# Relationships Between Vertical and Horizontal Roadway Alignments and the Incidence of Fatal Rollover Crashes in New Mexico and Georgia

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**Survey data on curvature and grade collected at the sites of fatal single-vehicle rollover crashes and at random comparison sites in New Mexico and Georgia were analyzed to determine the relationship of horizontal and vertical alignment to such crashes. The results showed that road sections with extreme horizontal and vertical alignments were as much as 50 times more common at crash sites than at comparison sites. Although sharp left curves and steep downgrades were overrepresented in both states, the relative importance of downgrades was greater in New Mexico than in Georgia. Because the relative importance of the two alignments can be expected to vary in other states as well, no overall set of priorities for hazard identification was developed. It is recommended that each state develop its own priorities for hazard identification based on comparisons between the bivariate curve-grade distributions of fatal single-vehicle crash sites and those of a representative roadway sample. A method for setting such priorities that can be used by individual states is presented.**

In a recent review of the condition of highway systems in the United States (*1*) it was concluded that about two-thirds of all rural roadways were deficient in terms of pavement condition, geometric design, cross section, or operational features. Some geometric design deficiencies were present in about one-third of all rural roadways. Almost 90 percent of the deficient road sections were on rural collectors. In view of the substantial "substandard safety and geometric characteristics" found on segments of the rural collector system, it is not surprising that although rural collectors accounted for only less than 10 percent of all vehicle miles traveled in 1981, their share in fatal crashes was more than 15 percent (*2*). This situation is unlikely to improve substantially in the foreseeable future; it has been estimated by the U.S. Department of Transportation that less than half of the annual expenditure of $3.8 billion needed to eliminate all deficiencies will be available over the next 20 years (*1*). There is no evidence that safety-related projects will be funded above average levels; thus it is of paramount importance that available funds be allocated in the most effective manner. A critical step in the cost-effective allocation of the available funds for the improvement of the geometrical design of the highway system is the identification of hazardous sites.

Most methods for identifying hazardous sites rely on past crash experience or on inventories of roadway and roadside features. The methods based on crash rates or crash counts assign a high priority to upgrading sites that had more crashes than was typical of other roadways with similar characteristics (*3–5*). Such sites with high crash rates are often referred to as "black spots." However, most short roadway sections rarely have more than one or at most two crashes in a given period, regardless of how hazardous they may be. Moreover, some sections that are not particularly hazardous could also have one or more crashes due to driver error, weather conditions, or a combination of very unusual circumstances. Because of such random fluctuations, crash rates for short sections based on short time periods are not effective measures of hazardous operational features such as adverse road geometry. Aggregating crashes over longer sections and longer time periods, or both, would reduce the fluctuations but only at a cost. Because roadway geometry typically varies substantially along most roads, aggregation over long stretches of roadways would dilute the effect of severely adverse geometrical hazards and therefore make it impossible to set optimally cost-effective priorities for their reduction. Waiting for crash data to accumulate before a hazardous site is corrected is rarely cost-effective or even tolerable. In any case, as Hauer and Persaud have shown (*6*) in their study of the regression-to-the-mean phenomenon, the severe selection bias that arises in studies of black spots persists even if the crash histories extend over many years.

Inventory-based models typically involve developing indices to rank the severity of specific roadside hazards and their potential for involvement in a collision (*7–11*). In these models it is recognized that the probability that any specific roadway section will be the site of a crash is low. The crash event is thought of as a chain of minor events with low individual probabilities. These probabilities are estimated and multiplied, and their products are summed to obtain the overall probability of the crash. For example, in the Glennon model (*7, 8*) an injury-producing roadside fixed-object crash is defined as the sequence of four conditional events:

1. The vehicle is within the incremental part of the roadway where collisions with roadside objects are possible,
2. There is an encroachment onto the roadside,
3. The lateral displacement of the vehicle is sufficiently large to permit a collision with the object, and
4. The collision is of sufficient magnitude to produce an injury.

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This type of model is difficult to validate, because the incidence and severity of injuries depend on many factors such as occupant age, restraint use, and vehicle design and because implementing such models requires collecting vast amounts of data. These include measures for estimating the potential for roadside encroachments, complete inventory (e.g., type and location) of all roadside features and fixed objects, the injury-reducing potential of improvements, and the costs associated with each candidate roadside improvement scenario.

In 1974, Wright and Robertson (*11*) compared the roadway alignments found at the sites of fatal fixed-object crashes with the alignments at comparison sites chosen 1.6 km (1 mi) away from these crash sites. In subsequent studies with similar designs, the alignments at fatal rollover crash sites were assessed by Wright and Zador (*12*) and Hall and Zador (*13*). All three studies reported that the two most important features that distinguish crash sites from comparison sites are horizontal and vertical roadway alignment. Specifically, sharp curves (5 to 6 degrees or greater) and steep grades (3 percent or greater) are significantly associated with crash sites.

In other research, the influence of geometric design on crash rates has been analyzed in terms of single factors without detailed analysis into the combined effects of grade and curvature. Most crashes occur on straight and level sections of the roadway; however, curved sections with steep grades generally have higher crash rates. Several studies have computed the crash rates of roadway sections by curvature and have reported that higher crash rates are associated with sharper curves, more frequent curves, and isolated sharp curves (*14*). It was also found that crashes on curves tend to be more severe than crashes on tangent sections (*3*). Studies of vertical alignment have found that roads with steep grades, particularly in combination with sharp curves, have higher crash rates (*14*). However, crash rates of tangent sections were reported to be not significantly influenced by grade. Despite the vast body of evidence that poor geometric features are associated with crash sites, only a few of the hazard location models explicitly consider them (*9, 11*). A survey of state highway departments found that although most employ formal guidelines for selection of sites for implementation of low-cost countermeasures, few consider roadway geometry as a factor (*15*). The most common factors were crash history and traffic volume.

In this paper detailed comparisons between fatal rollover crash sites and comparison sites are presented in terms of both vertical and horizontal alignments. A procedure for incorporating results of this type in an effective strategy for reducing the frequency of fatal single-vehicle crashes is also outlined.

## METHODS

### Data Collection

The data for these analyses are from four independent sources: studies of fatal single-vehicle rollover crashes in Georgia (*12*) and New Mexico (*13*) and surveys of randomly selected sites in these states. Engineering surveys were conducted, usually by three-person teams, at the locations of fatal rollover crashes and at the comparison locations. The surveys were confined to a 0.3-km (0.2-mi) section at each of the locations. The measurements at the crash location were referenced to the point along the roadway edge at which the rollover of the vehicle commenced, which is termed the crash reference point. As shown in Figure 1, a point 1.6 km before the crash reference point was designated as the comparison site. In the location of comparison sites, turn choices at T- or Y-intersections were made at random (by flipping a coin).

Measurements of curvature were made beginning 15 m (50 ft) from the crash and comparison sites and at 30-m (100-ft) intervals for 137 m (450 ft) both upstream (before the site in the direction from which the vehicle approached) and downstream (beyond the site in the direction in which the vehicle was traveling) from these sites. The gradient was measured every 30 m for 152 m (500 ft) both upstream and downstream from the sites. Thus, 10 curvature and 11 gradient measurements were obtained for each crash site and its comparison site.

A 30-m cloth tape was used for measuring distances. Horizontal curvature was measured by the middle ordinate method. The curve measurements were usually taken on the edge of the roadway. The middle ordinates were converted to degrees of curvature of the centerline of the roadway. Gradients were measured at the center of the lane used by the driver approaching the crash location. Measurements were made with a specially designed instrument consisting of a 1.2-m (4-ft) carpenter's level with an adjustable calibrated leg. On Interstate highways, curvature and gradient data were taken from plan and profile sheets.

