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Abridgment

Superelevation and Roadway Geometry: Deficiency at Crash Sites and on Grades

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ABSTRACT

Survey data on roadway superelevation, curvature, and grade collected at the sites of fatal rollover accidents and at comparison sites in New Mexico and Georgia were analyzed to determine the effect of grade on superelevation after adjustment for curvature. These adjusted data were then used to determine the effect of superelevation on accidents. After adjustment for curvature, it was found that in comparison with flat roadway sections (grade +2.5 to -2.5 percent) sections with grade (greater than +2.5 or less than -2.5 percent) had less superelevation. After adjustments for both curvature and grade, fatal rollover accident sections were found to have less superelevation than comparison sections. Inadequate superelevation presents a risk that should be eliminated from the roadway system.

The influence on accidents of superelevation rates--the vertical cross-slope or banking of the pavement on curved roadways--is a feature of highway design that has not been examined in detail. In a correlational analysis of rural highway geometry and accidents in Louisiana, it was reported that roadways with relatively flat cross-slopes have higher accident rates than those with greater cross-slope (1). However, this analysis did not account for the roadway curvature or vehicle speeds. A study of rural isolated curves using surrogate measures for accident experience found the degree of curve and superelevation deficiency to be the best predictors (R^2 = 0.68) of the accident rate for vehicles running off the road (2). Engineering surveys of sites of single-vehicle accidents all found that, on the average, the superelevation rates at these sites were higher than those at the comparison sites, but this result was most likely because of higher frequency of curves at the accident sites (3-6). These studies also noted that the superelevation rates at the sites of fixed-object accidents tended to be greater than those at the sites of rollover accidents.

The results of investigations on two distinct but related questions are reported. First, after adjustment for curvature, what is the relation between superelevation and grade? Second, after adjustments for both curvature and grade, what is the effect of superelevation on fatal single-vehicle rollover accidents? (A more detailed report of the statistical analysis and results is available from the authors at the Insurance Institute for Highway Safety.)

METHODS

Engineering survey data from rural primary roads (principal arterials and Interstates) and secondary roads (minor arterials and collectors) in Georgia and New Mexico were analyzed. Surveys were made at locations centered on a reference point where a fatal single-vehicle rollover accident had occurred, at comparison locations 1 mi upstream from the accident location, and at a stratified random sample of 300 sites representing the rural roadway system of each of the states in terms of average daily traffic.

At each accident and comparison location, 10 curvature and superelevation and 11 gradient measurements were obtained along a 100-ft roadway section centered on the accident or comparison location. At random sites, measurements of curvature, superelevation, and grade were taken 50 ft before and after the reference points. The methods for obtaining these measurements are given in detail elsewhere (5,6).

The basic units for statistical analysis were roadway sections 100 ft long, which were described by one measurement of superelevation rate and curvature and two measurements of vertical alignment. The grade of a section was taken to be the average value of the grade at its beginning and at its end. Sections that were straight, had excessive curvature, or had large increases in curvature relative to adjacent sections (e.g., curve transition sections) were eliminated from the analyses. Sections were classified as downhill, flat, or uphill according to whether the average grade was below -2.5 percent, between -2.5 percent and +2.5 percent, or above 2.5 percent, respectively. Sections were also classified as accident sections (upstream from the actual accident); downstream sections (just past the actual accident); or comparison sections (including sections 1 mi away from the accident site, and those randomly selected).

The effects of grade and section type on the linear relationship between superelevation rate and curvature was studied by using regression analysis [SAS general linear model procedure (7)]. In these analyses the superelevation rate was assigned a negative sign when the edge of the traveled lane was below the center of the traveled roadway (typical for right curves) and a positive sign when it was above the center of the roadway (typical for left curves). Curves turning left were assigned a negative sign and curves turning right were assigned a positive sign.

Equation 1 represents the model for studying the effect of grade:

$$\text{Superelevation}_{sk} = A_{0s} + A_{1s}\ \text{curvature}_{sk} + \text{error}_{sk} \qquad (1)$$

where

- s = 1 for crash sections,
- s = 2 for downstream sections,
- s = 3 for comparison sections, and
- k = 1,..., K_s corresponds to the different sections.

