Safety Effects of Geometric Improvements on Horizontal Curves

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The purpose was to (a) determine the horizontal curve features that affect accident experience on two-lane rural roads, (b) determine which types of geometric improvements on curves will affect accident experience, and (c) develop accident reduction factors based on these findings. Very little of this information has been available to highway safety engineers and designers. The results were based on an analysis of 10,900 horizontal curves in Washington State with corresponding accident, geometric, traffic, and roadway data variables. Statistical modeling revealed significantly higher curve accidents for sharper curves, narrower curve width, lack of spiral transitions, and increased superelevation deficiency. All else being equal, higher traffic volumes and longer curves were also associated with significantly higher curve accidents. Ranges of accident reductions for horizontal curves improvements were determined for flattening curves, widening lanes, widening paved shoulders, adding unpaved shoulders, adding a spiral transition, and improving superelevation. From the study findings, a variety of improvements were recommended for horizontal curves, including improving deficient superelevation whenever roadways are routinely repaved, using spiral transitions on curves with moderate and sharp curvature, and upgrading specific roadside improvements. Expected costs should be compared with estimated accident reductions to determine whether geometric improvements are warranted.

Horizontal curves are a considerable safety problem on rural two-lane highways. A 1981 study estimated that there are more than 10 million curves on the two-lane highway system in the United States (*1*). Accident studies further indicate that curves experience a higher accident rate than do tangents; rates for curves range from 1.5 to 4 times those of similar tangents (*2*).

Although accidents on horizontal curves have been a problem for many years, the issue may be more important in light of improvements being made related to resurfacing, restoration, and rehabilitation projects, commonly known as the 3R program. These improvements generally consist of selective upgrading of roadways within the available right-of-way usually following the existing alignment. Because the surface of the road must be continually repaved to protect the underlying roadbed structure, the issue of what else should be done at horizontal curves to enhance (or at least hold constant) the level of safety is critical.

Many questions remain unanswered, such as, Which curves (with which characteristics) should be improved to gain the maximum safety benefits per dollar spent? and Which countermeasures can be expected to produce this benefit?

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Part of the reason for the current lack of knowledge is that much of the past research has concentrated on only one aspect of the horizontal curvature question (e.g., degree of curve or pavement widening). Another reason is the research community's difficulties in consolidating all the knowledge gained from past evaluations in a scientifically sound manner. There is general knowledge of the types of countermeasures that can be implemented at horizontal curves, but little is known of their true effectiveness.

Thus, there has been a need to better quantify accident effects of curve features and to quantify the effects on accidents of flattening curves, widening curves, adding spiral transitions, improving deficient superelevation, and improving the roadside. This information on safety benefits could be used along with project cost data to determine which curve-related improvements are cost-effective under various roadway conditions.

The objective of this study was to determine the horizontal curve features that affect accident experience on two-lane rural roads and to determine which types of geometric improvements on curves will affect accident experience and to what extent. The development of accident relationships was based on an analysis of 10,900 horizontal curves in Washington State with corresponding accident, geometric, traffic, and roadway data variables. The resulting accident relationships and expected accident reduction factors thus apply specifically to individual horizontal curves on two-lane rural highways. The results of this paper were based on a larger study conducted in 1990 for FHWA (*3*).

LITERATURE REVIEW

Many studies have studied relationships between roadway geometric features and accidents. For example, studies by Dart and Mann (*4*) and Jorgensen and Associates (*5*) found a sharper degree of curvature to be associated with increased accident occurrence on rural highway sections. A study by Zador found that superelevation rates at fatal-crash sites were deficient compared with those at comparison sites, after controlling for curvature and grade (*6*).

Two studies of accident surrogates also attempted to quantify accident relationships on horizontal curves. On the basis of 25 curve sites in Michigan, Datta et al. concluded that degree of curve and superelevation deficiency have significant relationships to run-off-road accident rates; average daily traffic (ADT) and sideslope angle are related to rear-end accidents; and the distance since last event is related to outer-lane ac-

cident rates (*7*). Terhune and Parker found from 78 curve sites in New York State that only degree of curve and ADT have significant effects on total accident rate (*8*).

A four-state curve study by Glennon et al. is one of the most comprehensive studies conducted on the safety of horizontal curve sections (*2,3*). Using an analysis of variance on 3,304 curve sections with only roadway variables, they found that length of curve, degree of curve, roadway width, shoulder width, and state have a significant association with total accident rate. A discriminant analysis revealed that the variables significant in predicting low-versus high-accident sites were length of curve, degree of curve, shoulder width, roadside hazard rating, pavement skid resistance, and shoulder type (*2*). Simulation runs found potential safety problems of underdesigned curves, lack of spiral transitions, and steep roadside slopes. Deacon conducted further analyses on the accident data base to better quantify accident effects of curve flattening improvements (*9*).

