SAFETY EFFECTS OF GEOMETRIC IMPROVEMENTS ON HORIZONTAL CURVES

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INTRODUCTION

Background

Horizontal curves represent a considerable safety problem on rural two-lane highways. A 1980 study estimated that there are more than 10 million curves on the two-lane highway system in the U.S.[1] Accident studies further indicate that curves experience a higher accident rate than do tangents, with rates that range from one and a half to four times higher than similar tangents.[2]

While accidents on horizontal curves have been a problem for many years, the issue may perhaps 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 at this time.

A variety of 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 could be expected to produce this benefit at a specific curve. Part of the reason for this current lack of knowledge is that many of the past research studies have concentrated on only one aspect of the horizontal curvature question (e.g., degree of curve, pavement widening, etc.). Another reason has been the research community's difficulties in consolidating all of the knowledge gained from past evaluations in a scientifically sound manner. While there is general knowledge of the types of countermeasures that can be implemented at horizontal curves, little is known of the true effectiveness of these countermeasures.

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

The purpose of this research was to determine the horizontal curve features which affect accident experience on two-lane rural roads and, also, 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 accident relationships and expected accident reduction factors applied only to individual horizontal curves on two-lane, rural highways. The results of this paper were based on a larger study conducted in 1990 by the Federal Highway Administration.

LITERATURE REVIEW

Several studies were reviewed which provided information on relationships between roadway geometric features and accidents. In the early phases of three FHWA studies, variables were listed which were believed to be related to accidents on horizontal curves, based on their review of the literature and also on judgment.[2,4,5] Twenty roadway variables were mentioned, by one or more of the studies, as having strong potential relationships to accidents, or as having a promising or potential accident relationship. Those variables most often mentioned include degree and length of curve, various measures of superelevation, lane and shoulder width, shoulder type, roadside hazard, pavement friction, vertical alignment. Others include stopping sight distance, distance to adjacent curves, type of curve transition (e.g., spirals), number of access points on curve (e.g., intersection or driveways), traffic control devices (e.g., striping, delineators, curve warning signs) and others.

In terms of accident relationships with horizontal curvature, Dart and Mann, and Jorgensen and Associates both attempted to develop accident predictive models based on roadway and geometric features on sections of two-lane rural roads.[6,7] The model by Dart and Mann used "percent of section > 3 degrees" as a variable in its model.[6] However, this factor accounted for only a 7 percent difference in total accident rate between a nearly tangent section and a section with nearly continuous horizontal curves. Jorgensen found a 13 percent lower accident rate for short highway sections with less than 3 degree curves, compared to sections with horizontal curvature of 3 degrees or more.[7]

Several accident research studies involved analyzing accident and roadway data specifically on horizontal curve segments to determine accident-related variables. The four-State curve study represents one of the most comprehensive studies conducted to date on the safety of horizontal curve sections along with the more recent FHWA study.[2,3] Using an analysis of variance on 3,304 curve sections with only roadway variables, those found to have a significant association with total accident rate included: length of curve, degree of curve, roadway width, shoulder width, and state. A discriminant analysis (which included additional data items for 333 sites) revealed that the variables significant in predicting low and high-accident sites include:[2] length of curve, degree of curve, shoulder width, roadside hazard rating, pavement skid resistance, and shoulder type. While these results were useful for predicting high-accident curve sites, they did not provide measures of expected accident reductions due to curve improvements (e.g., curve flattening, roadside improvements, pavement surfacing).

Simulation runs using the HVOSM model in that study by Glennon et. al. revealed that an existing highway curve that is underdesigned for the prevailing operating speed can present a severe roadway hazard. Also, the addition of spiral transitions to highway curves dramatically reduces the friction demands of the critical vehicle traversals. Examination of roadside slope characteristics showed that skidding is very likely for even mild roadside slopes (6:1) and that on unstabilized roadside surfaces, there is a high expectation of vehicle rollover.

Deacon further analyzed the FHWA four-State curve data base to better quantify the expected change in accidents due to various types of geometric curve improvements.[8] Based on data tabulations, a model was derived for estimating the number of accidents on curved segments. Then expected accident reduction percentages were computed due to horizontal curve flattening projects. For various central angles and degrees of curve (before and after improvement), expected accident reductions from curve flattening range from 16 to 83 percent.

In addition to studying accident surrogates on curves in New York and Michigan, two additional studies also attempted to quantify accident relationships for both geometric and operational types of measures based on a more limited number of curve sites (78 and 25 sites, respectively).[4,5] Of nine basic variables tested, the New York study found that only degree of curve and average daily traffic (ADT) have significant effects on total accident rate.[4] The Michigan study concluded that degree of curve and superelevation deficiency have significant relationships to run-off-road (ROR) accident rates; ADT and sideslope angle were related to rear-end accident rates; and the distance to last event was related to outer-lane accident rates.[5]

A study by Zador found that the superelevation rates at fatal crash sites after adjusting for curvature and grade were deficient compared to those at comparison sites.[9] The authors conclude that "inadequate superelevation presents a risk that should be eliminated from the roadway system." While it is in fact possible for other roadway deficiencies (e.g., a large shoulder edge dropoff or poor sideslope design) to also play a role in contributing to a fatal crash, the laws of physics do suggest the need for adequate superelevation on sharp horizontal curves.