Rollover crash and comparison data provide insight about the role of various geometrical and roadway features relevant to crashes, but they do not necessarily provide a representative sample of roadways in either state. Typically, the comparison was on the same road as the crash site and thus many features were similar. For example, roadway characteristics such as pavement width and shoulder width and delineation were typically the same in both the crash and comparison sites. Features such as roadside object density and characteristics were also similar. More important, the influence of the terrain on horizontal and vertical alignment was similar. Although previous analyses had found that the crash sites had more severe alignments than the comparison sites (*12, 13*), these differences may have been underestimated because of the proximity of the comparison sites to the crash sites.

To address these issues, random sample surveys of the rural road systems were performed at 300 sites in each state. A two-way classification of rural roadways by average daily traffic and roadway function was obtained for Georgia and New Mexico. One-half of the survey sites were assigned in proportion to roadway mileage alone; the other half were selected in proportion to estimated miles traveled. After the number of sections was computed, specific sections were identified by randomly selecting milepost locations from computerized roadway files maintained by the states. The geometric data collected at the random sites also included the middle ordinate (curvature) and the gradient 15 m (50 ft) before and after the random site. The distribution of all the sites included in this analysis (i.e., crash, comparison, and random survey) by roadway functional class and average daily traffic is shown in Tables 1 and 2, which also include the distribution of rural system miles in each state.

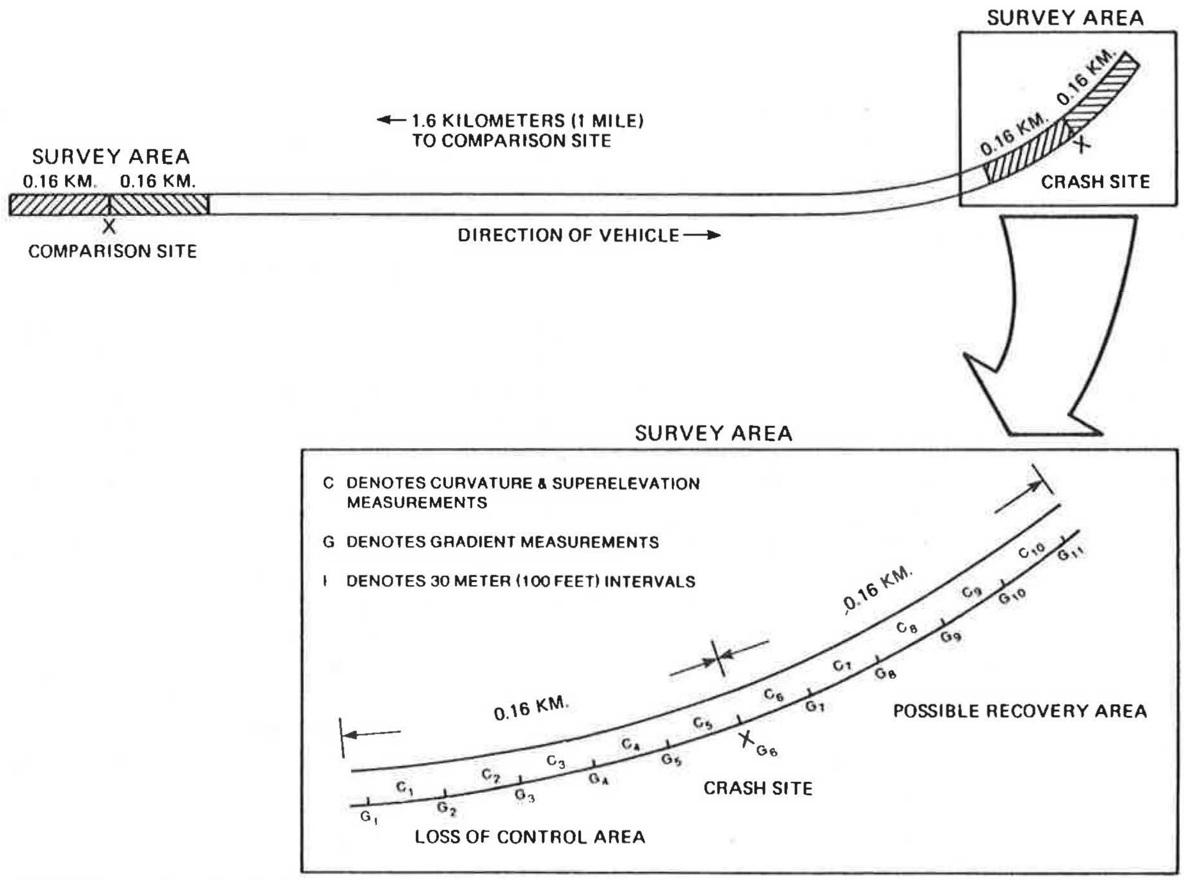


**FIGURE 1 Hypothetical fatal crash and comparison sites.**

## Analysis

As Figure 1 shows, curvature and grade were measured at alternate intervals 15 m apart. For the purpose of the present analyses, the curvature for left-turning roads and the grade for downhill roads were assigned minus signs. The 10 curvature measurements were taken in consecutive pairs and the paired curvature measurements at the beginning and end of the nine 50-m-long sections were averaged. The corresponding (weighted) average grade was calculated as one-fourth times the grade of the preceding section plus one-half times the grade for the section and one-fourth times the grade for the following section. These averages were used to represent the sections' curvature and grade.

Within each state, the sections surveyed at crash sites were grouped in terms of their position with reference to the actual crash reference point, marked *X* on Figure 1, where the vehicle left the road. Three of the sections immediately upstream from position *X* on Figure 1 were classified as the crash sections, and the last four, which were among those occupying the potential recovery area in Figure 1, were classified as the downstream sections. Sections surveyed 1.6 km upstream from the crash sites are termed comparison sections and sections chosen for the random survey are termed random sections. Thus, four section types were defined in each of the two states.

The analysis consisted of three main steps: determination of curvature and grade percentile distributions, summation of weighted sections, and comparison of the joint distributions of crash and comparison sections. As the first step in the analysis, selected percentiles of the curvature and grade distributions were determined separately for each of the section types in both states. (There is no prior reason for the frequency of sections with right turns or upward slopes to exceed the frequency of sections with left turns or downward slopes at random survey sites. The symmetry of these alignment distributions was achieved by including each random site twice in the analyses, once with the sign as measured for the alignments and once with the opposite sign.) For the random sections, the percentiles were determined by using two different methods for assigning section weights. With one method the sections were weighted in proportion to the total road length they represented. With the other method the section weights were proportional to the aggregate miles traveled on the part of the road system that the section represented.

As the second step, the weights of all sections with curvatures and grades subject to selected constraints were summed by section type. However, regardless of the section type, the constraints were defined in terms of the grade and curvature distributions of the segments from crash sites so that the resulting sums could be compared among the section types. Because extreme curvature and grade values are of primary interest in setting priority rules for hazard location, combined weights were computed for sections with both grade and curvature below or above selected extreme percentiles.

Table 3 shows the method of presentation for the cumulative distributions of road sections given in Tables 4–8. Entries are arranged in four quadrants (shaded) corresponding to the four combinations of the lower and upper tails of the grade and curvature distributions; the unshaded areas represent less extreme combinations of curvature and grade. The percentages shown in the upper-left quadrant correspond to the lower tails of both curvature and grade distribution; those in the upper right correspond to the upper tail for curvature and lower tail for grade; the lower-left quadrant corresponds to the lower tail for curvature and upper tail for grade; and the lower-right quadrant corresponds to the upper tail for both curvature and grade.

Each quadrant representing the extreme combinations of grade and curvature in Table 3 has 25 cells. There are 11 cells on the border of each quadrant representing the corresponding less extreme combinations of grade and curvature. Each cell contains the percentage of the grade and curvature distribution that would fall within the range of values specified for that cell.

