km/h SSD deficiency	
Move intersection or Y-diverge away from SSD restriction			Not cost effective under typical geometric, operational, or traffic conditions
Widen roadway at very short crest vertical curve		Very narrow, low-volume minor roads	Not cost effective Not cost effective under typical geometric, operational, or traffic conditions
Widen narrow bridge within SSD deficiency			
Warning signs, delineation, and pavement-marking schemes			Probably cost effective under all typical geometric, operational, or traffic conditions
Freeways			
Lengthen vertical curve			Not cost effective under typical geometric, operational, or traffic conditions
Cut earth or rock from inside of horizontal curve			Not cost effective under typical geometric, operational, or traffic conditions
Move entrance or exit ramp away from SSD deficiency			Not cost effective under typical geometric, operational, or traffic conditions

Table 12. Cost-effectiveness of countermeasures to SSD safety problems incorporated within planned rehabilitation projects on urban freeways.

Countermeasure	ADT Level Required for Potential Cost-Effectiveness	Geometric, Operational, and Traffic Conditions	Notes
Arterial streets			
Lengthen vertical curve			Not cost effective under typical geometric, operational, or traffic conditions
Warning signs, delineation, and pavement-marking schemes			Probably cost effective under all typical geometric, operational, or traffic conditions
Freeways			
Lengthen vertical curve with a 15 km/h deficiency in SSD	25,000	Significant hazard within SSD restriction	
Move entrance or exit ramps away from SSD deficiency of 15 km/h or more	40,000		
Rebuild retaining wall to increase horizontal SSD			Cost effectiveness is extremely variable and depends on the nature of the rehabilitation project and existing conditions
Flatten horizontal curve within a SSD deficiency			Not cost effective under typical geometric, operational, or traffic conditions
Widen median at controlling curves with narrow medians and barriers			Cost-effectiveness is extremely variable and depends on the nature of the rehabilitation project and existing conditions
Variable message signing (real time) near SSD deficiency			Probably cost effective under all typical geometric, operational, or traffic conditions
Marking and signing schemes on median shoulders in horizontal curves			Probably cost effective under all typical geometric, operational, or traffic conditions
Shift median barrier at controlling curve within existing median width			Probably cost effective under all typical geometric, operational, or traffic conditions

Three important findings resulted from the analysis.

1. Only inexpensive countermeasures such as clearing horizontal sight obstructions, signing, and delineation are potentially cost effective as spot improvements at locations with deficient SSD (based on AASHTO policy).
2. A greater potential for cost-effective treatment of SSD-deficient locations exists when a highway is planned for major rehabilitation or reconstruction. In such cases only the incremental costs of treating the SSD are attributable to a cost-effectiveness analysis. The result is that, for higher volume facilities, treatment of serious SSD deficiencies during rehabilitation may generally be cost effective. Also, inexpensive countermeasures such as clearing horizontal sight obstructions may be cost effective for a wide variety of site conditions.
3. Although many of the countermeasures studied were not potentially cost effective either as spot improvements or as part of a rehabilitation project, their application is recommended during the planning and design of new construction. The operational framework for SSD presented in this paper allows the highway designer to rationally plan and design for special situations not explicitly covered by AASHTO design policy. Provision for additional SSD at critical locations, special design values for highways with high truck volumes, and consideration of all geometric features in the design of SSD are all indicated by the research. The important point is that a sensitivity to the varying requirements and criticality of SSD can result in a better design at no incremental cost when it is applied in the initial design stage.

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