In addition to improvements to the roadway design at horizontal curves, numerous other treatments have been used, including:[10-21] signs (chevron alignment signs, advisory speed signs, arrow board signs, deceptive curve sign, curve warning signs), delineators (striped delineator panels, post-mounted reflectors, raised pavement markers), pavement markings (wide edgelines, reflectorized edgeline and/or centerline, transverse striping with decreasing spacing, widening of inside of curve), signals (flashing beacons with warning signs), guardrail, and others (e.g., rumble strips on pavements, crash cushions, etc.). However, not all of these treatments are known to be effective based on previous studies, and in fact, the actual effect of most of them is largely unknown. It is clear from the available literature that additional information is needed on the accident effects of specific geometric improvements on horizontal curves. Such accident effects are addressed in this paper.

RESEARCH DESIGN AND PRELIMINARY ANALYSIS

The Washington State data base of curves was the primary data source analyzed for determining the relationships between accidents and various traffic and roadway features. Although numerous potential curve data bases were considered for use in this study, the Washington State curves were selected as the primary data base for analysis because:

- There was an existing computerized data base of horizontal curve records for the State-maintained highway system (about 7,000 mi) (11,270 km) in Washington State.

- The curve files contained such information as degree of curve (i.e., curve radius), length of curve, curve direction, central angle, and presence of spiral transition on each curve.

- Corresponding computer files were available which could be merged with the curve file, including the roadway features file, vertical curve file, traffic volume file, and accident file. The accident file covered the period from January 1, 1982, through December 31, 1986. Being able to merge these files resulted in a study file with a large number of relevant traffic and roadway variables on curves.

- Roadside data (i.e., roadside recovery distance, roadside hazard rating) on 1,039 curves in Washington State was available from paper files from another FHWA study (on cross-section design) by matching mileposts. Data on superelevation were collected in the field at 732 of those 1,039 curves.

The resulting Washington State merged data base contained a large sample of 10,900 curves with many important variables needed to quantify the effects of roadway features on crashes.

In developing the curves data base, several key decisions were made. These 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, so isolated and non-isolated curves were included.

2. To minimize problems due to inaccurate accident location, it was decided to omit curves in the data base which were extremely short (i.e., < 100 ft (30.5 m), or .019 mi (.03 km)). Curve accidents were required to occur strictly within the limits of the curve.

3. The curve sample was restricted to only two-lane rural roads.

4. Superelevation data was collected from among the 1,039 curves where roadside data was also available. This would result in a sample of curves with a full range of available data variables.

After all files were merged, extensive data checking and verification was conducted.

Curve Inventory Data Base Characteristics

The definition of degree of curve used was that of degrees traveled per 100 ft (30 m) of arc. Of the 10,900 curves in the data base, the most prevalent curvature groupings have degrees of curve of 2.01 to 5 degrees (33.25 percent), 5.01 to 10 degrees (26.25 percent), and 1.01 to 2 degrees (15.23 percent). Only 1,156 curves (10.6 percent) have curvatures of less than 1 degree while 513 (4.7 percent) have greater than 20 degrees of curvature. In terms of curve length, the study sample was limited to curves of 100 ft, or .019 mi (30 m, or .031 km) or greater. Also, 81.2 percent of the study curves are .20 mi (.32 km) or shorter. It is also interesting to note that the predominance of sharp curves which were short, as is often found in mountainous areas. On the other hand, mild curves tended to be more uniformly distributed over various lengths.

The width of the surface width (i.e., two travel lanes) varied from 16 ft to 28 ft (4.9 m to 8.5 m) for curves in the data base, with nearly half (5,269 or 48.3 percent) of the curves having a 22 ft (6.7 m) roadway width (table 18). Roadway widths of 20 to 24 ft (6.1 to 7.3 m) accounted for 10,399 curves or 95.4 percent. Only curves with paved roadway surfaces were included in the data base.

Shoulder widths most often ranged between 2 and 4 ft (0.6 to 1.2 m) (6,654 curves or 61.0 percent), although 8-ft (2.4 m) shoulders were not uncommon (1,516 curves). The most common shoulder surfaces consisted of asphalt (8,442 curves), gravel (2,287 curves), concrete (24 curves), and soil (24 curves). Spiral transitions exist on both ends of the curve for 1,927 curves (17.7 percent), are not used on 8,913 curves (81.8 percent), and are present on only one end of the curve at 60 curves (0.6 percent).

The most prevalent Average Daily Traffic (ADT) ranges for these curves are 1,001 to 2,000 (30.6 percent), 2,001 to 5,000 (32.9 percent) and 501 to 1,000 (18.3 percent). ADT's of 500 or below occur at 1,222 curves (11.2

percent), while only 764 curves (7.0 percent) have ADT's of 5,000 or greater. It is apparent that curves in mountainous areas have generally lower traffic volumes than curves in flat or rolling areas. In fact, 86.5 percent (1,584 out of 1,832) of curves in mountainous areas have ADT's of 2,000 or less compared to 43.4 percent in level areas and 56.4 percent in rolling areas.

General Accident Characteristics

For the 10,900 curves in the Washington State data base, there were a total of 12,123 accidents. This is an average of 1.11 accidents per 5-year period, or 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), as shown in table 21. A total of 8,434 people were injured and 314 were killed in these accidents.