The variability of cell estimates depends on sample size. For counted data that can be expected to follow the Poisson distribution, the ratio for the estimates of the standard deviation and the mean is approximately equal to the reciprocal of the square root of the sample size ($n$), so that for $n \cong 10$ this ratio is about $1/3$. For $n$'s much below 10, cell estimates can be quite variable; however, the proposed standard table format with 144 cells need not be changed even for small data sets. This is because cells closer to the center of the table include all the data from the cells farther away from its center. For example, the data in the 100 cells not on the boundary of the table represent the data set as collapsed into its 10-by-10 subtable.

Examples of cell types are given in the following for grade and curvature values that are below the median; examples for the other sections are provided in the notes to Table 3. The 25 cells of the upper-left shaded section represent the extreme combinations of values for both curvature and grade. For example, Cell A is the (weighted) percentage of sections with curvature at or below the fifth percentile and grade at or below the first percentile. Cell D at the border of the lower-right corner is the percentage of sections with both curvature and grade between the 10th percentile and the median. The other five border cells in the same row as Cell D (e.g., Cell B) represent the percentage of sections with grade between the 10th percentile and the median and with curvature corresponding to the percentage given in the column heading. The five other border cells in the same column as Cell D (e.g., Cell C) represent the percentage of sections with curvature between the 10th percentile and the median and with grade corresponding to the row heading for that cell. The bottom row is the marginal distribution of curvatures and the right-hand column is the marginal distribution for grades.

As the third step in the analysis, the joint distribution of

TABLE 1 DISTRIBUTION OF NEW MEXICO RURAL ROAD SYSTEM AND SURVEY STUDY SITES

| | Average Daily Traffic | | | | | |
|---|---|---|---|---|---|---|
| Rural Roadway Classification | 0-999 | 1,000-1,999 | 2,000-3,999 | 4,000-7,999 | 8,000-16,000 | Total |
| **Interstate** | | | | | | |
| State Miles | 0 | 3 | 299 | 365 | 220 | 887 |
| Crash Sites | 0 | 0 | 13 | 13 | 14 | 40 |
| Comparison Sites | 0 | 0 | 13 | 13 | 14 | 40 |
| Random Sample Sites | 0 | 0 | 14 | 28 | 30 | 72 |
| **Principal Arterials** | | | | | | |
| State Miles | 519 | 717 | 684 | 154 | 76 | 2,150 |
| Crash Sites | 7 | 14 | 12 | 2 | 3 | 38 |
| Comparison Sites | 7 | 14 | 12 | 2 | 3 | 38 |
| Random Sample Sites | 12 | 23 | 32 | 12 | 11 | 90 |
| **Minor Arterial** | | | | | | |
| State Miles | 1,258 | 382 | 90 | 31 | 3 | 1,764 |
| Crash Sites | 7 | 6 | 1 | 2 | 1 | 17 |
| Comparison Sites | 7 | 6 | 1 | 2 | 1 | 17 |
| Random Sample Sites | 28 | 12 | 4 | 3 | 2 | 49 |
| **Collector** | | | | | | |
| State Miles | 5,263 | 348 | 166 | 54 | 1 | 5,832 |
| Crash Sites | 18 | 6 | 2 | 1 | 0 | 27 |
| Comparison Sites | 18 | 6 | 2 | 1 | 0 | 27 |
| Random Sample Sites | 67 | 11 | 7 | 4 | 0 | 89 |

## TABLE 2 DISTRIBUTION OF GEORGIA RURAL ROAD SYSTEM AND SURVEY STUDY SITES

| | Average Daily Traffic | | | | | | |
|---|---|---|---|---|---|---|---|
| **Interstate** | 0-9,999 | 10,000-19,999 | 20,000-29,999 | 30,000-39,999 | 40,000-60,000 | | Total |
| State Miles | 226 | 292 | 205 | 142 | 22 | | 887 |
| Crash Sites | 1 | 7 | 7 | 3 | 7 | | 25 |
| Comparison Sites | 1 | 7 | 7 | 3 | 7 | | 25 |
| Random Sample Sites | 4 | 13 | 15 | 14 | 3 | | 49 |
| **Principal Arterials** | 0-4,999 | 5,000-9,999 | 10,000-14,999 | 15,000-19,999 | 20,000-29,999 | | Total |
| State Miles | 2,176 | 416 | 78 | 13 | 9 | | 2,692 |
| Crash Sites | 31 | 4 | 0 | 0 | 2 | | 37 |
| Comparison Sites | 31 | 4 | 0 | 0 | 2 | | 37 |
| Random Sample Sites | 28 | 11 | 3 | 1 | 1 | | 44 |
| **Minor Arterials** | 0-999 | 1,000-1,999 | 2,000-2,999 | 3,000-4,999 | 5,000-9,999 | 10,000-39,999 | Total |
| State Miles | 1,199 | 2,355 | 1,224 | 893 | 473 | 115 | 6,259 |
| Crash Sites | 11 | 32 | 5 | 11 | 5 | 2 | 66 |
| Comparison Sites | 11 | 32 | 5 | 11 | 5 | 2 | 66 |
| Random Sample Sites | 8 | 24 | 15 | 15 | 12 | 6 | 80 |
| **Major Collectors** | 0-999 | 1,000-1,999 | 2,000-2,999 | 3,000-4,999 | 5,000-9,999 | 10,000-19,999 | Total |
| State Miles | 10,932 | 2,019 | 602 | 370 | 282 | 59 | 14,264 |
| Crash Sites | 22 | 4 | 5 | 0 | 1 | 0 | 32 |
| Comparison Sites | 22 | 4 | 5 | 0 | 1 | 0 | 32 |
| Random Sample Sites | 82 | 21 | 8 | 6 | 7 | 3 | 127 |

## TABLE 3 BIVARIATE CUMULATIVE DISTRIBUTION OF SECTIONS BY CURVATURE AND GRADE PERCENTAGES

| | | Curvature Percentages | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Lower Tail | | | | | Median | | Upper Tail | | | | | |
| | 0.0 | 0.5 | 1.0 | 2.5 | 5.0 | 10.0 | 50.0 | 10.0 | 5.0 | 2.5 | 1.0 | 0.5 | 0.0 | All |
| Grade Percentages — Lower Tail | 0.5 | | | | | | | | | | | | | |
| | 1.0 | | | | A | | | | | | | | | |
| | 2.5 | | | | | | | | | | | | | |
| | 5.0 | | | | | | C | | | | | | | |
| | 10.0 | | | | | | | | | | | | | |
| | Median (50.0) | | B | | | | D | | | | | | | |
| Upper Tail | 10.0 | | | | | | | F | | | | | | |
| | 5.0 | E | | | | | | | | | | | | |
| | 2.5 | | | | | | | | | | | | | |
| | 1.0 | | | | | | | | | | | | | |
| | 0.5 | | | | | | | | | | | | | |
| | 0.0 | | | | | | G | | | | | | | |
| | All | | | | | | | H | | | | | | |

In this table, roadway sections are accumulated from low to high values below median (lower tail) and from high to low above median (upper tail). Entries are percentages of all sections with both curvature and grade bracketed by the corresponding lower tail (e.g., P0.5) or upper tail (e.g., UP0.5) percentiles, for example:

A: (Curvature $\leq$ P5.0, Grade $\leq$ P1.0),
B: (Curvature $\leq$ P1.0, P10.0 < Grade $\leq$ Median),
C: (P10.0 < Curvature $\leq$ Median, Grade $\leq$ P5.0),
D: (P10.0 < Curvature $\leq$ Median, P10.0 < Grade $\leq$ Median),
E: (Curvature $\leq$ P0.5, UP10.0 < Grade),
F: (Median < Curvature $\leq$ UP10.0, Median < Curvature $\leq$ UP10.0),
G: (P10.0 < Curvature $\leq$ Median, UP0.5 < Grade),
H: (UP10.0 < Curvature).

