# *Effect of Alignment on Highway Safety*

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The highway designer working on the plans for a new highway will always strive for gentle highway alignment consisting of flat horizontal curves, noncritical grades, and long vertical curves. During the last 45 years, this process has been guided by the design policies of the American Association of State Highway and Transportation Officials (AASHTO), which has defined acceptable limits on these design features based on perceived safety and operational effects. Although cost-effectiveness has always been an underlying basis for design, these design limits have been largely governed by acceptable performance criteria rather than cost-effectiveness considerations.

When considering the safety enhancement of resurfacing, restoration, and rehabilitation (RRR) projects, the designer has a different perspective than when he is designing a new highway. Changes in existing alignment are very expensive and require careful cost-effectiveness comparisons with competing alternatives for funds. For this reason, it is important to know the expected safety benefits for any proposed changes to existing alignment.

This critical review of the literature was undertaken to synthesize the available knowledge on the relationships between highway alignment and safety in order to provide guidance in selecting cost-effective improvements that will enhance safety on RRR projects. This review was basically limited to the physical aspects of highway alignment that relate to vehicle dynamics. Another review evaluating the safety aspects of sight distance considers the safety relationship between alignment and stopping sight distance.

The available research on the accident effects of horizontal and vertical alignment is limited. A search of the literature produced 24 references that appear to have contributed to the state of knowledge. This body of literature is critically analyzed in the following sections of this paper.

## HIGHWAY CURVES

Highway curves are a necessary and important element of nearly all highways. Their form has evolved from what appeared to be reasonable to the builder's eye to the more modern geometrically designed form of a circular curve with superelevation, cross-slope transitions, and often spiral transitions.

Despite a reasonably well-conceived design procedure, which considers a tolerable level of lateral acceleration on the driver, highway curves continually show a tendency to be high-accident locations. Several studies have indicated that highway curves exhibit higher accident rates than tangent sections, and that the accident rate increases as the degree of curve increases. But degree of curve may be just one element that is interdependent with other elements that together contribute to accident rate. For example, the sharpest curves tend to be located on lower quality highways; those with narrow roadways, narrow shoulders, marginal sight distance, hazardous roadsides, and the like.

The highway curve is one of the most complex features on the highways. The elements or aspects of highway curves given in Table 1 are all potential candidates for study in relating highway design to safety.

TABLE 1 Elements of Highway Curves

| Element | Description |
|---|---|
| Horizontal alignment | Radius of curvature<br>Length of curve<br>Superelevation runoff length<br>Distribution of superelevation runoff between tangent and curve<br>Presence and length of transition<br>Stopping sight distance around curve |
| Cross sectional | Superelevation rate<br>Roadway width<br>Shoulder width<br>Shoulder slope<br>Roadside slope<br>Clear-zone width |
| Vertical alignment | Coordination of edge profiles<br>Stopping sight distance on approach<br>Presence and length of contiguous grades<br>Presence and length of contiguous vertical curves |
| Other | Distance to adjacent highway curves<br>Distance to nearest intersection<br>Presence and width of contiguous bridges<br>Level of pavement friction<br>Presence and type of traffic control devices<br>Type of shoulder material |

### Characteristics of Highway Curve Accidents

Few studies have attempted to characterize the accidents that occur on highway curves. A 1983 study of four states by Glennon et al. compared the accident experience on 3,304 rural two-lane curve segments to 253 rural two-lane tangent segments *(1)*. Each segment was 0.6 mi long and was carefully selected to minimize variance associated with intersections, bridges, nearby urban development, and nearby curvature. Figure 1 shows a summary of the significant characteristics of accidents on highway curves in this data base.