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/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 percent of nighttime traffic volume. The most frequent vehicle types involved in curve crashes were passenger cars (60.2 percent) followed by pickup trucks (27.9 percent).

The mean accident rate for the curve sample was 2.79 crashes per million vehicle mi (1.61 km). Accidents per 0.1 mi (0.16 km) per year averaged 0.2 and ranged from 0 to 9.5.

The distribution of curves by various accident frequencies revealed that 6,073 of the 10,900 curves (55.7 percent) had no accidents in the 5-year period. Another 3,432 curves (31.5 percent) had 1 or 2 accidents, 985 curves (9.0 percent) had 3 to 5 accidents, and 307 curves (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. Thus, as expected, the accident distribution is highly skewed toward low accident frequencies.

DATA ANALYSIS

As stated earlier, the overall goal of this research was to develop strong predictive models relating crashes on curves to various geometric and cross-section variables. Modeling requires four steps - (1) determination of the most appropriate accident types to serve as dependent variables; (2) the development of the strongest predictive model; (3) verification of this model; and (4) modification for redevelopment of parallel models for use in definition of accident reduction factors.

Overall Accident Modeling

Preliminary data analyses were directed toward answering two basic questions. The first was to identify which characterizations of reported accidents were most strongly associated with horizontal curves. A secondary goal was to determine a subset of covariates 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), by accident severity, weather conditions, light conditions, vehicle type, and sobriety of driver. Each accident characterization (e.g., head-on accidents, fatal accidents, nighttime accidents) was included as the dependent variable in a logarithmic regression model of the type used by Zegeer, et al (1987). These models included ADT, length of curve, and degree of curve as independent variables.

Virtually every accident characterization studied was found to be significantly correlated with degree of curve. Since, however, the correlations, generally, tended to increase with increasing accident frequency, total accidents was chosen as the primary dependent variable to be analyzed. Potential independent variables included:

- Maximum grade for curve
- Maximum superelevation*
- Maximum distance to adjacent curve
- Minimum distance to adjacent curve
- Roadside recovery area*
- Roadside rating scale*
- Outside shoulder width
- Inside shoulder width
- Outside shoulder type
- Inside shoulder type

- Surface width
- Surface type
- Terrain type
- Presence of transition spiral

where

* indicates the variable was only available on a subset of the data.

From the initial models, only one additional independent variable was found to be statistically significant, namely, a total width variable, which was defined as (surface width + inside shoulder width + outside shoulder width), hereafter referred to simply as "width (W)".

A large proportion of the Washington curves had zero accidents over the time span of the data collection. Thus, to use a logarithmic transformation, it was necessary to add a small quantity (e.g., .01) to each accident frequency. It was found that while the resulting logarithmic models seemed to fit well to curves having very low accident frequencies, the models substantially under predicted higher accident frequencies, and thus, were not satisfactory for further analyses.

A type of model which provided a much better representation of the data was based on a linear regression model fit to accident rates per million vehicle miles by a weighted least squares procedure. The weight function was taken as w = (ADT)(section length). The weighted procedure was justified by the fact that accident rate variance tended to decrease inversely with increasing values of w.

Using this model form, the variable indicating spiral transitions was also found to be statistically significant, and the basic estimated model for total accident rate was given by:

$$\text{Total acc. rate} = \text{Total acc./million vehicle miles}$$

$$= 1.94 + \underset{(.008)}{.24}\ \text{Deg} - \underset{(.006)}{.026}\ \text{Width} - \underset{(.062)}{.25}\ \text{Spirals} \qquad (1)$$

with all coefficients significant at the p = .0001 level (standard errors are shown in parentheses). Total accidents per curve per year could be estimated by the model

$$\text{Total acc.} = (\text{ADT})(\text{Length})\ (1.94 + .24\ \text{Deg} - .026\ \text{Width} - .25\ \text{Spirals}) \qquad (2)$$

Model (1) can be thought of as a continuous variable analogue of a (weighted) analysis of variance of accident rate on the three factors Degree, Width and Spiral.

Subtracting the predicted values from the corresponding actual values, squaring, and summing led to the computation of the quantity, SS residual, which when divided by SS Total which is the sum of squares of the deviations of the actual values from the overall average, yielded

$$Q = \frac{\text{SS residual}}{\text{SS Total}} = .64 \quad .$$

In the case of a least squares fit, $R^2 = 1-Q$. Since model (2) does not represent a least squares fit to total accidents, the total sum of squares is not partitioned into a sum of squares due to regression and a residual sum of squares. Still Q seems to be a meaningful quantity and $1-Q = .36$ may be thought of as a sort of pseudo R^2.

Verification of Basic Model Through Analysis of Matched Pair Data

From the complete data set, a subset was extracted consisting of 3,427 curves for which there was an adjacent tangent section of length at least equal to the length of the curve. For these curves, accident data from the corresponding tangent section (of length equal to that of the curve) were appended to the existing curve data. This subset is referred to as the "matched pairs data set," and was used to carry out a type of validation of model(1).