The model for studying the effect of section type was similar except that s = 1 if the section had a downhill grade, s = 2 if it was flat, and s = 3 if it had an uphill grade. Both of these models were estimated separately for all combinations of parameters, including state (New Mexico or Georgia) and type of roadway (Interstates and principal arterials or minor arterials and collectors).

The regression coefficients in Equation 1 were estimated and the regression lines corresponding to the effect studied (e.g., grade or section type) were compared. To assess the effect of vertical alignment on superelevation, the estimated excess superelevation was calculated for both uphill and downhill sections by using the flat sections as the standard, that is, by subtracting the estimate for the flat section from the estimate for the graded section. Similarly, to assess the effect of superelevation on accidents, the estimated excess superelevation at accident sections was calculated by using the comparison sections as the standard reference. Thus, negative excess resulting from a comparison of a specific section with a standard section indicates deficient superelevation.

RESULTS

The regression coefficient of superelevation on curvature, A_{1s} in Equation 1, was predictably negative and statistically significant for all combinations of state, roadway class, vertical alignment, and section type.

The superelevation deficiency estimates for all uphill and all downhill comparison sections (upstream and random) are plotted in Figure 1 by state and road class. Sections with substantial curvature and grade had deficient superelevation except for primary roads in New Mexico. This was true regardless of the direction of turn. In all four cases, the intercepts of the regression lines describing superelevation as a function of curvature were found to vary significantly by grade. The regression coefficients of curvature were significantly different by grade for all cases where deficient superelevation was found (i.e., except for primary roads in New Mexico). It should be noted that for sections with positive vertical alignment the results display a somewhat erratic pattern for primary roads; this is probably because of the small sample sizes (N = 25 in New Mexico and N = 22 in Georgia).