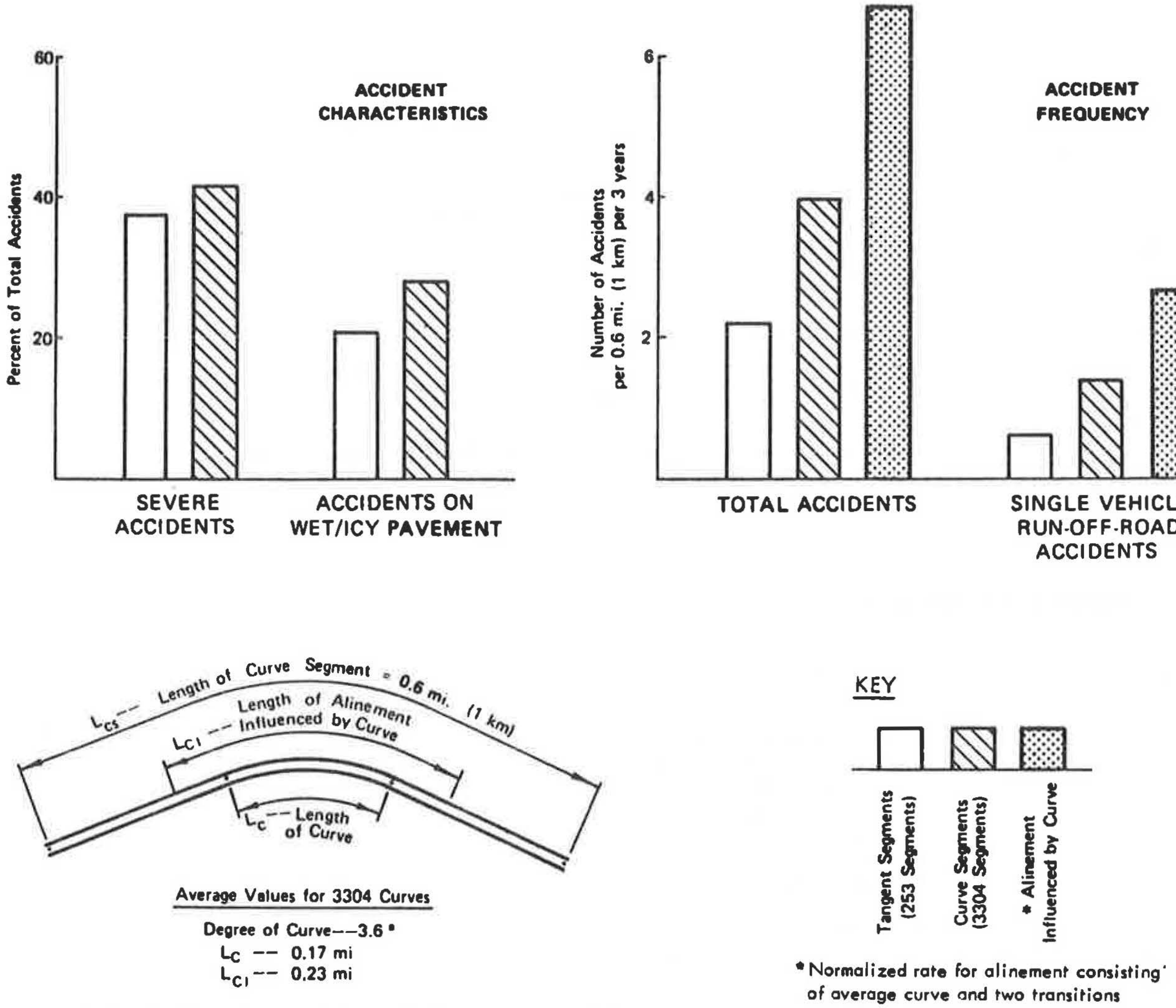

*FIGURE 1 Accident characteristics on highway curves* (1).

For example, curve segments have higher proportions of severe, wet-icy, and single-vehicle run-off-road accidents. Also, the accident rates on tangent and curve segments were used to compute an effective rate over a portion of the curve segments that included only the length of curve plus 150-ft transitions at each end of the curve. This computation yielded the following conclusions:

1. The average accident rate for highway curves is about three times the average accident rate for highway tangents.
2. The average single-vehicle run-off-road accident rate for highway curves is about four times the average single-vehicle run-off-road accident rate for highway tangents.

Although these conclusions are general, and may vary considerably by degree and length of curve, they do show that curves are substantially more hazardous than tangents and that single-vehicle run-off-road accidents are a prevalent aspect of curves. Another study by Perchonok et al. further defines the characteristics of single-vehicle run-off-road accidents on curves as follows *(2)*:

| *Degree of Curve* | *Percentage of Run-Off-Road Accidents* | |
|---|---|---|
| | *Outside* | *Inside* |
| 0–4 | 67 | 33 |
| 4.1–8 | 74 | 26 |
| 8.1–12 | 78 | 22 |
| Above 12 | 84 | 16 |

When considering roadside safety countermeasures on curves, this table indicates a much stronger need for treatment on the outside of the curve.

## Relationship of Accident Rate to Degree of Curve

Past research has generally indicated increasing accident rates with increasing degrees of curve. Figure 2, prepared by Jack E. Leisch and Associates *(3)*, shows the results of five studies *(4–8)*. Although these studies represent different road types and countries, there appears to be some general concurrence in their findings, however, they all have most of the following deficiencies:

1. The effect of traffic volume on accident rates and its intercorrelations with degree of curve was neither controlled nor accounted for.
2. One-year accident periods were too short to provide stable accident samples for highway curves.
3. Accident rates were computed by degree of curve ignoring the accident effects of length of curve. However, because curve length was used as part of the exposure base

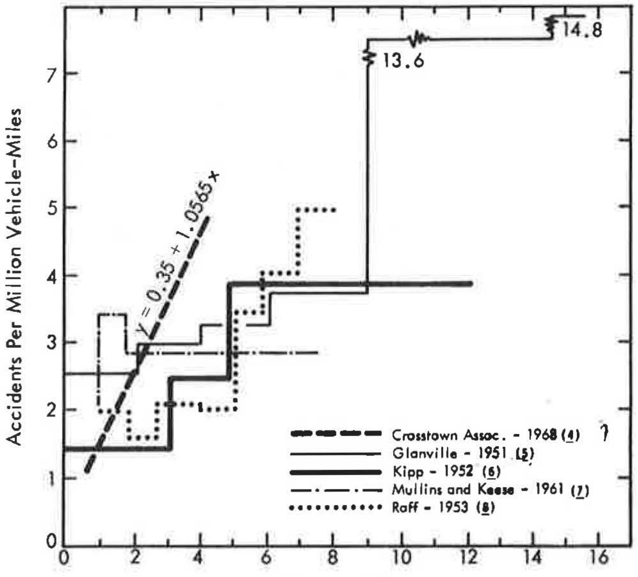

FIGURE 2 *Accident rate related to horizontal curvature* (8).

in the accident rate calculation, bias was introduced because sharp curves are usually short and flat curves are usually longer.