For the matched pairs data, accidents on the tangent sections could potentially be used as controls for accidents on the corresponding curved sections, thus, tending to remove effects of factors except those characterizing the curve itself. Model (1) with degree and spirals set equal to zero should represent a model for accident rates on tangents as a function of roadway width. A model of this form fit to data on the difference (i.e., curve accident rate - tangent accident rate) should result in the constant term and the width effect dropping out while the effects of degree and spirals should remain about the same. Specifically, in a model of the form

$$\text{Rate diff.} = \beta_0 + \beta_1 \text{ Degree} + \beta_2 \text{ Width} + \beta_3 \text{ Spirals} \quad (3)$$

it should be the case that

$$\beta_0 = 0, \ \beta_1 = .24, \ \beta_2 = 0, \text{ and } \beta_3 = -.25$$

for the estimates to be consistent with those of model (1). When model (3) was fit to the rate differences on the matched pairs data set, the estimated model was

$$\text{Rate diff.} = \underset{(.404)}{-.186} + \underset{(.020)}{.190} \text{ Degree} - \underset{(.011)}{.0007} \text{ Width} - \underset{(.120)}{.174} \text{ Spiral} \quad (4)$$

The coefficients β_0, β_2, and β_3 do not differ significantly from the values specified above, but β_1 (the degree effect) is significantly lower. Numerically, however, the values .19 in (4) versus .24 in (1) are reasonably close. Thus, results from the matched pairs data seems to be in reasonable agreement with those from the complete data set. This close agreement lends support to the relative effects of degree of curve, width, and presence of spiral on accidents.

Estimation of Superelevation Effect

Of the 10,900 curves in the Washington State curves file, superelevation data were collected for 732 of those curves. The effect of superelevation on curve accidents was considered to be an important question to be addressed with the Washington data base. The superelevation deviation variable was constructed as (optimal superelevation) - (actual superelevation), where optimal superelevation was determined from the AASHTO Design Guide as a function of degree of curve and terrain type.[15]

Since the effects of Spirals and Width estimated from this data subset differed substantially from those estimated from the full data set, a model which contained unknown Degree and Superelevation Deficiency effects, but with fixed effects for Width and Spirals was estimated over the data subset. This resulting model, which combines information from the full data set with information from the superelevation subset and represents our best estimate of a model containing effects for both spirals and superelevation, was:

$$\text{Total acc. rate (per MVM)} = 1.53 + .28\ \text{Deg.} - .026\ \text{Width} - .25\ \text{Spiral} + 9.52\ \text{Sup. Def} \quad (5)$$

It should be noted that superelevation deviation, spirals, and roadway width were all correlated. Superelevation deviation was significantly correlated with width, but not with spirals. The presence of spirals was strongly correlated with width on the superelevation subset; curves having spirals were wider by an average of 5 ft (1.5 m) than those not having spirals. Superelevation deviation tended to decrease as width increased (i.e., wider curves had less deficiencies in superelevation), and was about 10 percent less on curves having spirals.

Models estimated over the large data set contained roadway width and spirals as competing variables and in most cases both variables were found to be statistically significant. Some of the effects that are attributed to these variables might, however, be due to superelevation.

To get an idea of the magnitude of the effect of superelevation relative to accident reduction, model (5) was used to calculate a percent reduction in crashes corresponding to a reduction of .02 in superelevation deviation with "typical" values for the other variables, namely degree = 3°, width = 30 ft (9.1 m), no spiral, and .3 million vehicle mi (.5 million vehicle km) of traffic. These calculations yielded an accident reduction of 10.6 percent.

Estimation of Effects Due 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 of the 10,900 in the Washington State curves 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 be due, in part, to the limited variability of these quantities in the data.

ACCIDENT REDUCTION FACTORS

Development of Models for Accident Reduction Factors

While model (1) described above seemed 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 roadway improvements. In particular, the improvement of curve flattening involves reducing the degree of the curve while increasing the curve length. The product of length times degree or central angle remains, essentially, constant for this procedure. The accident prediction model (2) contains the product degree x length x ADT, and, therefore, is not suitable for the estimation of changes of this type.

A model which represents an extension of a model developed by TRB, allows for determining the effects of curve flattening, roadway widening, and of adding spirals.(8) This model was fit to the data on total curve accidents and was of the form

$$A = [\alpha_1 (L \times V) + \alpha_2 (D \times V) + \alpha_3 (S \times V)] (\alpha_4)^W + \epsilon \qquad (6)$$

where

A = Number of total accidents on the curve in a 5-year period

L = Length of the curve in mi (1.6 km)

V = Volume of vehicles in million vehicles 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

W = Width of the roadway on the curve in ft (.3048 m)

The width effect α_4 was reparemeterized 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

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

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

$$A = [1.55 \, (L)(V) + .014 \, (D)(V) - .012 \, (S)(V)] \, (.978)^{(W-30)} \qquad (7)$$

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 $\hat{p}$ = .022. Even though the coefficient of spirals was not found to be statistically significant at the .05 level in model (7), it was retained in the model, since it was found to be an important factor in numerous other analyses. The error sum-of-squares ratio, Q, was computed to be Q = .65 for model (7), or a pseudo R^2 of .35. This value is very close to that for the linear model (2) for accident frequencies (i.e., .36).