For accident sections, the regression lines did

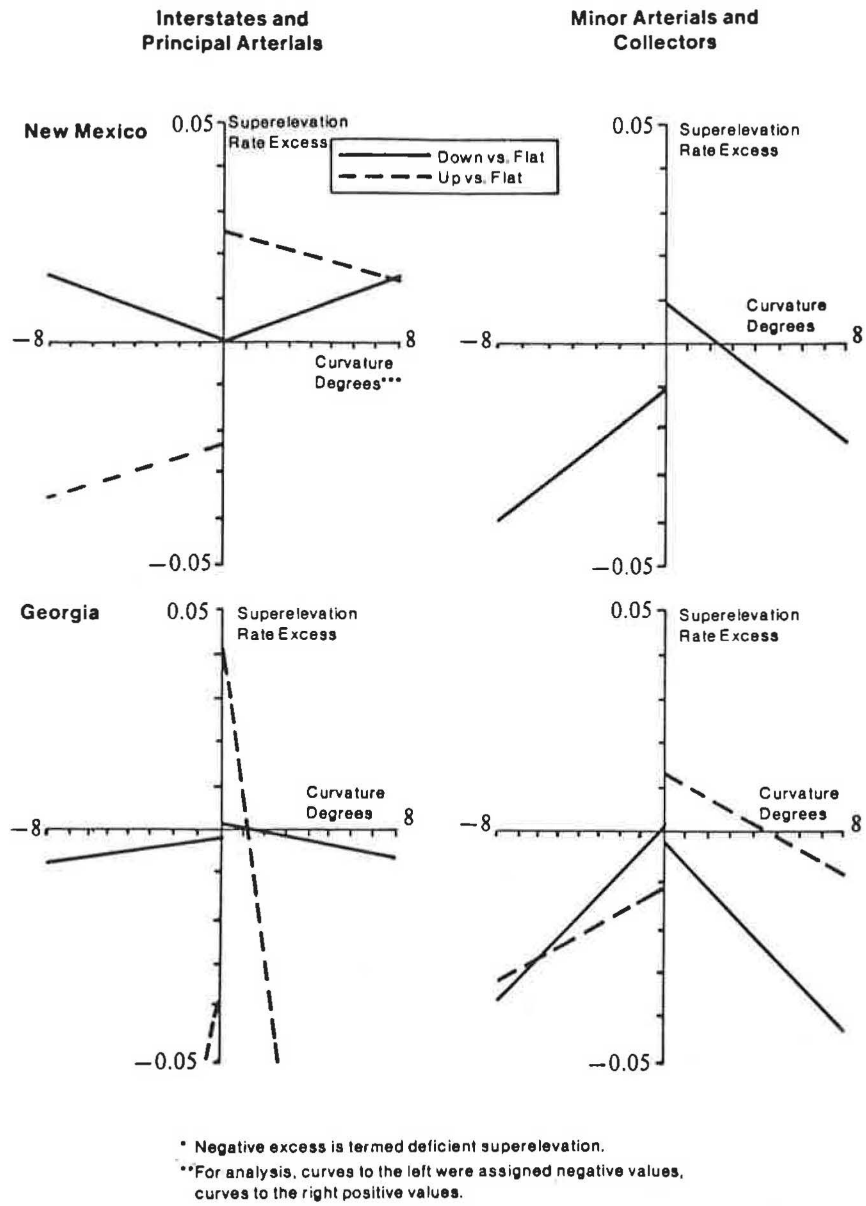

FIGURE 1 Excess of superelevation for roadway sections with uphill or downhill grades versus flat sections based on regression estimates for comparison sites by state, road class, and vertical alignment.

not vary significantly by grade. For downstream sections, there was significant variation in the slopes of the regressions by grade for primary roads in Georgia, and superelevation deficiencies were observed for sections with higher curvature values.

The excess in superelevation for accident sections relative to that of comparison sections is plotted for flat sections in Figure 2 by state and road class. A consistent pattern of deficiency is indicated with the single exception of right-curving sections on secondary roads in New Mexico. In all the other comparisons by state and road class, the regression coefficient of curvature varied significantly by section type.

For sections with grade, the regression coefficients for curvature varied significantly by section type only for primary roads in Georgia. Overall, the results indicated a deficiency for sections with downhill vertical alignment. For sections with uphill vertical alignment the sample size was small (N = 22), and the results showed superelevation excess.

The proportion of accident sections among flat accident and comparison sections was modeled as a function of curvature, grade, and superelevation excess by using the method of logistic regression (8). The results are given by direction of curve, road class, and state in Table 1. As an illustration, among left curves on secondary roads the estimated proportion (p) of crash sections in New Mexico is $p = 1/(1 + e^{-x})$ where $x = -0.78 - 0.31c - 0.12g - 0.26s$ (c = curvature, g = grade, and s = superelevation excess). Note that this proportion of accident sections increases for sharper left curves, steeper downgrades, and increasing superelevation deficiency.

As the chi-square results in Table 1 show, the model accounted for a significant amount of the variation in the proportion of accident sections in all eight analyses. The rank correlations between