4. The accident effects of superelevation, lane width, shoulder width, sight distance, approach conditions, contiguous grades, intersections, and structures were not controlled or accounted for. That some of these elements are important was generally demonstrated by Kihlberg and Tharp who showed that intersections, grades, and structures increased accident rates on curves *(9)*. Also, many of the features mentioned earlier tend to be intercorrelated with degree of curve. In other words, sharp curves tend to be located on otherwise poorly designed roadways and flat curves tend to be located on otherwise well-designed roadways.

5. The accident effects of roadside hazards, slopes, and fixed objects, were not controlled or accounted for. These effects may be large when the proportion of roadside accidents on curves is considered. Roadside hazard is another feature that tends to be highly intercorrelated with degree of curve.

Other studies have considered highway curvature as one of several variables that potentially affects accident rates *(10–12)*. These studies have used either some form of multivariate analysis or a sufficiency rating scheme to identify the incremental effects of highway curvature. None of these studies offers any reliable method of determining the accident effects of changing horizontal curves.

A recent study that performed analysis of covariance on 0.6-mi sections that included one curve may shed some light on the net accident reduction associated with curve flattening *(1)*. Although the analysis of covariance results did not indicate any strong relationships, the raw regression found between the accident rate on the section and the degree of curve can be used as a comparison with the five studies cited in Figure 2. This regression indicates a net accident reduction such that the effect on accident rate, $\Delta R$, of a change in degree of curve, $\Delta D_c$, is

$$\Delta R = 0.056\,\Delta D_c \tag{1}$$

Although this study used a 3-year accident period and more effectively measured net accident difference than the studies cited in Figure 2, most of the same caveats listed for these studies would also apply here.

In 1982 the Illinois Department of Transportation conducted a cost-effectiveness analysis of highway curve rehabilitation projects. Two-year, before-after accident comparisons were made on eight highway curves ranging from 4.0 to 10.7 degrees that were reconstructed to include curves ranging from 2.5 to 5.0 degrees *(13)*. Although the study found a 61 percent mean reduction in accident rates, it is not clear over what lengths these rates were calculated. Also, the reported accident effects may very well be influenced by features other than curvature that were improved, including lane width, shoulder width, superelevation, skid surface, and the like.

### Computing Accident Reductions from Available Relationships

The accident effects of highway curves is one of the most misunderstood areas of highway safety. Perhaps the most confounding aspect is the interaction between degree and length of curve. To truly evaluate the safety effectiveness of curve flattening, the net safety effect must be calculated over the total length of highway changed rather than the lengths of curves themselves.

To illustrate the misunderstanding that can be generated by this confounding effect, consider a fairly liberal interpretation of the results in Figure 2, which indicate that accident rate, $R$, is related to degree of curve, $D_c$, such that $R = 0.4 + D_c$. Using this relationship unconditionally, when a 10-degree curve is flattened to 5 degrees, the curve accident rate is reduced from 10.4 to 5.4 accidents per million vehicle miles. But this comparison is not reasonable because, for a given central angle, when the degree of curve is reduced by one-half, the length of curve is doubled. Therefore, the net safety effect along the highway must be analyzed over the total length of highway affected by the change. If, in the example, the original length of curve was 500 ft, the final length of curve would be 1,000 ft. Therefore, if the preceding accident rate relationship is true, 1,000 ft of 5-degree curve with an accident rate of 5.4 must be compared with the combination of 500 ft of 10-degree curve with a rate of 10.4, and 500 ft of tangent section must be compared with a rate of 0.4. The combined rate for this "before" condition is 5.4 accidents per million vehicle miles and, for this example, flattening the curve would be expected to produce a zero net accident reduction.

Under the preceding example, the same net result is evident for any combination of before-and-after curvature. Although this result would appear to make flattening curves a totally futile proposition, remember that the studies cited predicted the relationship between accident rate and degree of curve while ignoring the confounding effect of length of curve. To truly evaluate the net accident effects of curve flattening requires knowledge of the accident rates for tangent and curve sections by both length and degree of curve.

That the results of the previously cited studies are influenced by the distribution of curve lengths in each data base is illustrated by the data in Table 2, which show the distribution of curve lengths by degree of curve in the data base collected by Glennon et al. *(1)*. These data, which represent every available curve segment in the sampled areas that met study constraints, show a very strong inverse relationship between degree of curve and length of curve. More particularly, sharp curves tend to be short and flat curves tend to be long.