This model form (7) was chosen for several reasons. First of all, as shown in Table 1, it predicts accident rates quite well for various data subsets (about as well as the linear model). Also, the interaction of traffic and roadway variables are reasonable, and make sense in terms of accident occurrences on curves. Note that both D and L are used in the model, since both the degree of curve and length of curve are needed to characterize a curve and define the curve central angle. This model form had the basic form similar to that developed by Deacon for TRB.[8]

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 2. Note that each combination degree of curve and central angle defines a curve length, since,

$$I = \text{Central angle} = (D)(L)(52.8), \text{ or}$$

$$L = \frac{I}{D(52.8)}$$

where

I = central angle of curve (in degrees)
D = degree of curve (in degrees)
L = length of curve (in mi (1.61 km))

When L is expressed in ft,

$$L = \frac{I}{D} \times 100$$

Thus, for example, a 1-degree curve with a central angle of 10 degrees would correspond to a curve length of $\frac{I}{D} \times 100 = \frac{10}{1} \times 100 = 1{,}000$ ft (305 m). Similarly, values of L are given for each combination of D and I in table 2.

For a 5-degree curve with a 50-degree central angle, an ADT of 2,000 and a 22-ft (6.7-m) roadway width, the model predicts 1.59 curve accidents per 5 years. Under similar conditions (i.e., 5-degree curve, 50-degree central angle, and ADT of 2,000) with a 40-ft (12.2-m) 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.

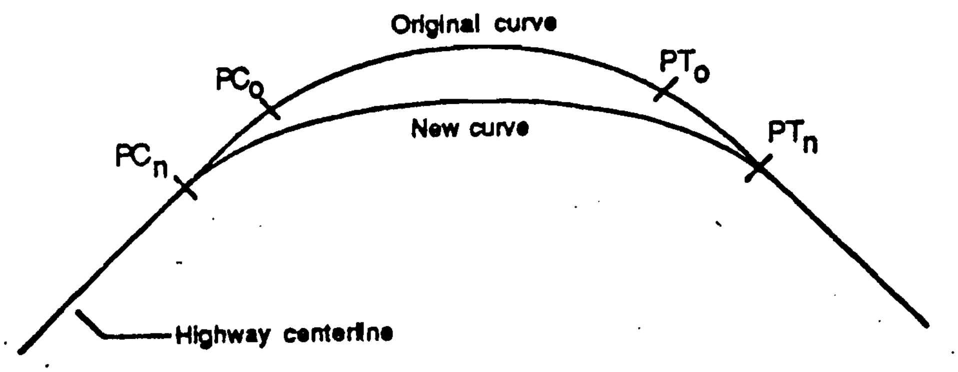
One seemingly illogical trend in the table requires discussion. We would expect, for example, that accidents would increase as degree of curve increases (for equal curve lengths, road widths, etc.) Notice that for a given ADT, road width and central angle, A_p decreases in some cases for higher degrees of curves. For example, consider the column in the table with 1,000 ADT and a roadway width of 34 ft (10.4 m). For a central angle of 30 degrees, values of A_p are 1.50 for a 1-degree curve, .41 for a 5-degree curve, .38 for a 10-degree curve, and .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 milder curves. As in the previous example for a 30- degree central angle, values of L are 3,000 ft (914 m) for a 1-degree curve, 600 ft (183 m) for a 5-degree curve, 300 ft (91 m) for a 10-degree curve, and 100 ft (30 m) 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 .5 for a 1-degree curve, .68 for a 5-degree curve, 1.27 for the 10-degree curve, and 7.5 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 in a later section).

The combined effects of roadway and traffic variables on curve accidents are illustrated in figures 1 through 3, as developed from accident prediction model (7). For example, for an ADT of 2,000 on curves with a 30-ft (9.1-m) roadway and no spiral (i.e., a typical situation), the relationship between degree of curve and curve length on accidents is given in figure 1. Notice that increases in accidents occur as degree of curve increases, and accidents increase as curve length increases. The relationship of degree of curve and roadway widths on crashes is shown in figure 2 for a curve length of .10 mi (.16 km), an ADT of 2,000 and no spiral. Accidents decrease slightly with increasing roadway width for each degree of curve category. For a 20-degree curve under these conditions, widening the curve from 20 ft (6.1 m) to 30 ft (9.1 m) will reduce accidents from about 2 (accidents per 5 years) down to about 1.6, a 20 percent reduction.

The effect on total crashes of ADT combined with degree of curve is shown in figure 3. Notice the more rapid increase in accidents for higher degree of curve as ADT increases and the linear increase in accidents as ADT increases within each curvature category. Likewise, accidents increase linearly for various roadway widths as ADT increases. Finally, the effect of spirals on accidents revealed that accidents are consistently lower for curves with spiral transitions than for curves without spirals.

Curve Flattening Effects

To use the predictive model for estimating the effects on crashes of curve flattening, consider the sketch given below of an original curve (from the PC_o to 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 (7) 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

$$A_n = [(1.55)(L_n)(V) + .014(D_n)(V) - (.012)(S_n)(V)](.978)^{(W_n-30)} \qquad (8)$$

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) due to the flattening project and is expressed as:[10]

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

or

$$\Delta L = (2)(\tan I/2)(R_n - R_o) \qquad (9)$$

where ΔL is given in mi, I in degrees and tan I/2 in radians. As discussed in reference 8, ΔL is very small for central angles of 90 degrees or less.