crash sections by curvature and grade was compared with the joint distribution of random comparison sections. (Comparisons with downstream sections and comparison sections were also made but are not discussed here.) This was done by taking the base 2 logarithms of the ratios of summed weights in corresponding cells. (Use of base 2 logarithms allows quick calculation of ratios to within a factor of 2 for order-of-magnitude comparisons.) Large (positive) values in the resulting ratio table (see Tables 7 and 8) are indicative of more crashes than would have been expected on the basis of proportionality to the weights in the "denominator" table that correspond to the random sections. Large negative values indicate fewer than the expected number of crashes. Zero indicates precisely the expected number of crashes. In the log ratio tables the cells that had zero weights both for the numerator and the denominator are marked by a period. The cells in which there were no crash sites are marked with a minus sign, and cells in which there were no random survey sites are marked with a plus sign. The minus sign in the tables is a reminder of an extreme deficiency in crash sites and the plus sign is a reminder of an extreme excess of crash sites compared with comparison sites.

Thus, entries in the ratio tables based on travel volume make it possible to compare crash rate estimates for travel over roads with differing geometries. For example, if $\alpha$ and $\varphi$, say, are two entries in the same ratio table, then $2^{b-a}$ is an estimate for the ratio of the crash rate per volume of travel corresponding to the cell containing $\varphi$ divided by the crash rate corresponding to the cell containing $\alpha$. Similar calculations using the ratio table based on road miles allow comparisons of crash rates per road mile. It should be noted that straight and flat sections tend to be underinvolved in crashes. Here both underinvolvement and overinvolvement refer to the average, and therefore the overinvolvement of sections with adverse geometry compared with flat and straight sections would be even higher than the numerical values in the table indicate.

## RESULTS

The curvature and grade distributions are plotted in Figures 2–5 on normal probability paper. The estimated percentiles are shown on the vertical axes and the corresponding percentages are plotted on the horizontal axes. In these figures, the horizontal axes are scaled so that normally distributed data would give rise to straight lines. The figures point to marked departures from normal distributions, especially for curvature. In interpreting these figures, it should be kept in mind that the middle positions of the distributions between the 10th and 90th percentile are represented by the 50th percentile only. Because this investigation was concerned with the identification of geometrical hazards, the details of the distributions for the normal ranges of curvature and grade were not explored.

Figure 2 presents the curvature distributions for crash sections, comparison sections, and random sections weighted by

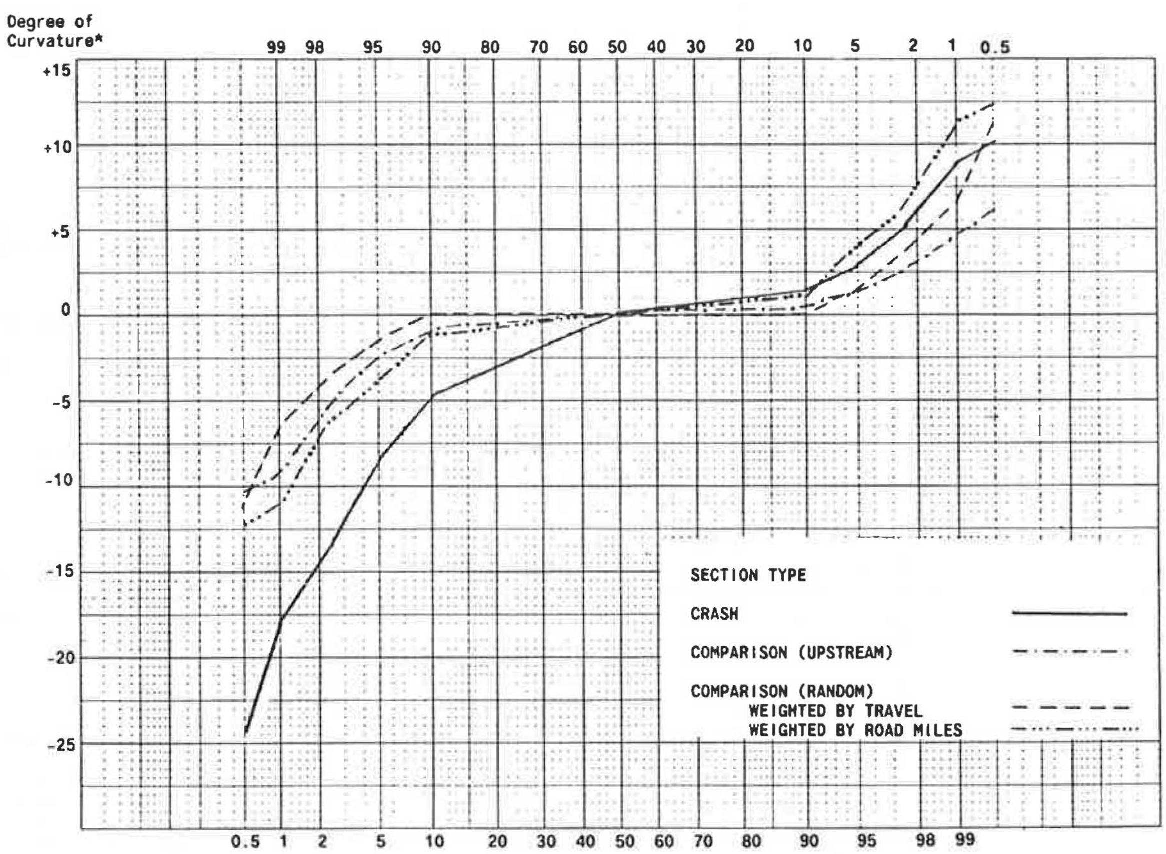


**FIGURE 2 Probability distribution of curvature values in New Mexico by section type.**

both road miles and travel volume in New Mexico. The comparable distributions for Georgia are given in Figure 3. The most remarkable feature of both figures is the evidence for very long left tails corresponding to left curves of the crash site curvature distributions. For example, for both states none of the comparison sites included left curves of 15 degrees or sharper but about 2 percent of the crash sites did. The differences between the right tails of the distributions corresponding to right curves are less pronounced, although this effect is still clear for the Georgia data.

Figures 4 and 5 present the grade distributions for New Mexico and Georgia, respectively. As these figures show, sharp downgrades were considerably more common at crash sites than at any of the other site types in both states, except in Georgia where the upstream sites and the crash sites had nearly identical grade distributions.

The joint curvature and grade distributions for crash sites are given in Table 4 for both states. Cell percentages based on at least 10 sections are marked with an asterisk and have expected standard errors less than or equal to about 30 percent of the estimate. The joint curvatures and grade distributions for the New Mexico random survey sites are given in Table 5 using both travel volume and road miles as the weights. These distributions are presented for Georgia in Table 6. Because the cumulative distributions presented in Tables 4–6 are accumulated from the most extreme to the least extreme cases, they can be used conveniently for setting priorities for roadside hazards.

Tables 7 and 8 present comparisons between the crash and the random survey data. The logarithms of the ratios of the corresponding percentages in Table 4a divided by those in Tables 5a and 5b are given for New Mexico in Tables 7a and 7b, respectively; the corresponding log ratios for Georgia are given in Tables 8a and 8b. As in Table 4, cells based on 10 or more sections are marked with an asterisk.

## HOW TO SET IMPROVEMENT PRIORITIES

Tables 4–8 and Figures 2–5 can be used to assess the importance of improving road sections that have particular combinations of geometric hazards by using the following four-step procedure. (These tables, however, are not intended for direct use in states other than Georgia and New Mexico.)