TABLE 2 Distribution of Curve Analysis Segments by Degree and Length of Curve *(1)*

| Length of Curve (mi) | Number of Segments by Degree of Curve (deg) | | | | | | Average Curvature (deg)[a] |
|---|---|---|---|---|---|---|---|
| | <1.00 | 1.00–2.99 | 3.00–4.99 | 5.00–7.99 | ≥8.00 | Total | |
| <0.100 | 104 | 272 | 124 | 218 | 385 | 1,103 | 5.8 |
| 0.100–0.199 | 236 | 571 | 198 | 108 | 40 | 1,153 | 2.7 |
| 0.200–0.299 | 113 | 383 | 99 | 18 | 6 | 619 | 2.3 |
| ≥0.300 | 79 | 313 | 31 | 5 | 1 | 429 | 1.9 |
| Total | 532 | 1,539 | 452 | 349 | 432 | 3,304 | 3.6 |
| Average length[b] | 0.20 | 0.20 | 0.15 | 0.10 | 0.05 | 0.15 | |

[a] Rounded to nearest 0.1 degree of curvature.
[b] Rounded to nearest 0.05 mi.

The studies analyzed may provide a practical range for the net accident reduction that might be expected from curve flattening. If the five studies cited in Figure 2 indicate that zero may be a lower bound, then the Glennon et al. study might indicate an upper bound. Using the standard accident rate formula, the previously cited relationship for net accident rate reduction can be transformed to the more practical relationship as follows *(1)*:

$$\Delta A = \frac{(\Delta D_c)\ (\text{ADT})}{81{,}540} \qquad (2)$$

where

$\Delta A$ = the net number of accidents reduced per year,
$\Delta D_c$ = the change in degree of curve, and
ADT = average daily traffic.

This net accident effect can be illustrated by the following example:

| | *Existing Condition* | *Improvement* |
|---|---|---|
| Degree of curve | 10 degrees | 5 degrees |
| Analysis period | 10 years (before) | 10 years (after) |
| Average ADT | 5,000 | 5,000 (projected) |
| Number of accidents | 30 | 26.9 (calculated) |

The analysis of this section shows a definite trade-off between degree and length of curve. Although most designers would agree that flatter curvature is more desirable, the effect of trading more curved roadway for tangent roadway can negate some of the advantage of the flatter curve.

### Roadside Features as a Predominant Accident Factor on Highway Curves

As part of a multifaceted investigation of the safety of highway curves, Glennon et al. conducted an additional analysis of the 3,304, 0.6-mi curve segments *(1)*. In an attempt to maximize the potential for discovering accident relationships, two groups of sites were selected on the basis of either a very high or a very low accident rate. Differences in the geometric characteristics of these high- and low-accident populations were then investigated.

The sites were partitioned into three ADT classes to control for any effects of traffic volume. Sites that had accident rates at least twice the mean rate for that state's ADT class were designated as high-accident sites. For all but the highest ADT class, low-accident sites experienced no accidents over a 3-year period. A total of 330 sites that had extreme accident histories was thus selected.

Field measurements were taken at all 330 sites to further define their geometric and environmental features. The formal analysis of the high- and low-accident sites used a statistical technique known as discriminant analysis, which is used to statistically distinguish between two or more populations. The discriminating variables were the geometric and environmental features measured in the field.

Discriminant analysis distinguishes between the populations being studied by forming a linear combination of the discriminating variables whose value is $D$. The best-derived discriminant function is shown in Figure 3. Roadside rating is developed from Table 3, and the pavement rating is a measure of pavement skid resistance, SN60.

The relative discriminating power of the variables in the discriminant equation is shown in the following table. For example, the roadside rating, *RR*, contributes twice as much as the pavement rating, *PR,* to the ability to distinguish between high and low accident sites.

| *Variable* | *Relative Discriminating Power* |
|---|---|
| Roadside rating, *RR* | 2.1 |
| Shoulder width, *SW* | 1.4 |
| Length of curve, *LC* | 1.4 |
| Degree of curve, *DC* | 1.1 |
| Pavement rating, *PR* | 1.0 |

The discriminant analysis procedure predicts or classifies a site as being a high- or low-accident site based on the distribution of *D* values for the two groups. The procedure decides on whether each *D* score belongs to the high or low distribution by calculating if its probability is more or less than 50 percent. Using this criterion, the discriminant analysis procedure correctly classified 76 percent of the high-accident sites and 60 percent of the low-accident sites.

The value of discriminant analysis is primarily in its ability to predict high-accident locations. Because the *D* score distributions of the high- and low-accident sites overlap considerably, it is probably more efficient to concentrate on sites that have relatively high probabilities of being high-accident sites.