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 based on model (8) as:

$$A_T = (1.55)(L_n - L_o + \Delta L) V (.978)^{(W_o-30)} \qquad (10)$$

The accidents on the old alignment = accidents on the old curve (A_{oc}) plus the accidents on the old tangent segments (A_T), i.e.,

$$A_o = A_{oc} + A_T = [(1.552)\ L_oV + (.014)\ D_oV - (.012)\ S_oV]\ (.978)^{(W_o - 30)}$$

$$+ [(1.552)\ (L_n - L_o + \Delta L)\ V]\ (.978)^{(W_o - 30)} \qquad (11)$$

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

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

Thus, the percent reduction in accidents may be computed as the difference between accidents on the old alignment (A_o) and the accidents on the new alignment (A_n) divided by the accidents on the old alignment (A_o). 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:

$$AR_R = \frac{A_o - A_n}{A_{oc}} \qquad (12)$$

where AR_R = the revised accident reduction factor. Note that the denominator, A_{oc}, 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 multiply AR_R times the number of accidents on the old curve to compute the estimated number of accidents reduced.

Accident reduction percentages for curve flattening using model 11 are given in table 3 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 non-isolated curves (from the Washington State model), where isolated curves are considered to have tangents of at least 650 ft (198 m), or .124 mi (.20 km) or greater on each end. AR factors are higher for flattening isolated curves, compared to non-isolated 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 non-isolated 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 percent reduction in accidents is slightly larger for lower central angles than for greater central angles. For example, flattening a 20-degree non-isolated curve to 10 degrees will reduce accidents 48 percent for a 10-degree central angle, but by only 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. For example, for a 25-degree curve with a 50-degree central angle, and ADT of 1,000 (V = 1.825), a 30-ft (9.1m) width with no spiral, the curve length would be:

$$L = \frac{I}{D\ (52.8)} = \frac{50}{25\ (52.8)} = .038 \text{ mi } (.061 \text{ km}).$$

The predicted accidents (A_p) using model (8) would be:

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

$$= [(1.55)\ (.038)\ (1.825) + (.014)\ (25)\ (1.825) - (.012)\ (0)\ (1.825)] \times (1)$$

$= \boxed{.75}$ accidents per 5 years on the curve for a 25-degree curve with a 50-degree central angle

For a central angle of 10 degrees and a 25-degree curve, (all other factors being equal)

$$L = \frac{I}{D\ (52.8)} = \frac{10}{25\ (52.8)} = .0076 \text{ mi., and}$$

$$A_p = [(1.55)\ (.0076)\ (1.825) + (.014)\ (25)\ (1.825) - 0] \times (1)$$

$= \boxed{.66}$ accidents per 5 years on the curve for a 25-degree curve with a 10-degree central angle

Thus, the net reduction in accidents would be greater for a given flattening project for high central angles than for low central angles.

It should also be mentioned that a wide variety of curve flattening projects are provided in table 5, including the flattening of 30-degree curves to much flatter (e.g., 5 and 10 degree) curves. Although less than 10 percent of the Washington curves data base had curves of 30 degrees or sharper, it is the sharpest curves which typically have the greatest accident problems, and thus are most in need of flattening. Flattening of a sharp curve, however, may be more practical on roadway sections where a sharp or poorly designed curve is experiencing an abnormally high accident experience within a roadway section.

Roadway Widening Improvements

The widening of the roadway lanes or shoulders and shoulder surfacing are other geometric curve improvements which were considered in terms of their effects on accidents. Accident reduction percentages were first developed based on inputting various roadway widths into accident prediction model (8). Accident reductions range from 4 percent for 2 ft (0.6 m) of total roadway widening (e.g., for widening a 24 ft (7.3 m) roadway to 26 ft (7.9 m)) to 36 percent for 20 ft (6.1 m) of total roadway widening.

The predictive model alone did not allow for further determining the accident restrictions which would result from widening the lanes vs. adding paved shoulder vs. adding unpaved shoulder. This is because the variable "total roadway width" was the only width-related variable in the final accident prediction model (instead of lane width, paved shoulder width, and unpaved shoulder width). However, based on the 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, compared to widening paved or unpaved shoulders.[3]

Based on that model, accident reduction factors were estimated for various amounts of lane widening and widening of paved and unpaved shoulders (see Table 4). Note that the table only provides values for up to 4 ft (1.2 m) of lane widening per side (i.e., up to 8 total ft (2.4 m) of widening). This is because widening lanes beyond 12 ft (3.7 m) is considered to be adding to the shoulder width, and lane widths less than 8 ft (2.4 m) fall outside the limits of this data base.

The values in table 4 need to be applied properly to account for the amount and type(s) of widening. For example, assume that a 20 ft (6.1 m) roadway (two 10-ft (3.0-m) lanes with no shoulder)) was to be widened to 32 ft

(9.8 m) of paved surface. Assuming that the lanes would be widened to 12 ft (3.7 m), then two 4-ft (.9-m) paved shoulders would also be added. Thus, table 6 indicates a 12-percent accident reduction due to widening the lanes a total of 4 ft (1.2 m). Then, 8 ft (1.8 m) of total shoulder paving 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. Instead, the overall accident reduction (AR) should be computed as follows:

$$AR = 1 - (1-AR_1)\ (1-AR_2)\ (1-AR_3)\ (1-AR_4)\ \ldots \qquad (13)$$

where:

AR_1 = the accident reduction factor of the first improvement

AR_2 = the accident reduction factor of the second improvement

AR_3 = the accident reduction factor of the third improvement, etc.