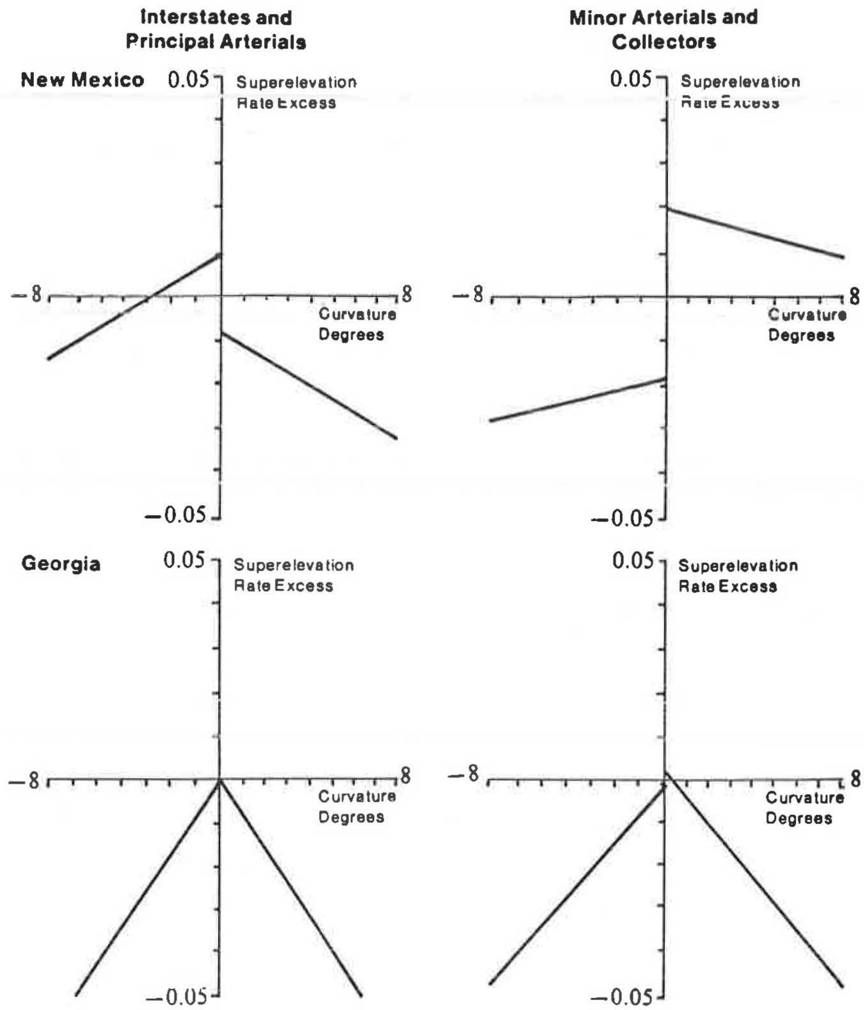

FIGURE 2 Excess of superelevation rate at accident sites over superelevation rate at comparison sites based on regression estimates for flat roads by state and road class.

TABLE 1 Determinants of Accident Sites: Comparison of Accident and Comparison Sections with Flat Vertical Alignment by State, Road Class, and Direction of Curve

		Interstates and Principal Arterials		Minor Arterials and Collectors	
Direction of Curve	Parameter	New Mexico	Georgia	New Mexico	Georgia
Left	Intercept	1.01[a]	−1.21[b]	−1.00[b]	−0.78[a]
	Curvature	−0.08	−0.38[a]	−0.09	−0.31[b]
	Grade	0.67[b]	−0.42	−0.53[a]	−0.12
	Excess superelevation	0.21	−0.22	−0.22[c]	−0.26[b]
	Chi-square (3 DF)	15.7[a]	17.6[b]	18.0[b]	36.6[b]
	Concordant pairs	0.74	0.70	0.71	0.71
	Rank correlation	0.49	0.41	0.44	0.42
	N (accident)	78	58	51	117
	N (comparison)	31	79	74	93
Right	Intercept	−1.21[c]	−0.75[c]	−1.53[a]	−0.76[a]
	Curvature	0.54	0.63[a]	0.44[a]	0.21[a]
	Grade	−0.65[b]	0.13	−0.73[c]	0.01
	Excess superelevation	−0.34[c]	0.01	1.20[b]	−0.19[b]
	Chi-square (3 DF)	20.7[b]	15.2[a]	39.7[b]	17.7[b]
	Concordant pairs	0.75	0.66	0.86	0.69
	Rank correlation	0.50	0.35	0.73	0.40
	N (accident)	45	66	34	72
	N (comparison)	59	52	42	83

Note: Dependent variable y = 1 for accident sites and y = 0 for comparison sites. DF = degrees of freedom.
[a]Significant at 0.01 level.
[b]Significant at 0.001 level.
[c]Significant at 0.05 level.

predicted probability and observed response varied between 0.35 and 0.73. The proportion of accident sections increased for sharper curves in all eight analyses, and this effect was statistically significant in five analyses. Although in these analyses of flat sections grade was limited to the range from -2.5 percent to +2.5 percent, the proportion of accident sections increased for steeper downgrades in five of eight analyses and in three of four analyses where the effect was significant. The proportion of accident sections also increased with increased superelevation deficiency in five of the eight analyses and in four of the five analyses when the effect was statistically significant. (The one anomalous result appears to be statistically unstable.) The adverse effects of sharp curves, downhill grades, and superelevation deficiency are most clearly present on secondary roads.

DISCUSSION AND CONCLUSIONS

The relationship between superelevation and grade was examined for roadways in New Mexico and Georgia. Compared with rates for flat road sections, the rates of superelevation were found deficient on both uphill (grade greater than +2.5 percent) and downhill (grade less than -2.5 percent) sections. Because these results were based on comparisons between the linear regression estimates of superelevation rates as functions of curvature, the deficiency in superelevation cannot be due to curvature differences between flat road sections and those with grade. This finding holds true for many of the parameters examined, including state, road class, and section type, although the strength of the relation did not reach statistical significance in all comparisons. However, in all cases with statistically significant differences the sections with uphill or downhill grades were deficient in superelevation.