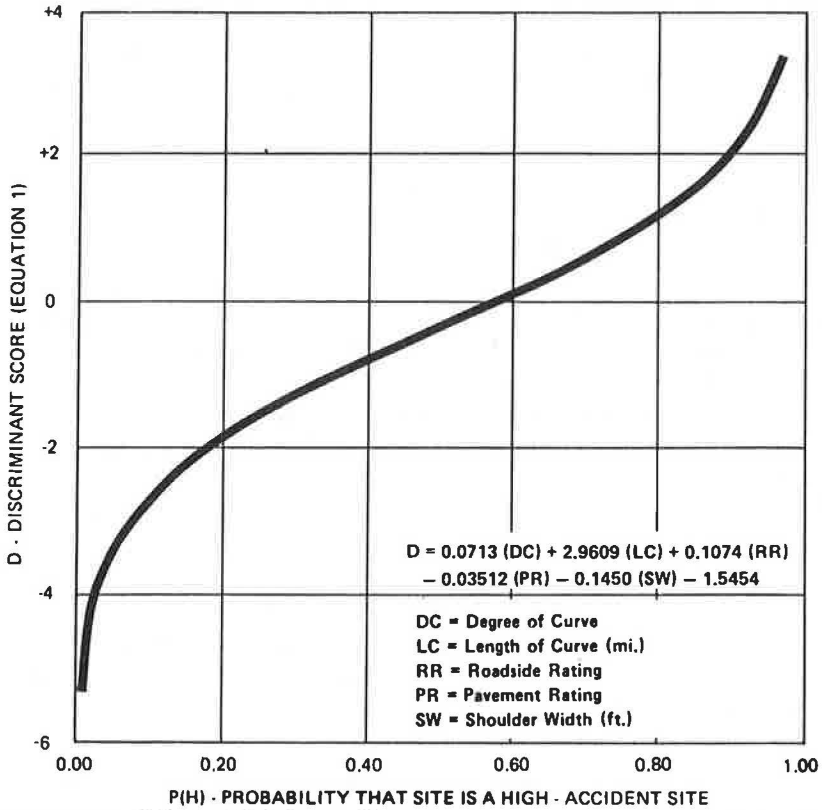

FIGURE 3 *Relationship between discriminant score and the probability that a site is a high-accident site* (1).

TABLE 3 Roadside Hazard Rating *(1)*

| Side Slope | Coverage Factor[a] | Lateral Clear Width (ft) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 30 | 25 | 20 | 15 | 10 | 5 | 0 |
| 6:1 or flatter | 90 | 24 | 28 | 32 | 34 | 42 | 46 | 47 |
| | 60 | 24 | 27 | 29 | 30 | 35 | 38 | 39 |
| | 40 | 24 | 27 | 27 | 27 | 32 | 34 | 34 |
| | 10 | 24 | 24 | 24 | 24 | 25 | 26 | 26 |
| 4:1 | 90 | 35 | 37 | 39 | 41 | 44 | 48 | 49 |
| | 60 | 35 | 36 | 38 | 39 | 40 | 43 | 44 |
| | 40 | 35 | 36 | 37 | 37 | 39 | 41 | 41 |
| | 10 | 35 | 35 | 35 | 35 | 36 | 37 | 37 |
| 3:1 | 90 | 41 | 42 | 42 | 43 | 44 | 48 | 49 |
| | 60 | 41 | 42 | 42 | 42 | 43 | 45 | 46 |
| | 40 | 41 | 42 | 42 | 41 | 41 | 44 | 45 |
| | 10 | 41 | 42 | 42 | 41 | 41 | 42 | 42 |
| 2:1 or steeper | 90 | 53 | 53 | 53 | 53 | 45 | 49 | 50 |
| | 60 | 53 | 53 | 53 | 53 | 46 | 49 | 50 |
| | 40 | 53 | 53 | 53 | 53 | 48 | 50 | 50 |
| | 10 | 53 | 53 | 53 | 53 | 50 | 50 | 50 |

NOTE: The roadside hazard rating represents the probability of an injury or fatal accident (%), given a roadside encroachment as defined by Glennon *(14)*.

[a] The coverage factor represents the probability of impact with a fixed object (%), given a certain lateral displacement as defined by Glennon *(14)*.

The procedure enables analysis of any probability criterion level. Figure 3 shows the relation between *D* score and *P(H)*, the probability that a site is a high-accident site. Selection of any *P(H)* criterion level can be translated into a minimum *D* score for analysis purposes.

A *P(H)* criterion of 80 percent was chosen for further study. The criterion classified 46 of the 330 study sites as high-accident sites with 42 of the 46 being correctly classified. As observed from the data in Table 4, with this criterion it appears that almost all sites that have high roadside hazards would qualify as high-accident sites. Likewise, almost all sites that have low roadside hazards would not qualify. The results are more mixed with moderate roadside hazards. Generally, moderate roadside hazards must be combined with either very sharp curvature or a combination of two variables that are moderate or worse.

For application at existing curves, the discriminant analysis indicates that improving roadside design, pavement skid resistance, and shoulder width may be candidate countermeasures. The reduction of curvature may not be practical or productive because of high costs and the apparent trade-off between degree and length of curve for a given central angle. This study also suggests that other design deficiencies, such as extremely unsatisfactory approach sight distances, narrow lanes, transitions, and extreme shoulder slope breaks, might be considered in an improvement program.

Glennon et al. also conducted a cost-effectiveness analysis of highway curve improvements by developing a rational relationship between accident rate for a 0.6-mi highway segment (with a curve) and the probability that the segment is a high-accident location *(1)*. Figure 4 shows this relationship, which was based on relating accident rates to discriminant scores and on an intuitive link between their large data base of 3,304 curve segments and their smaller data base of 330 high- and low-accident curve segments.