1. The rate of overinvolvement of sections with a selected combination of curvature and grade is read from Tables 7 and 8.
2. The estimated percentage of travel and road miles corresponding to this level of hazard is determined by reference to Tables 5 and 6.
3. The curvature and grade percentiles are determined from Figures 2 through 5.
4. Table 4 is used to estimate the percentage of fatal rollover crashes that would be reduced by correcting the designated geometric hazards.

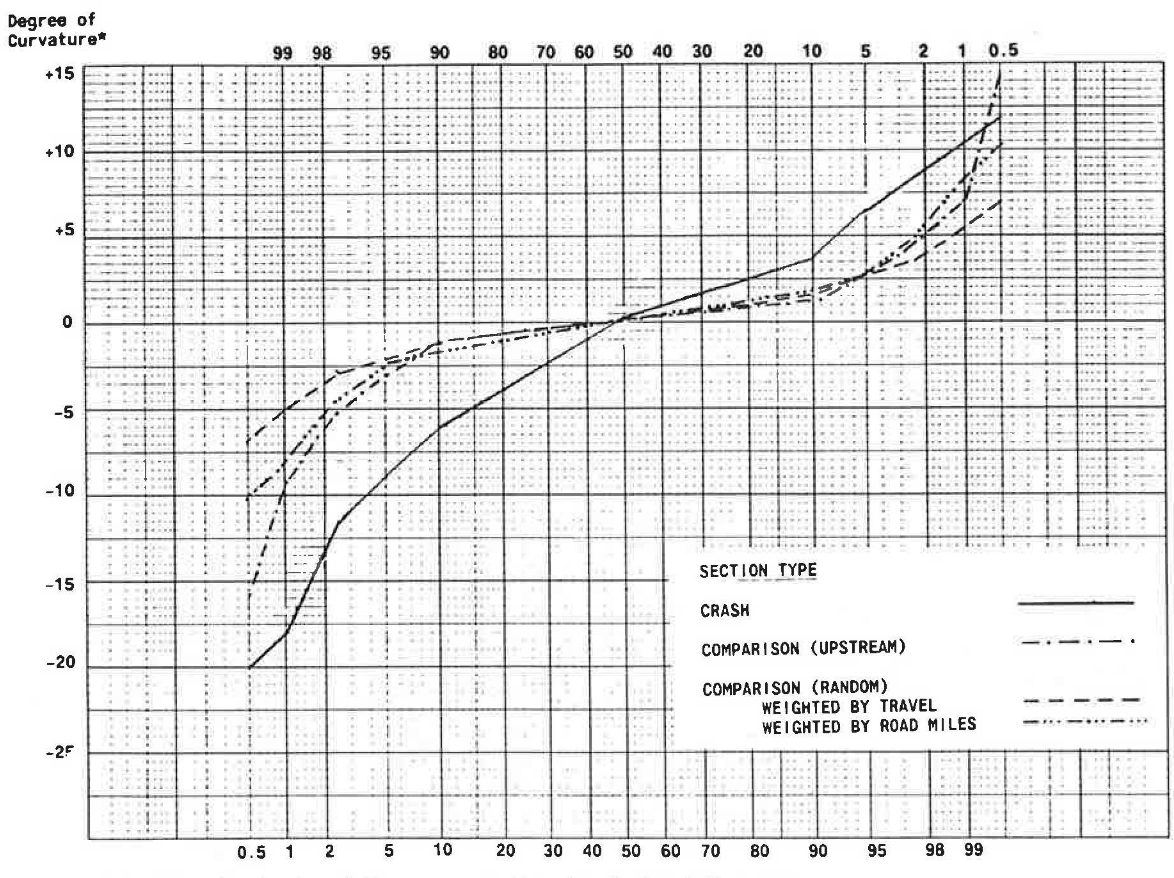


**FIGURE 3 Probability distribution of curvature values in Georgia by section type.**

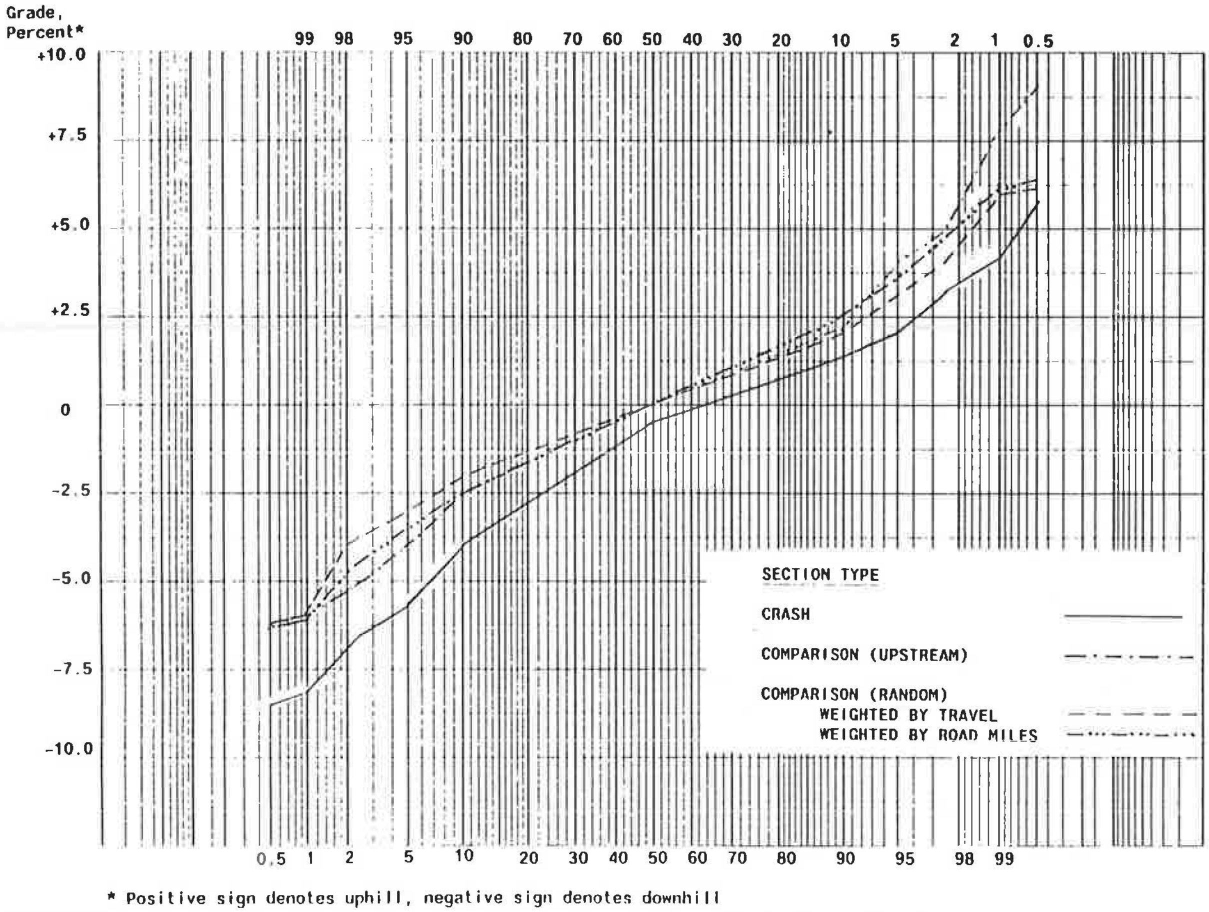


**FIGURE 4 Probability distribution of gradient values in New Mexico by section type.**

This four-step procedure was applied to New Mexico data for sections with curvature and grade at or below the lower tail 10th-percentile cutoff as follows:

1. The value of the logarithm (base 2) in Table 7 is 3.9; therefore, the overinvolvement is $2^{3.9} = 14.9$. This means that such sections have fatal rollover crashes about 15 times as frequently per volume of travel as do the average road sections. The corresponding overinvolvement per mile of roadway is by the factor of $4.6 = 2^{2.2}$.
2. Table 5 shows that 0.24 percent of the travel volume and 0.76 percent of the roadway miles are subject to this level of extreme geometry.
3. Figures 2 and 4 show that the 10th percentiles of curvature and grade are about –5 degrees and –4 percent.
4. Table 4 shows that overall about 3.5 percent of all fatal rollover crashes in New Mexico occurred at crash sites of similar extreme curvature and grade.