Superelevation is intended to counter the outward forces generated when the direction of the vehicle's motion changes along curved paths of travel. Because speeds on downhill grades tend to be higher than on otherwise similar flat grades and the outward forces increase with speed, the superelevation rates on such grades should not be less than those at comparable flat curves. If downhill grades were designed for realistic travel speeds, the rate of superelevation would be higher at curves with downhill grades than that at comparable flat curves because of the higher average speeds of vehicles traveling downhill. Although AASHTO only partially endorses a policy of using increased banking to adjust the design speed on downhill curves to allow for the higher speeds of travel on such curves (9,p.194), the prevalence of reduced superelevation rates at such locations is clearly dangerous. In computer simulation analyses with the highway-vehicle-object simulation model (HVOSM) it was found that the most critical parameter in assessing friction demands on curves was the vehicle speed (10). Increasing the operating speed of the vehicle 12 mph increased tire versus pavement friction needs by at least 50 percent, which was often significantly above AASHTO design values.

The superelevation rates at accident sections were found to be deficient compared with those at comparison sections. Because these analyses were also adjusted for curvature, this deficiency cannot be due to curvature differences. Although statistical significance was reached mostly for flat road segments (-2.5 percent to +2.5 percent grade), this finding is also generally valid regardless of state, road class, and grade. Moreover, a majority of the logistic regression analyses for separating accident sections from comparison sections in terms of grade and curvature were significantly improved when a measure for superelevation deficiency was added to the other alignment measures.

Other roadway characteristics that may be statistically associated with the occurrence of single-vehicle rollover accidents (e.g., pavement condition, maximum superelevation rate, and design speed) were not considered in this paper. Although the effects of these characteristics on accidents, if any, were partly controlled for in that approximately three-quarters of the comparison sections were located on the same roads (1 mi upstream from the accident site) as the accident sections, these results should not be construed to mean that the three roadway alignment components are the only important environmental factors playing a role in single-vehicle accidents.

A possible explanation for the observed deficiency of superelevation at curves on grades is that current design practices were not successfully applied. In general, this does not appear to be the case. However, because many of the roads investigated have been in use over a considerable time, their superelevation deficiencies may be the result of out-of-date design, construction, or maintenance practices. The possibility of the settling of road foundations cannot be excluded. However, the analysis indicated that accident sections had significantly lower superelevation rates (particularly for flat curves) than nearby downstream sections. Alternatively, it is possible that in many instances the design speed is simply set too low, so that the superelevation is nominally adequate but not in line with actual travel speeds.

Regardless of the historical causes, the widespread deficiencies found in the rates of superelevation at locations where challenging road geometry tests both driving skills and vehicle handling present a clearly defined added risk that should be systematically monitored and gradually eliminated from the roadway system.

Discussion

Timothy R. Neuman*

The authors of this paper are to be commended for addressing a subject that receives too little attention. Appropriate design of highway curvature must include consideration of superelevation. Much recent research, including other studies published by these same authors, strongly demonstrates the importance of highway curvature in safe operation of high-speed highways. It is also noted that studies of this nature that address minutely varying design elements are extremely difficult to conduct. It is remarkable that any sensitivities were uncovered at all, given the narrow range of superelevation variance and the many other factors that play a role.

In general, the findings reported here appear reasonable. However, certain important questions need addressing before full acceptance of the research is possible. These questions relate to certain unmentioned but important variables and apparent assumptions that may be imprecise.

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First, the research focuses exclusively on the deficiencies in superelevation at curve sites. It is noted that, among other factors, pavement friction plays a role in vehicle stability. Clearly, available pavement friction and its relationship to vehicle dynamics as well as its distribution at accident versus comparison sites should be considered. Assumed friction factors for design purposes are nominally equivalent to superelevation, as shown by the standard curve formula

$$e + f = V^2/15R$$

where

- e = superelevation (ft/ft),
- f = friction,
- V = design speed (mph), and
- R = radius of curve (ft).