The effectiveness of highway curve improvements can be evaluated by combining the relationships shown in Figures 3 and 4 and the discriminant equation shown in Figure 4 as follows:

1. Compute the *D* score for the existing highway curve and determine from Figure 3 its probability of being a high-accident location.
2. Compute the *D* score for the proposed improved highway curve and determine its probability of being a high-accident location.
3. Compute the accident rate reduction over a 0.6-mi highway segment for the improvement using Figure 4.
4. Compute the net accident reduction for the improvement using Equation 3.

$$\Delta A = \frac{(\Delta R)\ (\text{ADT})}{4{,}566} \tag{3}$$

where

$\Delta A$ = net accident reduction per year for the improvement;
$\Delta R$ = change in accident rate per 0.6-mi segment, accidents per million vehicle miles; and
ADT = average daily traffic.

## Cross-slope Breaks on Highway Curves

The cross-slope break is the difference between pavement and shoulder slopes. For the outside of highway curves, AASHTO policy limits the cross-slope break to 8 percent, which in turn puts constraints on either the maximum superelevation rate or the amount of shoulder slope *(15)*. Under this criterion, if the selected superelevation rate is 6 percent, the maximum outside shoulder slope is –2 percent. If, however, the selected

TABLE 4 Percent Probability that a Curve Segment is a High-Accident Location *(1)*

| | Shoulder | Degree of Curve | | | | |
|---|---|---|---|---|---|---|
| Curve Length (mi) | Width (ft) | 1 | 3 | 6 | 12 | 20 |
| Low Roadside Hazard Rating (*RR* = 20)/Low Pavement Rating (*PR* = 20) | | | | | | |
| Long (0.30) | 0 | 75 | 77 | 80 | 86 | 91 |
| | 8 | 50 | 53 | 60 | 70 | 78 |
| Moderate (0.17) | 0 | 68 | 71 | 75 | 84 | 89 |
| | 8 | 42 | 45 | 52 | 61 | 71 |
| Short (0.05) | 0 | 61 | 64 | 68 | 77 | 85 |
| | 8 | 35 | 38 | 44 | 53 | 65 |
| Moderate Roadside Hazard Rating (*RR* = 35)/Moderate Pavement Rating (*PR* = 35) | | | | | | |
| Long (0.30) | 0 | 91 | 92 | 93 | 95 | 97 |
| | 8 | 73 | 79 | 82 | 87 | 92 |
| Moderate (0.17) | 0 | 87 | 89 | 90 | 93 | 96 |
| | 8 | 66 | 72 | 75 | 81 | 87 |
| Short (0.05) | 0 | 82 | 84 | 86 | 90 | 94 |
| | 8 | 59 | 65 | 68 | 74 | 82 |
| High Roadside Hazard Rating (*RR* = 50)/High Pavement Rating (*PR* = 50) | | | | | | |
| Long (0.30) | 0 | 94 | 95 | 95 | 97 | 98 |
| | 8 | 87 | 90 | 90 | 93 | 96 |
| Moderate (0.17) | 0 | 93 | 94 | 94 | 95 | 98 |
| | 8 | 84 | 87 | 87 | 90 | 95 |
| Short (0.05) | 0 | 91 | 93 | 93 | 94 | 97 |
| | 8 | 79 | 83 | 83 | 86 | 93 |