Applying the foregoing procedure for Georgia did not produce similarly dramatic results. The overinvolvement rates could not be explicitly estimated because there were in fact no such extreme sections found among the comparison sites in a random sample of 300 sections. However, about 0.4 percent of the crash sections did have curvatures sharper than the 10th percentile for the curvature distribution (6.4 degrees left) and grades steeper than the 10th percentile for the grade distribution (3.3 percent downgrade). Thus, eliminating this small number of geometrical hazards could be expected to reduce fatal rollover crashes by about one-half of 1 percent.

Roadway sections in Georgia with extreme left curves with slight downgrades are of more concern.

1. Sections with curvature below the 10th percentile and grade over the 10th percentile but below the median were overrepresented by a factor of $18.4 = 2^{4.2}$ in terms of travel volume (Table 8a) and by a factor of $55.7 = 2^{5.8}$ in terms of road miles (Table 8b).
2. Only about 0.25 percent of all travel on only about 0.08 percent of all roads occurred at these extremely hazardous sites (Table 6).
3. The 10th percentile of the curvature distribution was –6.4 in Georgia (Figure 3). The 10th and 50th percentiles of the grade distributions were –3.3 and –0.5 percent (Figure 5).
4. These sections accounted for about 4.6 percent of all fatal rollover crashes (Table 4).

As these comparisons between sets of data on fatal rollover crashes in New Mexico and in Georgia show, severe curvature and severe grade may have substantially different relative effects on these events in different states. Part of the New Mexico road system is at very high elevations and severe

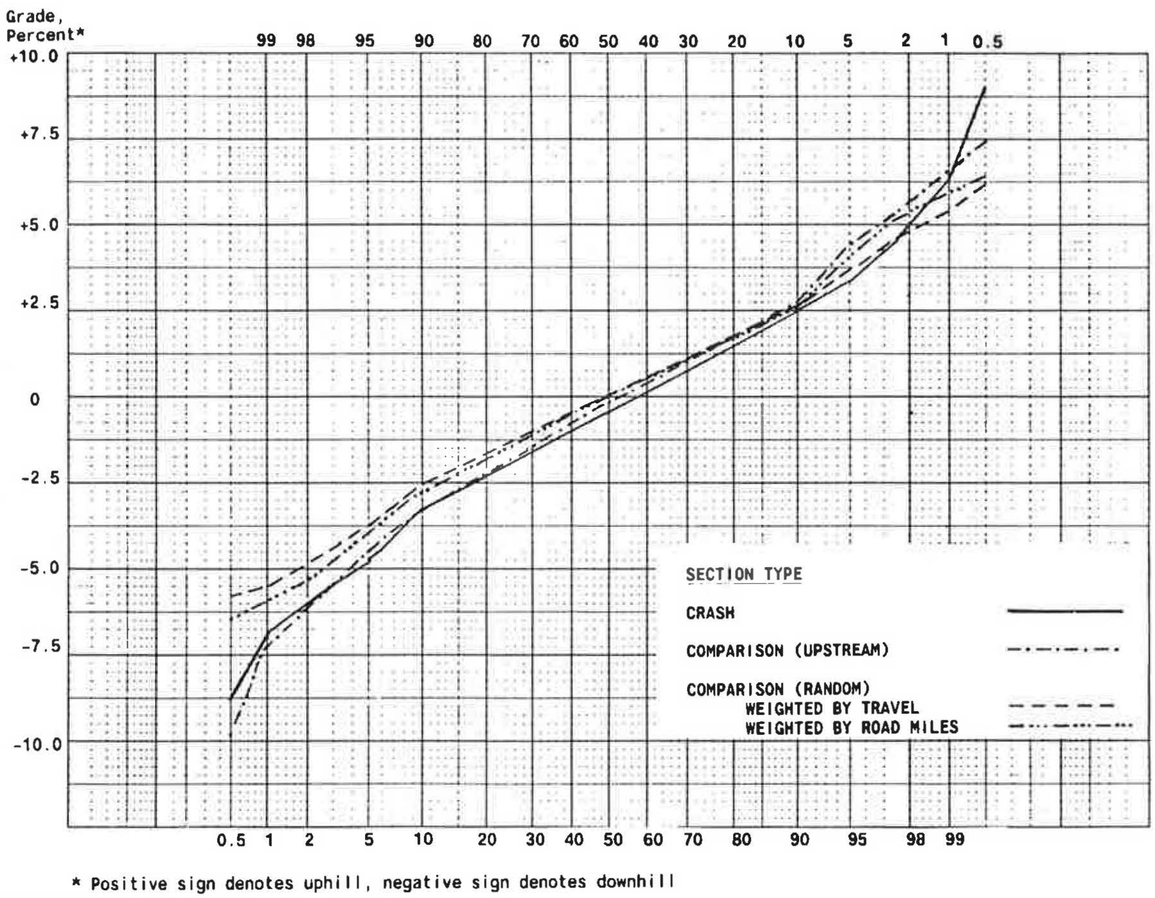


**FIGURE 5 Probability distribution of gradient values in Georgia by section type.**

grades appear to be a significant factor in many of the fatal rollover crashes there. Georgia is generally of lower elevation and severe grades tend to be less important than severe curves. It is probable that each state or geographical region in the United States has its own unique distribution of curvature and grade problems related to fatal rollover or, more generally, fatal single-vehicle crashes. The procedure for setting priorities outlined below is based on the assumption that data bases similar to those assembled in Georgia and New Mexico can be developed for analyses. In the absence of such a data base, some weighted combination of the data from New Mexico and Georgia could be selected to describe the situation in other regions.

This procedure was designed to be both practical and relatively cost-effective. To be practical a procedure must generate candidate sites for improvement in sufficient numbers to allow allocation of available funds. However, it is not necessary to assign priorities to all parts of the roadway all at once. Systematic surveys of all geometric features throughout the state may result in a wasteful allocation of resources because such surveys can be costly even when they identify the right kind of candidate sites.

For the procedure to be cost effective, only candidate sites with very high rates of overinvolvement should be included in the list of proposed improvements and only limited funds and effort should be spent on sites with less than extreme rates of overinvolvement. However, in most states the variation in crash involvement rates due to curvature and gradient is not known. Therefore, the definition of what constitutes overinvolvement in a given state and the selection of sites for proposed improvement need to be carried out at the same time, at least at the outset. Thus the basic steps toward a cost-effective allocation of roadway improvement, described below, will need to be performed repeatedly. Although the preparation of an operational plan is beyond the scope of this paper, a description of the basic steps needed for a cost-effective allocation of roadway improvement funds is provided.

In this paper, overinvolvement rates were compared in terms of miles traveled and in terms of road miles. Although differences between the two measures may exist, they tend to be more of degree than of kind. In any case, the final choice of improvement projects cannot be made without reference to their estimated reduction in risk. Consideration of these factors was, however, outside the scope of this study.

A cost-effective allocation of roadway improvement funds should involve the following steps.

- Collect a geometric inventory of short roadway sections that includes potential candidates for improvement. Only sections with very adverse geometry (e.g., curvature and grade above some locally chosen thresholds) need to be included in the inventory.