Identically designed curves (in terms of superelevation and radius) would have distinctly different safety and operating characteristics given actual differences in pavement friction. This, in fact, is shown by previous research, including detailed studies of highway curves recently completed by Jack E. Leisch and Associates (JEL) for FHWA. In those studies, available pavement friction was found to be a small but significant variable in prediction of high-accident curve sites. The fact that comparison sites were closely downstream from the curves in the data base does not totally control for pavement friction variances. Pavement wear is variable, with curves (particularly sharper ones) wearing faster than tangent sections.

An additional variable of extreme importance is that of the method of developing superelevation and its effects on dynamics and safety. Analysis of vehicle behavior on approaches to curves shows the transition area (150 ft each side of the PC) to be the most critical part of the curve. Again, identically designed curves in terms of radius and maximum superelevation would operate differently under various methods of developing the superelevation. (It is noteworthy that the JEL curve studies uncovered a slight but statistically significant contribution of amount of superelevation at the PC to high-accident location prediction.)

The statistical analysis itself is predicted on a simplification of the relationship between curvature (defined in terms of degree of curve) and maximum superelevation. The simplification, that the two are linearly related, causes potential problems given that the true relationship is nonlinear. Figure 3, the design curves of superelevation for e_{max} of 0.10, demonstrates the true nonlinear relationship. (It is assumed here that curves in the study sample were designed to a nonlinear policy similar or identical to the relationship shown in Figure 3. This is undoubtedly the case, because design practice in this area has remained essentially unchanged for many years.) If the sample of accident sites is even slightly overrepresented by curves of greater than 5 or 6 degrees, a different linear model would be expected than one created by comparison sites. In other words, differences between the two models may be explained more by the underlying sample distributions of curvature within the accident and comparison sites than by differences in design of superelevation. This point is important given that differences that were observed were very slight (which would be expected given the narrow design range of superelevation).

A far more important question, and one that appears to be at the heart of the authors' findings, is the subject of design speed. In attempting to explain the reasons for accident occurrence, the authors focus on superelevation deficiency. It is more likely, and entirely within reason given the type and age of roads in the study sample, that design speed explains the results. Many of the curves are undoubtedly designed for a speed much too low for prevailing operating conditions. Such curves could be characterized as deficient in terms of superelevation. More likely, and more to the point in terms of design, the deficiency is in the curvature itself.