In addition to improvements to the roadway design at horizontal curves, many other treatments have been used, including signs (chevron alignment, advisory speed, arrow board, curve warning), delineators (striped delineator panels, post-mounted reflectors, raised pavement markers), pavement markings (wide edgelines, reflectorized edgeline or centerline), signals (flashing beacons with warning signs), guardrail, and others (*3*). However, previous studies indicate that these treatments are not always effective; in fact, the accident effect of most of them is largely unknown. It is clear from the available literature that additional information is needed on the specific accident effects of geometric improvements on horizontal curves, which is the focus of this paper.

DATA BASE

The Washington State data base of curves was the primary data source for this study. Although many potential curve data bases were considered, the Washington State data base was selected for analysis because

- There was a computerized data base of horizontal curve records for the state-maintained highway system (about 7,000 mi).
- The curve files contained essential information such as degree of curve, length of curve, curve direction, central angle, and presence of spiral transition on each curve.
- Supplementary computer files were available that could be merged with the curve file, including files for roadway features, vertical curve, traffic volume, and accident. The accident file covered January 1, 1982, through December 31, 1986.
- Roadside data (i.e., roadside recovery distance, roadside hazard rating) on 1,039 curves were available in paper files from another FHWA study (on cross-section design) by matching mileposts. It was necessary, however, to collect superelevation data in the field at 732 of these curves for which roadside data were also available.

In developing the curves data base, the key decisions included

1. A curve was considered to include the full length from the beginning to the end of the arc. If a spiral transition existed, the spiral length on both ends of the curve was included as part of the curve. Curves were included regardless of their adjacent tangent distance; thus, isolated and nonisolated curves were included.
2. To minimize problems due to inaccurate accident location, it was decided to omit curves that were extremely short (i.e., less than 100 ft). Curve accidents were required to occur strictly within the limits of the curve.
3. Only paved two-lane rural roads were included in the data base.

After all files were merged, data were checked and verified extensively.

The resulting Washington State merged data base thus contained basic information on 10,900 curves, supplemental roadside information on 1,039 curves, and field-collected superelevation information on 732 curves. The variables available for analysis as predictor (curve descriptor) variables included the following:

- Maximum grade for curve (%),
- Maximum superelevation (ft/ft),
- Maximum distance to adjacent curve (ft),
- Minimum distance to adjacent curve (ft),
- Roadside recovery area (ft),
- Roadside rating scale,
- Outside shoulder width (ft),
- Inside shoulder width (ft),
- Outside shoulder type,
- Inside shoulder type,
- Surface width (ft),
- Surface type,
- Terrain type,
- Presence of transition signal, and
- Total roadway width (surface width plus width of both shoulders; this variable is referred to as "width" in all subsequent results).

The variables for maximum superelevation, roadside recovery area, and roadside rating scale were available only on a subset of the data.

In the full FHWA report (*3*), details of the characteristics of this population of curves are included. In general, the sample of rural two-lane curves appears to be similar to what would be expected in other similar states that are characterized by all three types of terrain—level, rolling, and mountainous areas. Curve characteristics included mostly degree of curve between 0.5 and 30 degrees, curve length from 100 to more than 1,000 ft (with many sharp curves also being short curves because of their location in the mountainous areas), 11-ft lanes, 0- to 8-ft shoulders (most often asphalt with some gravel shoulders), curves with and without spiral transition sections, and ADT from less than 500 to greater than 5,000. The ranges of values within each of these variables were wide enough to allow for suitable analysis.

In terms of accident characteristics of the curves, during the 5-year study period, there were 12,123 accidents, an average of 0.22 accidents per year per curve. Crashes by severity included 6,500 property-damage-only accidents (53.6 percent), 5,359 injury accidents (44.2 percent), and 264 fatal accidents (2.2 percent).

The most common accident types were fixed-object crashes (41.6 percent) and rollover crashes (15.5 percent). In terms of road condition, wet pavement and icy or snowy pavement conditions each accounted for approximately 21.5 percent of the accidents with the other 57.0 percent on dry pavement. Crashes at night accounted for 43.7 percent of curve accidents, which is probably higher than the percentage of nighttime traffic volume. The mean accident rate for the curve sample was 2.79 crashes per million vehicle miles. Accidents per 0.1 mi/year averaged 0.2 and ranged from 0 to 9.5.

The distribution of curves by various accident frequencies revealed that 55.7 percent had no accidents in the 5-year period. Another 31.5 percent had 1 or 2 accidents, 9.0 percent had 3 to 5 accidents, and 2.8 percent had between 6 and 10 accidents in the 5-year period. A total of 84 curves had between 11 and 20 accidents, and only 19 of the 10,900 curves had more than 20 accidents in the 5-year period. As expected, the accident distribution is highly skewed toward low accident frequencies.