## TABLE 4 BIVARIATE CUMULATIVE DISTRIBUTION OF CRASH SECTIONS BY CURVATURE AND GRADE PERCENTAGES: NEW MEXICO VERSUS GEORGIA

a. New Mexico

| Grade Percentages | Curvature Percentages: Lower Tail 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | Median 10.0–50.0 | 50.0–10.0 | Upper Tail 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.27 | 0.27 | 0.27 | 0.27 | 0.00 | 0.27 |
| 0.5–1.0 | 0.00 | 0.27 | 0.27 | 0.27 | 0.27 | 0.00 | 0.00 | 0.55 | 0.55 | 0.55 | 0.27 | 0.00 | 0.82 |
| 1.0–2.5 | 0.27 | 0.82 | 0.82 | 0.82 | 0.82 | 0.55 | 0.00 | 1.09 | 0.82 | 0.55 | 0.27 | 0.00 | 2.46 |
| 2.5–5.0 | 0.27 | 0.82 | 0.82 | 0.82 | 1.37 | 1.91 | 0.27 | 1.37 | 1.09 | 0.82 | 0.27 | 0.00 | 4.92* |
| 5.0–10.0 | 0.27 | 0.82 | 0.82 | 1.37 | 3.55* | 3.55* | 0.55 | 2.19 | 1.64 | 0.82 | 0.27 | 0.00 | 9.84* |
| Median 10.0–(50.0) | 0.00 | 0.00 | 1.09 | 3.01 | 4.92* | 15.57* | 15.30* | 4.37* | 1.37 | 0.27 | 0.00 | 0.00 | 40.16* |
| (50.0)–10.0 | 0.00 | 0.00 | 0.55 | 0.55 | 1.37 | 16.39* | 20.49* | 1.91 | 1.09 | 0.55 | 0.00 | 0.00 | 40.16* |
| Upper Tail 10.0–5.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 4.64* | 3.83* | 1.37 | 0.82 | 0.82 | 0.55 | 0.27 | 9.84* |
| 5.0–2.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 2.73 | 1.37 | 0.82 | 0.82 | 0.82 | 0.55 | 0.27 | 4.92* |
| 2.5–1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.37 | 0.27 | 0.82 | 0.82 | 0.82 | 0.55 | 0.27 | 2.46 |
| 1.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.82 | 0.82 | 0.82 | 0.55 | 0.27 | 0.82 |
| 0.5–0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.27 | 0.27 | 0.27 | 0.00 | 0.00 | 0.27 |
| All | 0.27 | 0.82 | 2.46 | 4.92* | 9.84* | 40.16* | 40.16* | 9.84* | 4.92* | 2.46 | 0.82 | 0.27 | 100.00 |

See text and Table 3 for interpretation of this table.
*Percentage based on ten or more crash sections.

b. Georgia

| Grade Percentages | Curvature Percentages: Lower Tail 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | Median 10.0–50.0 | 50.0–10.0 | Upper Tail 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 | 0.21 | 0.21 | 0.00 | 0.00 | 0.00 | 0.42 |
| 0.5–1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.21 | 0.42 | 0.21 | 0.21 | 0.00 | 0.00 | 0.00 | 0.84 |
| 1.0–2.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.63 | 1.47 | 0.21 | 0.21 | 0.00 | 0.00 | 0.00 | 2.31* |
| 2.5–5.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.68 | 2.52* | 0.63 | 0.42 | 0.00 | 0.00 | 0.00 | 4.82* |
| 5.0–10.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.42 | 4.40* | 3.56* | 1.47 | 0.63 | 0.21 | 0.21 | 0.21 | 9.85* |
| Median 10.0–(50.0) | 0.21 | 0.63 | 1.05 | 2.10* | 4.61* | 6.77* | 14.88* | 3.98* | 2.31 | 1.26 | 0.42 | 0.00 | 40.25* |
| (50.0)–10.0 | 0.00 | 0.00 | 0.63 | 1.68 | 3.35* | 4.88* | 18.56* | 3.14* | 1.05 | 0.63 | 0.21 | 0.21 | 40.04* |
| Upper Tail 10.0–5.0 | 0.21 | 0.21 | 0.63 | 1.05 | 1.47 | 3.98* | 3.14* | 1.26 | 0.84 | 0.21 | 0.00 | 0.00 | 9.85* |
| 5.0–2.5 | 0.21 | 0.21 | 0.63 | 1.05 | 1.47 | 1.05 | 1.05 | 1.26 | 0.84 | 0.21 | 0.00 | 0.00 | 4.82* |
| 2.5–1.0 | 0.00 | 0.00 | 0.21 | 0.42 | 0.84 | 0.63 | 0.63 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 | 2.31* |
| 1.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.63 | 0.21 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.84 |
| 0.5–0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.42 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.42 |
| ALL | 0.42 | 0.84 | 2.31* | 4.82* | 9.85* | 40.04* | 40.25* | 9.85* | 4.82* | 2.31* | 0.84 | 0.42 | 100.00 |

[1]See text and Table 3 for interpretation of this table.
*Percentage based on ten or more crash sections.

## TABLE 5 BIVARIATE CUMULATIVE DISTRIBUTION OF RANDOM SURVEY DATA IN NEW MEXICO BY CURVATURE AND GRADE PERCENTAGES: NEW MEXICO VERSUS GEORGIA

### a. Travel Volume

Curvature Percentages (Lower Tail: 0.0–10.0; Median: 10.0–50.0–10.0; Upper Tail: 10.0–0.0)

| Grade Percentages | 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | 10.0–50.0 | 50.0–10.0 | 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.5–1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1.0–2.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2.5–5.0 | 0.00 | 0.00 | 0.00 | 0.12 | 0.12 | 0.74 | 0.00 | 0.34 | 0.34 | 0.00 | 0.00 | 0.00 | 1.20 |
| 5.0–10.0 | 0.00 | 0.00 | 0.00 | 0.12 | 0.24 | 1.25 | 0.07 | 0.78 | 0.66 | 0.33 | 0.14 | 0.14 | 2.34 |
| Median 10.0–(50.0) | 0.00 | 0.00 | 0.00 | 0.00 | 0.50 | 18.31 | 7.06 | 1.82 | 0.82 | 0.51 | 0.26 | 0.26 | 27.69 |
| (50.0)–10.0 | 0.00 | 0.00 | 0.00 | 0.24 | 0.36 | 34.90 | 16.49 | 1.69 | 1.01 | 0.38 | 0.00 | 0.00 | 53.44 |
| 10.0–5.0 | 0.00 | 0.00 | 0.00 | 0.47 | 0.59 | 10.06 | 4.31 | 1.58 | 0.85 | 0.47 | 0.12 | 0.12 | 16.54 |
| 5.0–2.5 | 0.00 | 0.00 | 0.00 | 0.35 | 0.47 | 5.76 | 2.40 | 1.26 | 0.78 | 0.47 | 0.12 | 0.12 | 9.89 |
| Upper Tail 2.5–1.0 | 0.00 | 0.00 | 0.00 | 0.21 | 0.33 | 2.28 | 1.26 | 0.78 | 0.54 | 0.24 | 0.12 | 0.12 | 4.64 |
| 1.0–0.5 | 0.00 | 0.00 | 0.00 | 0.21 | 0.33 | 1.12 | 0.65 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 2.22 |
| 0.5–0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.82 | 0.26 | 0.12 | 0.12 | 0.12 | 0.12 | 0.12 | 1.20 |
| ALL | 0.00 | 0.00 | 0.00 | 0.83 | 1.68 | 64.52 | 27.93 | 5.87 | 3.33 | 1.68 | 0.52 | 0.52 | 100.00 |

See text and Table 3 for interpretation of this table.