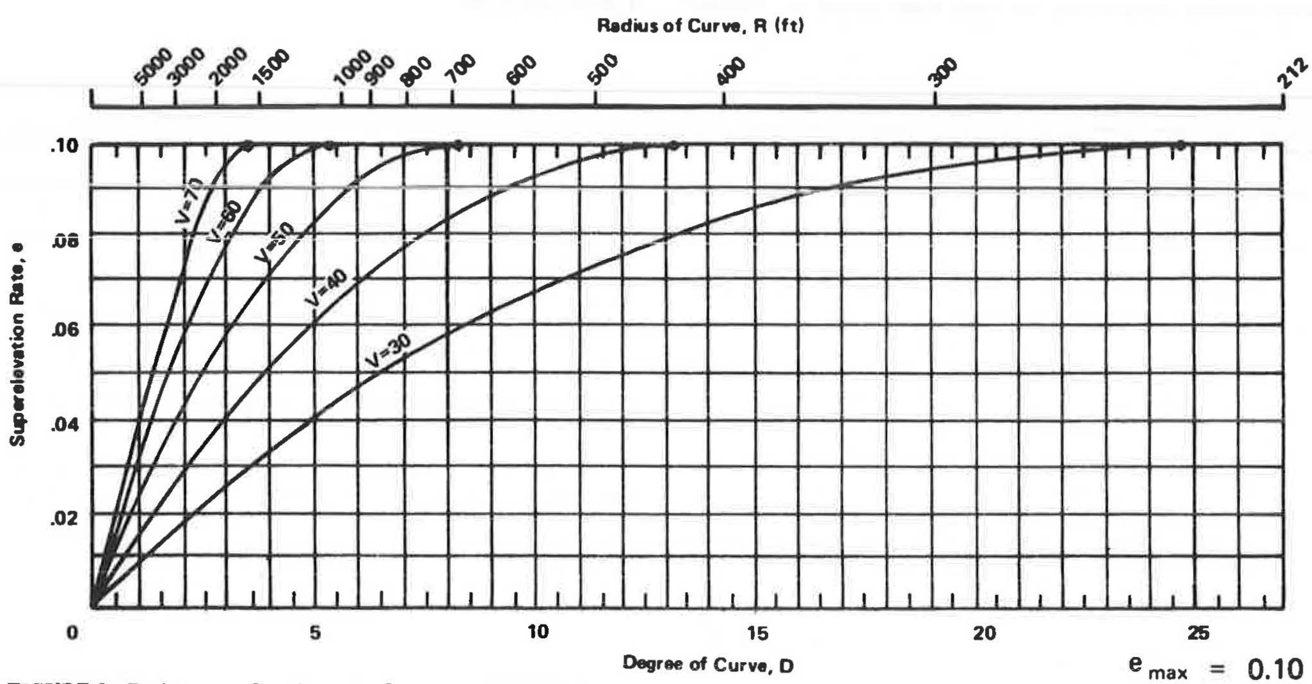

FIGURE 3 Design superelevation rates for e_{max} = 0.10 *(9)*.

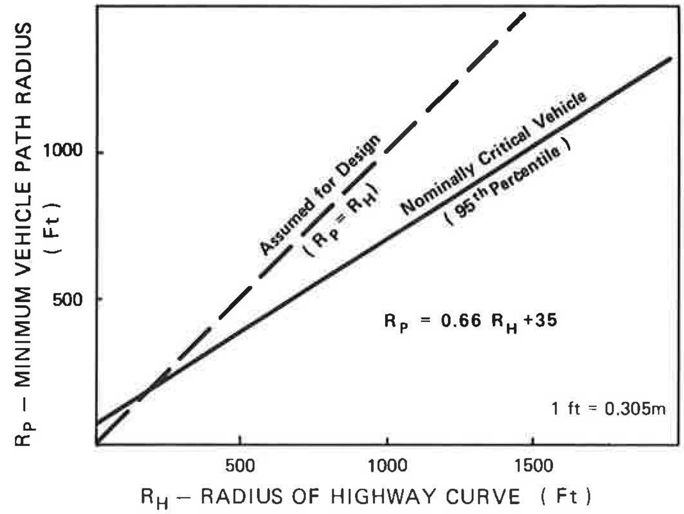

FIGURE 4 Relationship of vehicle path curvature to highway curvature *(11)*.

Glennon et al. demonstrated, in a recently published study of operations on highway curves (11), that the combination of entering speed and curvature is by far the most critical factor in vehicle control. Figure 4 shows the results of vehicle tracking behavior, which is strongly related to roadway curvature. To summarize, drivers tend to "overdrive" curves, that is, to track transient paths sharper than the curvature of the roadway. Furthermore, drivers' approach speeds are influenced very little by the impending curve, whether it is visible, signed, or not evident. Drivers also tend not to adjust their speed completely until they are well within the curve. Curves that are too sharp for the prevailing speeds of a given highway are thus prime candidates for the types of overturn and run-off-the-road accidents discussed here. And, in general, such curves tend to be so underdesigned (i.e., have nominal design speeds much lower than the operating speed) that marginal improvements to superelevation would be of little or no help.

To conclude, I agree that proper superelevation design is critical to safe operations on curves. However, more fundamental questions that appear to be addressed here are what the relationship is between curvature and design speed and what factors determine a safe and reasonable design speed for a curve.

Authors' Closure

We agree with Neuman that design speeds should be in line with the prevailing operating conditions. Slow design speeds are compatible with sharp curves, and a series of studies (3-6) sponsored by the Insurance Institute for Highway Safety over the last decade, including the study on which this paper is based, have demonstrated that the likelihood of single-vehicle crashes is greatly increased on curves of greater than 6 degrees, even where these curves are adequately superelevated. The new findings in this study were that inadequate superelevation poses additional hazard to drivers and that superelevation tends to be inadequate on roadways with grades. The first of these two findings was apparently also confirmed in the JEL curve studies referred to by Neuman.