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:

$$\begin{aligned} AR &= 1 - (1-.12)\ (1-.15) \\ &= 1 - (.88)\ (.85) \\ &= .25 \end{aligned}$$

that is, an expected 25 percent reduction in accidents.

Spiral Improvement

Based on the statistical analysis and modeling efforts described earlier, the presence of spiral transitions on a curve was generally found to have a significant effect in reducing accident frequencies on curves. The magnitude of the 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 percent 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 adding spiral transitions to a curve in view of the predictive model and other related analyses. While one may expect that spiral transitions are more beneficial on sharp curves than mild curves, such a differential effect was not adequately supported from the analysis. In summary, a 5-percent reduction in crashes was the value deemed most likely for the effect of adding spiral transitions.

Superelevation Improvements

The previous analyses and modeling also revealed that inadequate superelevation (i.e., not enough superelevation compared to AASHTO Greenbook criteria) will result in increased curve accidents. Correcting this superelevation deficiency (or "superelevation deviation") will 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 one model form, the typical accident reduction which 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

This study was intended to determine the horizontal curve features which affect 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 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.

   A data base of 10,900 curves was used to develop an accident prediction model for a general sample of horizontal curves, which exist on rural, two-lane roadways (e.g., typically not isolated from the influence of other nearby curves).

   This model was chosen since it predicts accident frequencies quite well, and the interaction of traffic and roadway variables makes sense in terms of crash occurrence on curves. The "pseudo R^2" for this model form was .35, which was among the highest values of all the models tested.

   For isolated curves (i.e., curves with tangents of at least 650 ft (198 m) on each end of the curve), the FHWA four-State data base of 3,277 curves was used to develop accident relationships with curve features. The results of this model were used to estimate crash reductions due to curve flattening improvements on isolated curves.

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 non-isolated 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 non-isolated curves, respectively. A table of accident reduction factors was produced for a variety of curve flattening improvements.

- Roadway widening effect on curves was determined based on the predictive model and crashes further refined for widening lanes versus shoulders and for widening paved shoulders vs unpaved shoulders.

  Widening lanes on horizontal curves is expected to reduce accidents by up to 21 percent for 4 ft (1.2 m) of lane widening (i.e., 8 ft (2.4 m) of total widening). Widening paved shoulders can reduce accidents by as much as 33 percent for 10 ft (3.0 m) of widening (each direction). Unpaved shoulders are expected to reduce accidents by up to 29 percent for 10 ft (3.0 m) of widening.

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

- Superelevation improvements 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 (i.e., increasing superelevation from .03 to .05 to meet AASHTO design guidelines) would be expected to yield an accident reduction of 10 to 11 percent. Higher percent reduction could result from superelevation improvements where greater deficiencies exist. 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.[22]

3. During routine roadway repaving, deficiencies in superelevation should always be improved. Spiral transitions were also recommended, particularly for curves with moderate and sharp curvature. Improvements of specific roadside obstacles should be strongly considered, and their feasibility should be determined for the specific curve situation based on 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 for various improvement(s) to determine whether such improvements are cost effective. An Informational Guide has been developed to provide guidance for the design of horizontal curves on new highway sections and for 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.[23]

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Table 1. Mean values of actual and predicted accident **rates** for selected curvature groups.

Accident Rate	Degree	No Spiral			Spiral		
		Width			Width		
		< 29	28-35	> 35	< 28	28-35	> 35
Actual	< 1°	2.08	1.63	1.56	.84	.82	1.21
Predicted (2)*		1.47	1.31	1.10	1.24	1.08	.90
Predicted (7)*		1.87	1.61	1.35	1.70	1.49	1.28
(Sample size)		(247)	(375)	(399)	(11)	(24)	(100)
Actual	2°- 2.99°	1.80	1.94	1.64	1.48	1.60	1.15
Predicted (2)		1.95	1.82	1.61	1.67	1.56	1.37
Predicted (7)		2.23	1.95	1.57	1.84	1.66	1.40
(Sample size)		(404)	(358)	(167)	(61)	(96)	(222)
Actual	5°- 9.99°	3.10	2.90	3.30	3.52	2.69	2.16
Predicted (2)		3.21	2.96	2.70	2.80	2.72	2.31
Predicted (7)		4.06	3.13	2.50	2.36	2.21	1.73
(Sample size)		(1511)	(809)	(169)	(122)	(138)	(112)
Actual	10°-14.99°	4.93	4.41	5.75	5.03	**	**
Predicted (2)		4.39	4.19	3.88	4.09		
Predicted (7)		6.09	4.93	3.93	3.61		
(Sample size)		(429)	(143)	(22)	(22)		
Actual	≥ 15°	7.24	8.43	13.32	8.28	**	**
Predicted (2)		8.09	6.82	7.54	5.52		
Predicted (7)		14.98	9.67	9.35	4.22		
(Sample size)		(782)	(132)	(25)	(24)		

*Rates derived from linear model(2) and non-linear model (7) dividing by ADT x L

**Cells with sample sizes of less than 10 curves.

Table 2. Predicted number of curve accidents (A_p) per 5-year period from the model (7) 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 3. Percent reduction (AR) in total accidents due to horizontal curve flattening -- non-isolated 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.