DATA ANALYSIS

Preliminary Analysis Results

As stated earlier, the overall goal of this research was to develop predictive models relating crashes on curves to various geometric and cross-section variables. This modeling required four steps: (a) determining the most-appropriate accident types to serve as dependent (outcome) variables, (b) developing the strongest predictive model, (c) verifying this model, and (d) modifying or redeveloping parallel models for use in definition of accident reduction factors. As will be noted, modification and redevelopment were necessary because the original models could not account for lengthening curves during the curve-flattening process.

Preliminary data analyses were directed toward answering two basic questions. The first was to identify those characterizations of reported accidents that were most strongly associated with horizontal curves (i.e., which accident type or types should be of major interest). A secondary goal was to determine a subset of predictor variables to be included in further analyses. The data file contained, for each roadway section, accident frequencies cross-classified by accident type (e.g., head-on, fixed object, rear end), accident severity, weather condition, light condition, vehicle type, and sobriety of driver. In preliminary modeling, each accident characterization was included as the dependent variable in a logarithmic regression model that included ADT, length of curve, and degree of curve as independent variables. The logarithmic form of the model was based on prior modeling efforts.

Virtually every accident characterization studied was found to be significantly correlated with degree of curve. Because the correlations tended to increase with increasing accident frequency, total accidents (rather than some subtype of accidents) was chosen as the primary dependent variable to be analyzed.

In the second step, models of various forms were explored in the attempt to develop the strongest model to predict total accidents. The potential independent variables in the data set included those listed earlier. Again, readers interested in the details of this major analytical effort are referred to the work by Zegeer et al. (*3*).

In summary, because logarithmic models substantially underpredicted on curves with higher accident frequencies, linear regression models fit to accident rates per million vehicle miles by a weighted least-squares procedure were developed. The weight was a function of ADT and curve length. Using this model form, the significant predictors of total accidents on curves were ADT, curve length, degree of curve, total surface width (lanes plus shoulders), and the presence of a spiral transition.

Validation of the basic model form and the values of the coefficients was attempted through use of a subset of the data including "matched pairs" of a curve and its adjacent tangent, where traffic mix and certain other "noncurve" variables such as clear zone and shoulder type would be expected to be the same on both parts of each pair. This analysis supported the relative effects of degree, width, length, and spiral on accidents found in the weighted model (the effect of superelevation was developed in a separate analyses of the subset of curves on which additional field data were collected).

With respect to roadside condition, data were obtained for analysis of roadside hazard (i.e., roadside hazard rating and roadside recovery area distance) for 1,039 curves in the data base. None of the analyses involving roadside rating scale or clear recovery area showed either of these variables to be significantly associated with curve accidents. These results may, however, be partly due to the limited variability of these quantities in the data.

Modeling for Development of Accident Reduction Factors

As noted earlier, although the weighted linear regression model developed in the initial analysis appeared to be well suited to describing relationships between accidents on curves and roadway characteristics, models of this form were not useful for estimating accident reductions due to certain roadway improvements. More specifically, curve flattening involves reducing the degree of the curve while increasing the length. The central angle, and thus the product of curve length times degree, remains essentially constant for this procedure. The linear accident prediction model contained the product degree *x* length, and, therefore, is not suitable for the estimation of changes of this type since any change in degree due to flattening would be accompanied by a related change in length, which would result in no change in the predicted number of accidents.

However, a model that represents an extension of a model developed earlier by Deacon for TRB does allow for determining the simultaneous effects of curve flattening, roadway widening, and the addition of spirals (*9*). Using the predictor variables shown important in the earlier models, this model was fit to the data on total curve accidents and was of the form

$$A = [\alpha_1(L \times V) + \alpha_2(D \times V) + \alpha_3(S \times V)](\alpha_4)^{W} + \varepsilon \quad (1)$$

where

A = total number of accidents on curve in a 5-year period,
L = length of curve (mi),
V = volume of vehicles (in millions) in a 5-year period passing through the curve (both directions),
D = degree of curve,
S = presence of spiral transitions where $S = 0$ if no spiral exists and $S = 1$ if spirals do exist, and
W = width of roadway on curve (ft).

The width effect α_4 was reparameterized as

$$\alpha_4 = e^{-\rho}$$

The model parameters were estimated by choosing a value for ρ in the interval $0 \leq \rho < .10$, fitting the regression model

$$A = \alpha_1(L \times V \times e^{-\rho w}) + \alpha_2(D \times V \times e^{-\rho w}) + \alpha_3(S \times V \times e^{-\rho w}) + \varepsilon$$

then searching on ρ to find the value which minimized the error sum of squares. This process led to the final estimated model

$$A = [1.55\ (L)(V) + .014\ (D)(V) - .012\ (S)(V)](.978)^{W-30} \quad (2)$$

In this model, α_1 and α_2 were statistically significant at $p = .0001$. For α_3, $p = .140$. No significance level or standard error was available for α_4 or $\hat{\rho} = .022$. Even though the spiral coefficient was not found to be statistically significant at the .05 level, it was retained in the model since it was found to be an important factor in the initial "best model" analyses.