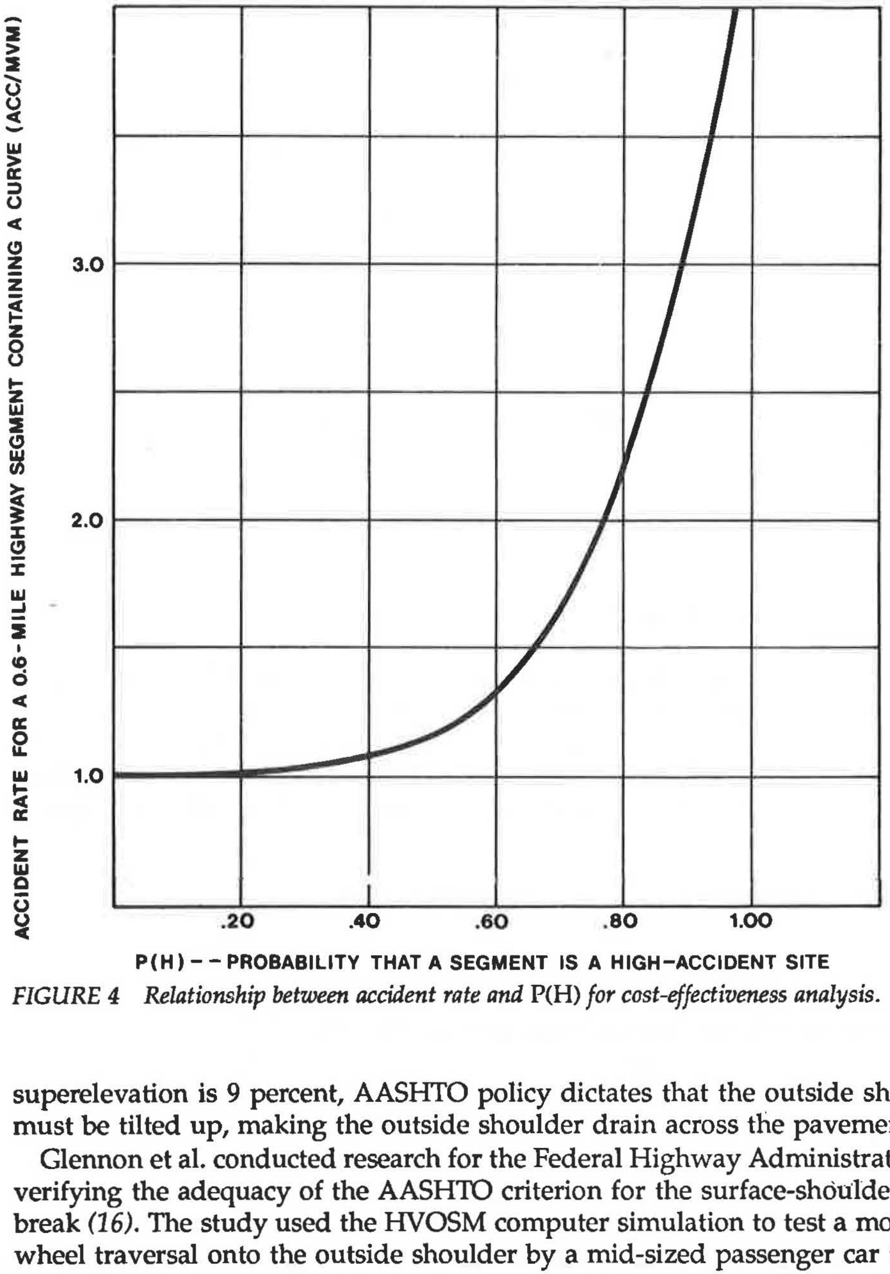

*FIGURE 4 Relationship between accident rate and* P(H) *for cost-effectiveness analysis.*

superelevation is 9 percent, AASHTO policy dictates that the outside shoulder slope must be tilted up, making the outside shoulder drain across the pavement.

Glennon et al. conducted research for the Federal Highway Administration aimed at verifying the adequacy of the AASHTO criterion for the surface-shoulder cross-slope break *(16)*. The study used the HVOSM computer simulation to test a moderate, four-wheel traversal onto the outside shoulder by a mid-sized passenger car traveling the controlling design speed of the highway curve. Recovery from the shoulder traversal was achieved by using the critical path measured by earlier field studies *(17)* on highway curves and a maximum driver discomfort factor of 0.3*g*'s.

For drivers who encroach onto the outside shoulder with a four-wheel traversal, the shoulder slope, rather than the cross-slope break, was found to be the critical design element. However, because of the relationship between radius and superelevation for controlling design curves, the relationship of critical vehicular dynamics to shoulder slope translates to a design criterion for cross-slope break of 8 percent for stabilized shoulders (6 ft or greater) that will accommodate a four-wheel recovery. This confirms the AASHTO criterion for full-width shoulders where a four-wheel traversal is possible.

For stabilized shoulders (5 ft or less) that will only accommodate a two-wheel traversal, the allowable cross-slope break increases as the shoulder becomes narrower as follows:

| *Shoulder Width (ft)* | *Allowable Cross-Slope Break (%)* |
|---|---|
| 5 | 9 |
| 4 | 12 |
| 3 | 15 |
| 2 or less | 18 |

These greater cross-slope breaks recognize the lesser "effective cross slope" experienced by a two-wheel vehicular recovery on a narrower shoulder that was not explicitly designed to accommodate a full four-wheel recovery. These greater allowable cross-slope breaks are particularly important in RRR highway improvements where either

1. The desire is to increase the superelevation on a roadway with a narrow shoulder and an existing 8 percent cross-slope break; or
2. The plan is to widen the traveled way at the expense of shoulder width, leaving shoulders that are 5 ft or less in width.

In both cases, the results of the referenced study indicate that greater cross-slopes do not compromise safety beyond the prior decision to allow the narrow shoulder.

### Other Factors Related to Highway Curve Safety

Over the years several authors have extolled the benefits of spiral transitions to highway curves. More recently, the combination of HVOSM computer simulation and field studies by Glennon et al. have strongly supported these arguments *(1)*. The field studies of path behavior on unspiraled curves indicate that drivers, in attempting to spiral their path from an infinite radius to the radius of the highway curve, always overshoot the curve radius thereby creating higher friction demands. HVOSM comparisons made on curves that were otherwise identical except for the presence of a spiral indicate that aggressive or inattentive drivers will experience a dramatic reduction in the maximum friction demand if a spiral transition is introduced.

The safety effects of curve warning signs and delineators have also been studied *(18–20)*. In 1980, Lyles examined the effectiveness of alternative advance warning sign configurations in reducing speeds on curves. He found that in spite of relatively large speed decreases near the beginning of the curve, no sign configuration was found consistently more effective than another in reducing speeds *(18)*.

Wright et al. studied the effects of reflectorized markers on nighttime accidents for curves of 6 degrees or more in Georgia *(19)*. Although the authors reported an effective reduction in accidents based on the assumption that the reflectors would have no effect on daytime accidents, their actual accident numbers showed a net increase in accidents after the placement of the reflectors. Taylor and Foody reported the before-after differences for the placement of roadside delineators on highway curves *(20)*. The study revealed that degree of curve was not the only important parameter on highway curves. The central angle of the curve was found to be a more efficient parameter.

Specifically, curves with curvature between 5 and 10 degrees and central angles between 20 and 40 degrees showed significant accident reduction when delineated.