Table 4. Percent 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) of widening where 1 ft = 0.3048 m.

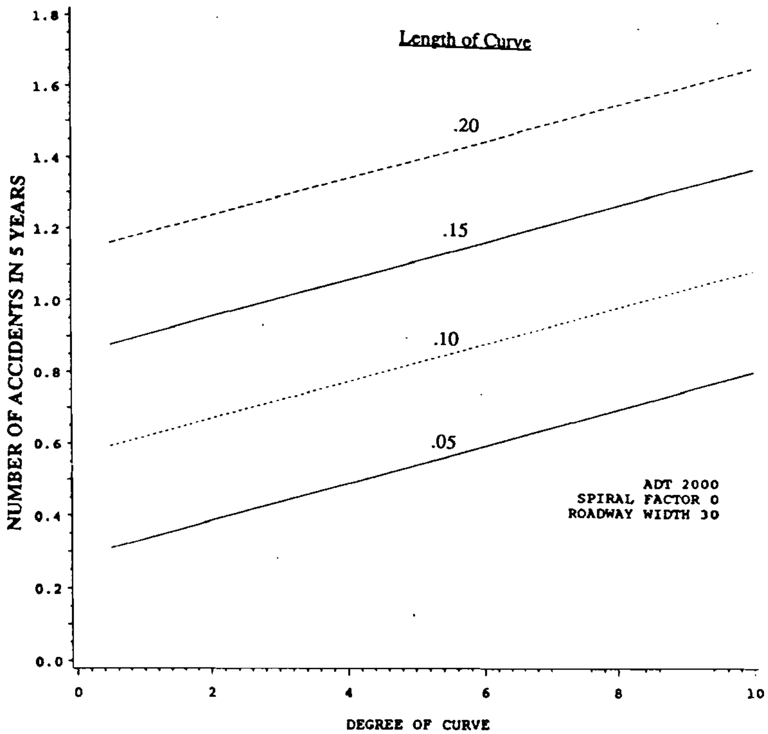

Figure 1. Predicted accidents (in 5 years) for degree of curve and curve length.

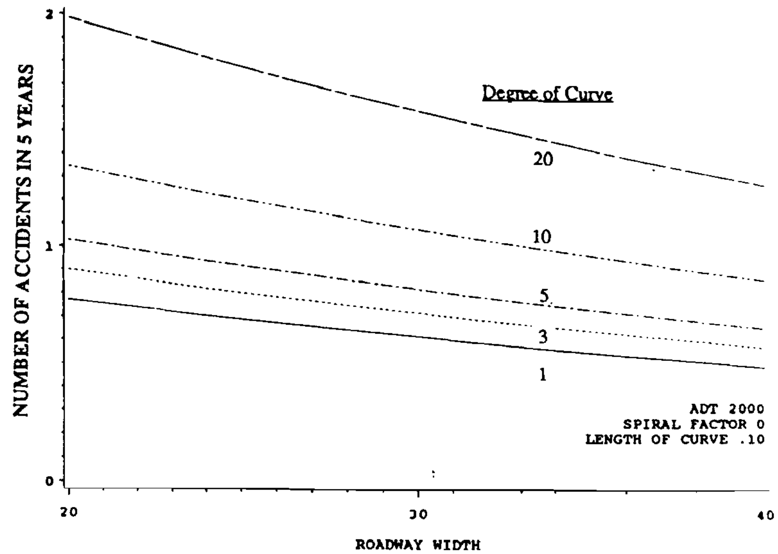

Figure 2. Predicted accidents (in 5 years) for degree of curve and road width.

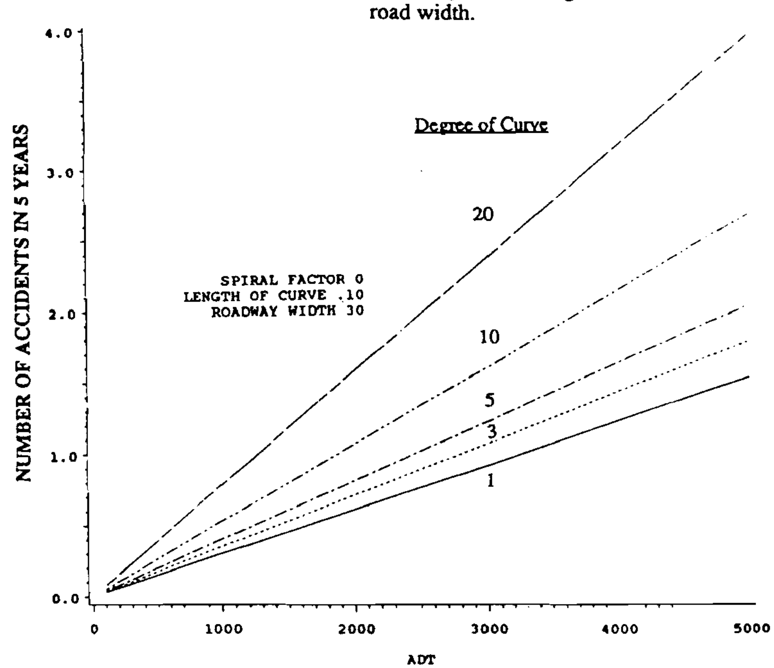

Figure 3. Predicted accidents (in 5 years) for degree of curve and ADT.