This model form (Equation 2) was chosen for several reasons. First, comparison of a measure of model fit (i.e., a pseudo R^2 based on the error sum of squares ratio, Q) indicated that the fit for this model form was very similar to the fit of the best-fitting weighted linear regression model. Second, as shown by tabular comparisons, it predicts accident rates quite well for various data subsets (about as well as the linear model). Third, the interactions of traffic and roadway variables are reasonable and make sense in terms of accident occurrences on curves. Fourth, both D and L are used as independent terms in the model, so changes in both can affect the predicted number of accidents even with the same central angle.

With respect to the third factor, the logical relationships found, the model generally predicts that increases in accidents occur both as degree of curve increases and as curve length increases. In addition, accidents decrease slightly with increasing roadway width for each degree of curve category. For example, for a 20-degree curve with no spiral and length of 0.1 mi, widening the curve from 20 to 30 ft will reduce accidents from about 2 (accidents per 5 years) down to about 1.6, a 20 percent reduction.

Figure 1 illustrates the combined effect of ADT and degree of curve on crashes. This figure reveals the more rapid increase in accidents for higher degree of curve as ADT increases, and the linear increase in accidents as ADT increases

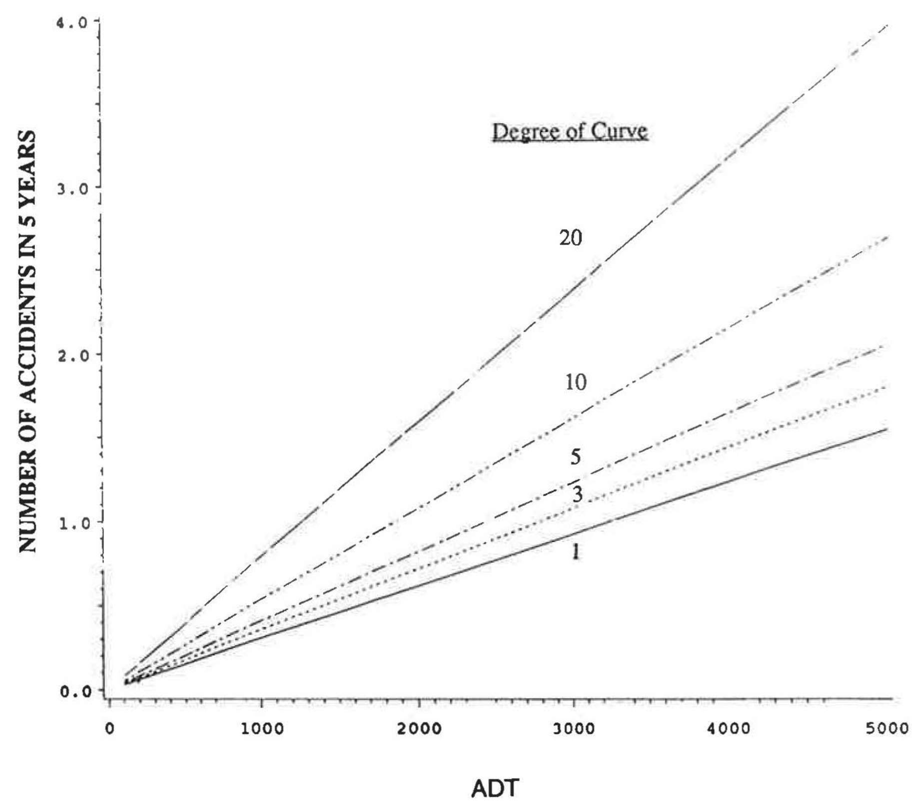

FIGURE 1 Predicted accidents (in 5 years) for degree of curve and ADT (no spiral; curve length = 1 mi; road width = 30 ft).

within each curvature category. The model also indicates that accidents increase linearly for various roadway widths as ADT increases, and that accidents are consistently lower for curves with spiral transitions than for curves without spirals.

To illustrate the results of the chosen accident prediction model, the number of curve accidents per 5 years, A_p, was computed for various values of degree of curve, central angle, length of curve, ADT, and roadway width, as shown in Table 1 (these results cannot be used for curve-flattening improvements).

For a 5-degree 1,000-ft curve with a 50-degree central angle, an ADT of 2,000, and a 22-ft roadway width, the model predicts 1.59 curve accidents per 5 years. Under similar conditions with a 40-ft roadway width, the predicted number of curve accidents (A_p) in a 5-year period would be 1.06. Throughout the table, A_p decreases with increasing road width, whereas A_p increases as ADT increases and as central angle increases, all of which are logical trends.