Pavement washboard and warp was highlighted as a safety problem on highway curves by Glennon et al. *(1)*. Based on some general analytics and results of previous full-scale vehicular studies, it was noted that very short, high-amplitude bumps cause both vertical and lateral wheel hop. Successive loading and unloading of first front and then rear tires, with contingent wheel hop, greatly increases the effective lateral acceleration on the tires. In addition, loss of steering authority occurs, which forces the driver to input larger steering angles than expected.

One other aspect of safety on highway curves discussed by Glennon et al. relates to roadside slopes *(1)*. They conclude that for identical roadside slope rates, roadside traversals on curves are more severe than on tangents. Because, for any encroachment line, the effective slope is steeper on a curve than on a tangent, vehicle occupants will experience higher vertical accelerations and the vehicle will have a much greater tendency for rollover and a higher probability of producing severe injuries.

## VERTICAL ALIGNMENT

The vertical alignment consisting of vertical curves and straight grades has been the subject of accident studies conducted worldwide. Some of these studies produced results that make general distinctions between grades and level sections, upgrades and downgrades, crests and sags, or flat and steep grades *(4, 7–9)*. Although all of these studies lack control of large variances associated with interdependent variables and length of grade, they indicate the following general conclusions:

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

An often-quoted, pre-1960 German study by Bitzel is one of the few studies that indicates a direct relationship between grade and accident rate *(21)*. However, the relationship found in this study appears to be related to a set of unusual circumstances, which included widely fluctuating annual accident rates over long stretches of highways, a high percentage of accidents involving stationary vehicles, a very high percentage (70 percent) of accidents involving trucks, and a large percentage of trucks with high weight-to-horsepower ratios. These circumstances render the results of this study useless for predicting the accident effects of grade improvement projects in the United States.

The remainder of the studies reviewed used some form of either multivariate analysis or a sufficiency rating scheme to identify the incremental effects of geometric elements including vertical alignment *(10–12)*. None of these studies produced any reliable measures of the accident effects of vertical alignment.

## APPLICATION OF RESULTS TO RRR PRACTICE

The incremental accident benefits of flattening grades has not been precisely determined in available studies but appears to be reasonably small within practical ranges of grade change. For highway curves, many past studies have shown substantially lower accident rates for flatter curves; but all of these studies have examined only the accident rate on the curve itself and have ignored the confounding effect of curve length. When these results are used to examine the next accident reduction associated with flattening a curve at a location where the central angle is held constant, the net accident benefits appear to be very small.

These results are consistent with the findings of a study that provided the following measure of net incremental difference in accidents associated with curves of various degrees:

$$\Delta A = \frac{(\Delta D_c)\ (\text{ADT})}{81{,}540}$$

where

$\Delta A$ = the net number of accidents reduced per year,
$\Delta D_c$ = the change in degree of curve, and
ADT = average daily traffic.

Although flatter curvature is desirable, there appears to be some trade-off (when central angle is held constant) between the benefits of flatter curvature and the disbenefits of more net roadway with curvature.

Another major conclusion is that, because of the high rate of single-vehicle accidents on highway curves, low-cost roadside safety improvements on highway curves may be one of the most effective RRR safety improvements. This is particularly true for improvement of low-height fill slopes and removal of trees to improve the clear-zone width on the outside of curves carrying more than 2,000 vehicles per day.

Another feature of highway curves that can become prominent in RRR projects is the break in cross slope between shoulders and superelevated pavements on curves. Designers of RRR projects face a dilemma because current AASHTO policy limits the break to 8 percent. On curves where increased superelevation is desirable or where shoulder widths will be sacrificed to improve narrow lanes, either the AASHTO criterion must be violated or extensive shoulder and roadside reconstruction must be planned.

Considering that the major function of the outside shoulder at such locations is to provide recovery from moderate roadway departures, recent research confirms the AASHTO policy for shoulders 6 ft or more in width where a four-wheel traversal is possible. For narrower width shoulders that are implicitly designed for two-wheel traversals, larger cross-slope breaks are possible as shown below:

| *Allowable Shoulder Width (ft)* | *Cross-slope Break (%)* |
|---|---|
| 5 | 9 |
| 4 | 12 |
| 3 | 15 |
| 2 or less | 18 |

These greater breaks recognize the less severe "effective" cross slope experienced during a two-wheel shoulder traversal where the inside wheels are still on the superelevated pavement. These greater breaks also do not compromise safety beyond the prior decision to allow the narrow shoulder.

In further consideration of the safety enhancement of RRR projects, other minor treatments on highway curves offer the potential for accident benefits at relatively low costs as follows:

1. Although the literature does not provide a measure of the incremental accident effects of superelevation, consideration should be given to increasing superelevation on highway curves in conjunction with highway resurfacing projects. This incrementally low-cost improvement might be particularly effective either where pavement drainage is inadequate or where the design speed of the curve is below the highway operating speed.
2. On resurfacing projects, attention should be given to eliminating existing pavement irregularities such as washboard, pot holes, bumps, and dips on highway curves. These irregularities have been shown by past research to create severe control problems for drivers on highway curves.
3. On resurfacing projects, quality control should be exercised on highway curves to avoid both reducing the existing superelevation and introducing pavement irregularities.

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