We also agree with Neuman that the choice of proper curves to match operating conditions and the choice of proper superelevations for these curves are fundamental to safe road design. If these choices are not correct, the curve will be underdesigned both in terms of its curvature and its superelevation. This, as Neuman points out, could be especially hazardous for drivers whose actual travel path is even sharper than that of the curve.

In his discussion of the statistical methods, Neuman notes that if the sample of accident sites contains more curves of greater than 5 or 6 degrees than does the sample of comparison sites, the reported superelevation deficiency at the accident sites may have been caused by incorrectly modeling the concave superelevation-curvature relationship by linear regressions (Figure 3). This observation is correct in theory, but it does not apply to most of the data analyzed in the paper (see Table 2). For the four matched comparisons between left and right curves in the two states that involved accident and comparison sites on flat (between -2.5 percent and +2.5 percent grade) primary roads, it can be seen from Table 2 that the 95th percentiles of curvature for the comparison sample always exceed those for the accident sample. Also, all four of the latter were below 5 degrees, which is well within the range over which the design superelevation-curvature function is linear.

For secondary roads, the situation is less clear-cut because all eight 95th percentiles of curvature exceeded 6 degrees and the 95th percentile of curvature for the accident sample was below the 95th percentile of the comparison sample only for right curves in New Mexico. It should be noted, however, that the operating speeds and the design speeds of these roads would most likely be lower than those on primary roads, and consequently the relationship between curvature and superelevation would remain linear over a larger range (Figure 3). In any case, most of the linear models fit the data quite well and explained about 60 percent of the variability in the superelevation rate.

Commenting on the study design, Neuman noted that it did not totally control for possible differences in pavement friction between the accident and comparison sites. This is true; however, some measure-

TABLE 2 Summary of 95th Percentiles of Curvature and Superelevation Rate Distributions for Flat Curves by State, Road Class, Section Type, and Direction of Turn

		Accident Site		Downstream Site		Comparison Site	
Road Class	Type of Curve	Curvature	Superelevation Rate	Curvature	Superelevation Rate	Curvature	Superelevation Rate
New Mexico							
Primary	Left	4.8	7.2	5.5	5.6	4.8	8.4
	Right	2.9	4.8	2.3	5.8	6.6	7.2
Secondary	Left	14.7	11.3	9.4	8.2	9.4	7.7
	Right	7.0	6.4	7.1	5.6	10.0	8.0
Georgia							
Primary	Left	4.5	9.1	4.5	8.4	5.5	8.8
	Right	2.6	4.6	8.8	8.2	2.8	6.3
Secondary	Left	12.0	8.0	10.5	7.5	6.3	8.9
	Right	12.8	12.6	10.0	6.6	7.4	8.2

Note: Primary road class = Interstates and principal arterials; secondary = minor arterials and collectors. Vertical alignment was defined as follows: down = grade < -2.5 percent, flat = -2.5 to +2.5 percent grade, and up = grade > 2.5 percent.

ments of friction were made in New Mexico and these indicated that no substantial differences in friction existed at matched accident and comparison sites (5). Moreover, even if such differences did exist, it could be argued that inadequate superelevation would tend to result in harder braking in the curve and therefore the superelevation inadequacy itself was the cause of the lowered friction.

It should be noted that the method of developing superelevation may be important for vehicle dynamics, but it is likely that this method was typically the same at accident and comparison sites that were only 1 mi apart. Because most of the comparison data in this study were collected at these matched sites, the effect on the results of such differences should be minimal. More generally, the matching technique used in these studies controlled for the effects of most other design-related differences as well.

The main findings are as follows:

1. After adjustment for curvature, it was found that in comparison with flat roadway sections (grade +2.5 to -2.5 percent) sections with grade (greater than +2.5 or less than -2.5 percent) had less superelevation.
2. After adjustments for both curvature and grade, sections with fatal rollover accidents were found to have less superelevation than comparison sections.

As stated in the paper, it is not yet known why these differences in superelevation exist. Possible explanations are being researched, but the lack of explanation for the differences does not diminish their importance. In addition, the adequacy of the key geometric design features (e.g., design speed, curvature, gradient, and superelevation) should be carefully assessed when roadway maintenance and rehabilitation are undertaken, and deficiencies should be corrected regardless of their source.

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