One seemingly illogical trend in Table 1 requires discussion. It would be expected, for example, that accidents would increase as degree of curve increases (for equal curve lengths, road widths, etc.) Notice that for a given ADT, road width and central angle, A_p decreases in some cases for higher degrees of curves. For example, consider the column in the table with 1,000 ADT and a roadway width of 34 ft. For a central angle of 30 degrees, values of A_p are 1.50 for a 1-degree curve, 0.41 for a 5-degree curve, 0.38 for a 10-degree curve, and 0.75 for a 30-degree curve. This is because the A_p values represent those accidents within the curve itself and, for a given central angle, curve lengths are longer for gentler curves. As in the previous example for a 30-degree central angle, values of L are 3,000 ft for a 1-degree curve, 600 ft for a 5-degree curve, 300 ft for a 10-degree curve, and 100 ft for a 30-degree curve. Thus, in that example, with a 30-degree central angle, accidents per 1,000 ft (305 m) of curve are 0.50 for a 1-degree curve, 0.68 for a 5-degree curve, 1.27 for a 10-degree curve, and 7.50 for a 30-degree curve. Thus, the model predicts that accidents per given length of curve increase as degree of curve increases, as expected. It should be noted that the A_p values in Table 2 should not be used to estimate the accident effects of curve flattening, since the original and new alignment of the roadway must be properly accounted for (as described in more detail later).

Curve-Flattening Effects

To use the predictive model for estimating the effects on crashes of curve flattening, consider the sketch in Figure 2 of an original curve (from the point of curvature PC_o to the point of tangency PT_o) and a newly constructed flattened curve (from PC_n to PT_n). To compute the accident reduction due to the flattening project, we must compute the accidents in the before and after condition from common points. Curve flattening reduces the overall length of the highway but increases the length of the curve, assuming that the central angle remains unchanged. Thus, we must compare accidents in the after condition between PC_n and PT_n along the new alignment with accidents in the before condition between PC_n and PT_n along the old alignment.

The number of accidents on the new curve (A_n) is computed using Model 2 with the new degree of curve D_n, new curve length (L_n), new roadway width (W_n), and new spiral condition (S_n), or

$$A_n = [1.55\,(L_n)(V) + .014(D_n)(V) - .012(S_n)(V)]\,(.978)^{W_n-30} \tag{3}$$

To compute accident reduction due to curve flattening, we must determine the accidents on the old curve alignment (A_o) by adding the accidents on the old tangent segments A_T to the accidents on the old curve A_{oc}. The lengths of the tangent segments are computed as ($L_n - L_o + \Delta L$), where ΔL is the amount by which the highway alignment is shortened (between PC_n and PT_n) because of the flattening project and is

TABLE 1 Predicted Number of Curve Accidents per 5-Year Period from Model Based on Traffic Volume and Curve Features

Degree of Curve (D)	Central Angle (I)	(Length of Curve in ft.)* (L)	Predicted Number of Accidents (A_p) per 5 year period															
			ADT = 500				ADT = 1,000				ADT = 2,000				ADT = 5,000			
			Roadway Width (w)				Roadway Width				Roadway Width				Roadway Width			
			22	28	34	40	22	28	34	40	22	28	34	40	22	28	34	40
1	10	(1,000)	.34	.29	.26	.22	.67	.59	.51	.45	1.34	1.18	1.03	.90	3.36	2.94	2.57	2.25
	30	(3,000)	1.00	.85	.75	.65	1.95	1.71	1.50	1.31	3.91	3.42	2.99	2.62	9.77	8.55	7.48	6.54
	50	(5,000)	1.62	1.41	1.24	1.08	3.24	2.83	2.48	2.17	6.47	5.66	4.95	4.34	16.18	14.15	12.39	10.84
5	10	(200)	.14	.12	.10	.09	.28	.25	.22	.19	.56	.49	.43	.38	1.40	1.23	1.08	.94
	30	(600)	.26	.24	.20	.18	.54	.47	.41	.36	1.07	.94	.82	.72	2.69	2.35	2.06	1.80
	50	(1,000)	.40	.35	.30	.27	.79	.69	.61	.53	1.59	1.39	1.22	1.06	3.97	3.47	3.04	2.66
10	10	(100)	.18	.16	.14	.12	.37	.32	.28	.25	.74	.64	.57	.50	1.85	1.62	1.41	1.24
	30	(300)	.25	.22	.19	.17	.50	.44	.38	.33	1.00	.87	.76	.67	2.49	2.18	1.90	1.67
	50	(500)	.31	.27	.24	.21	.63	.55	.48	.42	1.25	1.10	.96	.84	3.13	2.74	2.40	2.10
	90	(900)	.44	.39	.34	.30	.88	.77	.68	.59	1.76	1.54	1.35	1.18	4.41	3.86	3.38	2.96
30	10	(33)	.47	.41	.36	.31	.94	.82	.72	.63	1.87	1.64	1.44	1.26	4.69	4.10	3.59	3.14
	30	(100)	.49	.43	.38	.33	.98	.86	.75	.66	1.96	1.71	1.50	1.31	4.90	4.29	3.75	3.28
	50	(167)	.51	.45	.39	.34	1.02	.89	.78	.69	2.05	1.79	1.57	1.37	5.11	4.47	3.92	3.43
	90	(300)	.55	.48	.42	.37	1.11	.97	.85	.74	2.22	1.94	1.70	1.48	5.54	4.85	4.24	3.71

$*\text{Length} = \frac{\text{Central Angle}}{\text{Degree}} \times 100$ 1 ft = 0.3048 m

TABLE 2 Percentage Reduction in Total Accidents due to Horizontal Curve Flattening—Nonisolated and Isolated Curves

Degree of Curve		Central Angle in Degrees									
		10		20		30		40		50	
Original (Do)	New (Dn)	Non-Isolated	Isolated*	Non-Isolated	Isolated	Non-Isolated	Isolated	Non-Isolated	Isolated	Non-Isolated	Isolated
30	25	16	17*	16	17	16	17	15	16	15	16
	20	33	33	32	33	31	33	31	33	30	33
	15	49	50	48	50	47	50	46	50	46	50
	12	59	60	57	60	56	60	55	60	55	60
	10	65	67	64	66	63	66	62	66	61	66
	8	72	73	70	73	69	73	68	73	68	73
	5	82	83	80	83	79	83	78	83	78	83
25	20	19	20	19	20	18	20	18	20	17	20
	15	39	40	38	40	36	40	36	40	35	40
	12	50	52	49	52	48	52	46	52	46	51
	10	58	60	56	60	55	60	54	59	53	59
	8	66	68	64	68	62	68	61	67	60	67
	5	77	80	75	80	74	79	72	79	72	79
20	15	24	25	23	25	22	25	21	25	20	24
	12	38	40	36	40	35	40	34	39	33	39
	10	48	50	45	50	44	49	42	49	41	49
	8	57	60	54	60	52	59	51	59	50	59
	5	71	75	68	74	66	74	64	74	64	74
15	10	30	33	28	33	26	33	25	32	24	32
	8	43	46	40	46	37	46	35	45	34	45
	5	61	66	56	66	53	65	51	65	50	65
	3	73	79	68	79	64	78	63	78	63	78
10	5	41	49	36	48	32	48	29	47	28	47
	3	58	69	50	68	45	67	43	66	42	66
5	3	22	37	15	35	13	33	11	32	11	31

*Isolated curves include curves with tangents of 650 ft (.124 mi) or greater on each end.

expressed as (*10*)

$$\Delta L = [(2.17 \tan I/2) - (I/52.8)]\,(1/D_n - 1/D_o)$$

or

$$\Delta L = 2(\tan I/2)(R_n - R_o) \tag{4}$$

where ΔL is given in miles, I in degrees, and $\tan I/2$ in radians. As discussed by Terhune and Barker (*8*), ΔL is very small for central angles of 90 degrees or less.

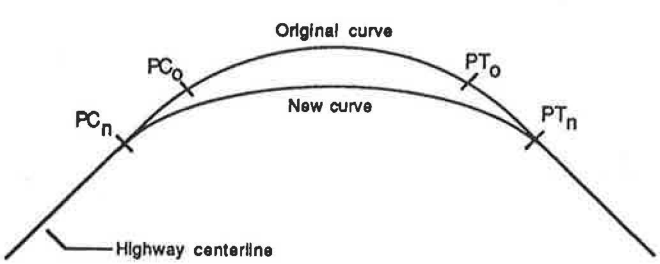

FIGURE 2 Illustration of original and new alignment due to curve flattening.

Assuming that the effects of volume and roadway width on accidents are the same on the associated tangents as on the curve, the number of accidents on the tangent (A_T) portions on the old alignment is computed on the basis of Model 3 as

$$A_T = 1.55(L_n - L_o + \Delta L)V(.978)^{W_o - 30} \tag{5}$$

The accidents on the old alignment consist of the accidents on the old curve (A_{oc}) plus the accidents on the old tangent segments (A_T), that is,

$$\begin{aligned} A_o = A_{oc} + A_T = {} & [(1.552)L_oV + (.014)D_oV \\ & - (.012)S_oV](.978)^{W_o - 30} \\ & + [1.552(L_n - L_o + \Delta L)V](.978)^{W_o - 30} \end{aligned} \tag{6}$$

The accident reduction factor for curve flattening (AR_F) is equal to

$$AR_F = \frac{A_o - A_n}{A_o}$$

Thus, the percentage reduction in accidents may be computed as the difference between accidents on the old align-

ment and the accidents on the new alignment divided by the accidents on the old alignment. However, to apply the *AR* factors in this form, one must know the number of accidents on the old alignment (i.e., accidents on the old curve plus the tangent portions, A_T). This number of accidents may not be easily determined from a practical standpoint.

A more simplified expression of the *AR* factor would be one which can be multiplied by the number of accidents on only the old curve (A_{oc}). The expression for this *AR* factor would then be

$$AR_R = \frac{A_o - A_n}{A_{oc}} \tag{7}$$

where AR_R is the revised accident reduction factor. Note that the denominator in this expression represents accidents on the old curve only. Thus, for a given flattening project (e.g., flattening from a 25-degree curve to a 10-degree curve), one should simply multiple AR_R by the number of accidents on the old curve to compute the estimated number of accidents reduced.

Accident reduction percentages for curve flattening using Model 6 are given in Table 2 for various combinations of central angle and degree of curve before and after flattening. *AR* factors are provided for both isolated curves (from the four-state model) and nonisolated curves (from the Washington State model), where isolated curves are considered to have tangents of at least 650 ft on each end. *AR* factors are higher for flattening isolated curves than for nonisolated curves. Flattening a 20-degree curve to an 8-degree curve with a 30-degree central angle would reduce curve accidents by approximately 52 percent for nonisolated curves or 59 percent for isolated curves. As expected, the greater the curve flattening, the higher the accident reductions.

It is also useful to mention that, for a given amount of curve flattening, the percentage reduction in accidents is slightly larger for lower central angles than for greater central angles. For example, flattening a 20-degree nonisolated curve to 10 degrees will reduce accidents 48 percent for a 10-degree central angle but only by 41 percent for a 50-degree central angle. However, it should be remembered that a 50-degree central angle curve would be expected to have a greater number of total accidents than a 10-degree central angle for a given degree of curve (all else being equal). Thus, the net number of accidents reduced may be greater on a 50-degree central angle than a 10-degree central angle for a given flattening improvement.

Roadway Widening Improvements

The widening of lanes or shoulders and shoulder surfacing are other geometric curve improvements that were considered in terms of their effects on accidents. However, Predictive Model 8 alone did not allow for further determining the accident restrictions that would result from widening the lanes versus adding paved shoulders versus adding unpaved shoulders because the variable for total roadway width was the only width-related variable in the final accident-prediction model. However, on the basis of previous safety literature, it is fairly clear that the roadway width effects on crashes will vary depending on the type of widening. The FHWA cross-section study, for example, provided accident reductions for widening lanes rather than widening paved or unpaved shoulders (*3*).

From that reference, accident reduction factors were estimated for various amounts of lane widening and widening of paved and unpaved shoulders (see Table 3). Note that the table only provides values for up to 4 ft of lane widening per side. This is because widening lanes beyond 12 ft is considered to be adding to the shoulder width, and lane widths less than 8 ft fall outside the limits of this data base.

The values in Table 3 need to account for the amount and type of widening. For example, assume that a 20-ft roadway (two 10-ft lanes with no shoulder) was to be widened to 32 ft of paved surface. Assuming that the lanes would be widened to 12 ft, then two 4-ft paved shoulders would also be added. Thus, Table 3 indicates a 12-percent accident reduction due to widening each lane by 2 ft. Then, paving 4 ft of both shoulders would correspond to an accident reduction of 15 percent. The resulting accident reduction factor for both widening improvements would not be the sum of the two accident reduction factors, however. Instead, the overall accident reduction should be computed as follows:

$$AR = 1 - (1 - AR_1)(1 - AR_2)(1 - AR_3)(1 - AR_4)\ldots \tag{8}$$

where

AR_1 = the accident reduction factor of the first improvement,

TABLE 3 Percentage Reduction in Accidents due to Lane Widening, Paved Shoulder Widening, and Unpaved Shoulder Widening

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

[1]Values of lane widening correspond to a maximum widening of 8 ft (2.4 m) to 12 ft (3.7 m) for a total of 4 ft (1.2 m) per lane, or a total of 8 ft (2.4 m) of widening where 1 ft = 0.3048 m.

AR_2 = the accident reduction factor of the second improvement,

AR_3 = the accident reduction factor of the third improvement, and so on.

In this example involving lane widening plus widening paved shoulder, with individual AR factors of 12 percent and 15 percent, respectively, the overall AR would be computed as

$$AR = 1 - (1 - .12)(1 - .15) = 1 - (.88)(.85)$$
$$= 0.25$$

that is, an expected 25 percent reduction in accidents.

Spiral Improvement

On the basis of the statistical analysis and modeling efforts described earlier, the presence of spiral transitions was found to have a significant effect on curve accidents (it is noted that for curves without spirals, the Washington policy was to attain two-thirds of the desired superelevation on the tangent, and the remaining one-third on the beginning of the curve). The magnitude of this effect was studied from the selected Predictive Model 8 as well as from other analyses. Depending on the degree of curve and central angle, the effect of having a spiral was found to range from about 2 to 9 percent, based on the predictive model. The influence of central angle and degree of curve was generally a function of the form of the model.

An overall reduction of 5 percent was determined to be the most representative effect of spiral transitions in view of the predictive model and other related analyses. One might expect that spiral transitions are more beneficial on sharp curves than mild curves, but such a differential effect was not adequately supported from the analysis.

Superelevation Improvements

As noted earlier, the effect of superelevation deficiency or "deviation" was determined through a separate modeling effort. Superelevation data were collected for 732 of the curves in the data base. A superelevation deviation variable was defined as optimal superelevation minus actual superelevation where optimal superelevation was determined from the AASHTO design guide as a function of degree of curve and terrain type (*11*).

The final accident prediction model chosen that included an effect for superelevation deviation was again a weighted linear model, but this time included fixed effects for spirals and width that were based on the results of modeling for the full data set. Part of the problem experienced in developing a model that contains effects for width, spiral, and superelevation stems from the correlations between the three variables. Thus, some of the effects that are attributed to width and spiral might be due to superelevation. (Again, refer to the work by Zegeer et al. (*3*) for details of the analysis.)

However, given these caveats, the modeling did indicate that inadequate superelevation will result in increased curve accidents. Correcting this superelevation deficiency (or superelevation deviation) will most likely result in a significant reduction in curve accidents. The precise magnitude of the effect was difficult to quantify due to the interaction of superelevation with other roadway features. However, using the final model form, the typical accident reduction that may result from correcting a superelevation deviation of .02 was approximately 10 to 11 percent. For superelevation deviations of greater than .02, even higher accident reductions may be possible. Having more superelevation than AASHTO criteria was not found to be associated with increased accidents on curves. A separate analysis of the FHWA four-state curve data base also revealed that further benefits may result from more gradual transition of superelevation beginning prior to the beginning of the curve.

The correction of superelevation deviation during a routine 3R project would involve providing sufficient additional asphalt and engineering design to upgrade the superelevation to the AASHTO and state specifications. While the cost of correcting superelevation may be a substantial increase in the cost of a routine pavement overlay on the curve, the relative cost would generally be much less than the cost of curve flattening or curve widening. Thus, because of the potential accident reduction, it is desirable to upgrade superelevation deviations on curves as a routine measure when roadways are repaved.

SUMMARY AND CONCLUSIONS

The goals of this study were to quantify the relationship between horizontal curve features and the level of safety, and to quantify the effects on accidents resulting from curve flattening, curve widening, adding a spiral, improving deficient superelevation, and clearing the roadside. A merged data base of variables from 10,900 Washington State curves was analyzed to determine the effects of these various countermeasures on curve crashes

The following are the key study results:

1. Statistical modeling analyses revealed significantly higher curve accidents for sharper curves, narrower curve width, lack of spiral transitions, and increased superelevation deficiency. All else being equal, higher traffic volume and longer curves were also associated with significantly higher curve accidents.
2. Based on the predictive models, the effects of several curve improvements on accidents were determined as follows:

—*Curve flattening* reduces crash frequency by as much as 80 percent, depending on the central angle and amount of flattening. For example, for a central angle of 40 degrees, flattening a 30-degree curve to 10 degrees will reduce total curve accidents by 66 percent for an isolated curve, and by 62 percent for a nonisolated curve. Flattening a 10-degree curve to 5 degrees for a 30-degree central angle will reduce accidents by 48 and 32 percent for isolated and nonisolated curves, respectively.

—*Widening lanes* on horizontal curves is expected to reduce accidents by up to 21 percent for 4 ft of lane widening (i.e., 8 ft of total widening).

—*Widening paved shoulders* can reduce accidents by as much as 33 percent for 10 ft of widening (each direction).

—*Adding unpaved shoulders* is expected to reduce accidents by up to 29 percent for 10 ft of widening.

—*Adding a spiral* to a new or existing curve will reduce total curve accidents by approximately 5 percent.

—*Improving superelevation* can significantly reduce curve accidents where there is a superelevation deficiency (i.e., where the actual superelevation is less than the optimal superelevation as recommended by AASHTO). An improvement of .02 in superelevation (e.g., increasing superelevation from .03 to .05 to meet AASHTO design guidelines) would be expected to yield an accident reduction of 10 to 11 percent. However, no specific accident increases were found for the small sample of curves with a superelevation greater than the AASHTO guidelines. Thus, no support can be given to the assumption of increased accident risk on curves with slightly higher superelevation than currently recommended by AASHTO (*10*).

3. During routine roadway repaving, deficiencies in superelevation should always be improved. Spiral transitions were also recommended, particularly for curves with moderate to sharp curvature. Improvements of specific roadside obstacles should be strongly considered, and their feasibility should be determined for the specific curve situation on the basis of expected accident reductions and project costs. As a part of routine 3R improvements, horizontal curves should be reviewed in terms of their crash experience to determine whether geometric improvements may be needed. In such cases, the accident reduction factors developed in this study should be considered along with expected costs to determine whether such improvements are cost effective. An informational guide has been developed to assist with the design of horizontal curves on new highway sections and with the reconstruction and upgrading of existing curves on two-lane rural roads. The guide also gives a step-by-step procedure for computing expected benefits and costs for a variety of curve improvements (*11*).

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Publication of this paper sponsored by Committee on Operational Effects of Geometrics.