### b. Road Miles

Curvature Percentages (Lower Tail: 0.0–10.0; Median: 10.0–50.0–10.0; Upper Tail: 10.0–0.0)

| Grade Percentages | 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | 10.0–50.0 | 50.0–10.0 | 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 0.5–1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1.0–2.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 2.5–5.0 | 0.00 | 0.00 | 0.00 | 0.38 | 0.38 | 0.53 | 0.08 | 0.26 | 0.26 | 0.00 | 0.00 | 0.00 | 1.25 |
| 5.0–10.0 | 0.00 | 0.00 | 0.00 | 0.38 | 0.76 | 1.03 | 0.30 | 1.33 | 0.96 | 0.70 | 0.10 | 0.10 | 3.42 |
| Median 10.0–(50.0) | 0.00 | 0.00 | 0.00 | 0.00 | 1.24 | 17.97 | 7.90 | 2.76 | 0.88 | 0.60 | 0.53 | 0.53 | 29.88 |
| (50.0)–10.0 | 0.00 | 0.00 | 0.00 | 0.07 | 0.44 | 30.22 | 12.41 | 2.96 | 1.83 | 0.86 | 0.00 | 0.00 | 46.02 |
| 10.0–5.0 | 0.00 | 0.00 | 0.00 | 0.85 | 1.23 | 11.59 | 5.60 | 2.26 | 2.16 | 1.51 | 0.38 | 0.38 | 20.68 |
| 5.0–2.5 | 0.00 | 0.00 | 0.00 | 0.47 | 0.85 | 6.76 | 2.39 | 2.02 | 1.94 | 1.51 | 0.38 | 0.38 | 12.02 |
| Upper Tail 2.5–1.0 | 0.00 | 0.00 | 0.00 | 0.32 | 0.70 | 3.74 | 1.27 | 1.25 | 1.18 | 0.76 | 0.38 | 0.38 | 6.96 |
| 1.0–0.5 | 0.00 | 0.00 | 0.00 | 0.32 | 0.70 | 1.48 | 0.48 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 3.04 |
| 0.5–0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.87 | 0.00 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 1.25 |
| ALL | 0.00 | 0.00 | 0.00 | 1.30 | 3.67 | 60.81 | 26.20 | 9.31 | 5.82 | 3.67 | 1.01 | 1.01 | 100.00 |

See text and Table 3 for interpretation of this table.

# TABLE 6 BIVARIATE CUMULATIVE DISTRIBUTION OF RANDOM SURVEY DATA IN GEORGIA BY CURVATURE AND GRADE PERCENTAGES: TRAVEL VOLUME VERSUS ROAD MILES

a. Travel Volume

Curvature Percentages

| Grade Percentages | | Lower Tail 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | Median 10.0–50.0 | 50.0–10.0 | 10.0–5.0 | Upper Tail 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail | 0.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.5–1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.06 | 0.06 | 0.00 | 0.00 | 0.06 |
| | 1.0–2.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.11 | 0.27 | 0.06 | 0.06 | 0.06 | 0.00 | 0.00 | 0.44 |
| | 2.5–5.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.22 | 0.58 | 0.06 | 0.06 | 0.06 | 0.00 | 0.00 | 1.86 |
| | 5.0–10.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.15 | 1.22 | 0.22 | 0.22 | 0.06 | 0.00 | 0.00 | 4.59 |
| Median (50.0) | 10.0–50.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.25 | 21.94 | 10.33 | 0.67 | 0.30 | 0.17 | 0.06 | 0.00 | 33.20 |
| | 50.0–10.0 | 0.00 | 0.00 | 0.00 | 0.06 | 0.24 | 33.70 | 16.98 | 0.73 | 0.00 | 0.00 | 0.00 | 0.00 | 51.65 |
| Upper Tail | 10.0–5.0 | 0.00 | 0.00 | 0.00 | 0.11 | 0.28 | 6.71 | 3.04 | 0.53 | 0.25 | 0.00 | 0.00 | 0.00 | 10.57 |
| | 5.0–2.5 | 0.00 | 0.00 | 0.00 | 0.06 | 0.22 | 2.94 | 1.21 | 0.22 | 0.00 | 0.00 | 0.00 | 0.00 | 4.59 |
| | 2.5–1.0 | 0.00 | 0.00 | 0.00 | 0.06 | 0.06 | 1.98 | 0.34 | 0.17 | 0.00 | 0.00 | 0.00 | 0.00 | 2.54 |
| | 1.0–0.5 | 0.00 | 0.00 | 0.00 | 0.06 | 0.06 | 0.11 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.17 |
| | 0.5–0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| ALL | | 0.00 | 0.00 | 0.00 | 0.17 | 0.77 | 65.51 | 31.57 | 2.15 | 0.77 | 0.23 | 0.06 | 0.00 | 100.00 |

See text and Table 3 for interpretation of this table.

b. Road Miles

Curvature Percentages

| Grade Percentages | | Lower Tail 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | Median 10.0–50.0 | 50.0–10.0 | 10.0–5.0 | Upper Tail 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail | 0.0–0.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| | 0.5–1.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.28 | 0.28 | 0.28 | 0.00 | 0.00 | 0.28 |
| | 1.0–2.5 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.55 | 0.40 | 0.28 | 0.28 | 0.28 | 0.00 | 0.00 | 1.23 |
| | 2.5–5.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.12 | 1.38 | 0.28 | 0.28 | 0.28 | 0.00 | 0.00 | 2.77 |
| | 5.0–10.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 3.21 | 2.66 | 0.43 | 0.43 | 0.28 | 0.00 | 0.00 | 6.30 |
| Median (50.0) | 10.0–50.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.08 | 17.99 | 11.13 | 1.31 | 1.03 | 0.83 | 0.28 | 0.00 | 30.51 |
| | 50.0–10.0 | 0.00 | 0.00 | 0.00 | 0.28 | 0.75 | 32.30 | 16.26 | 1.23 | 0.00 | 0.00 | 0.00 | 0.00 | 50.55 |
| Upper Tail | 10.0–5.0 | 0.00 | 0.00 | 0.00 | 0.55 | 0.71 | 7.29 | 3.85 | 0.80 | 0.08 | 0.00 | 0.00 | 0.00 | 12.64 |
| | 5.0–2.5 | 0.00 | 0.00 | 0.00 | 0.28 | 0.43 | 3.54 | 1.89 | 0.44 | 0.00 | 0.00 | 0.00 | 0.00 | 6.30 |
| | 2.5–1.0 | 0.00 | 0.00 | 0.00 | 0.28 | 0.28 | 2.46 | 0.84 | 0.16 | 0.00 | 0.00 | 0.00 | 0.00 | 3.74 |
| | 1.0–0.5 | 0.00 | 0.00 | 0.00 | 0.28 | 0.28 | 0.55 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.83 |
| | 0.5–0.0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| ALL | | 0.00 | 0.00 | 0.00 | 0.83 | 1.54 | 60.79 | 33.89 | 3.77 | 1.54 | 1.11 | 0.28 | 0.00 | 100.00 |

See text and Table 3 for interpretation of this table.

# TABLE 7 LOGARITHM OF THE RATIO OF THE BIVARIATE DISTRIBUTIONS OF CRASH AND RANDOM SEGMENTS IN NEW MEXICO BY CURVATURE AND GRADE PERCENTAGES: TRAVEL VOLUME VERSUS ROAD MILES

## a. Travel Volume

Curvature Percentages (Lower Tail / Median / Upper Tail)

| Grade Percentages | 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | 10.0–50.0 | 50.0–10.0 | 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | . | . | . | . | . | . | . | + | + | + | + | . | + |
| 0.5–1.0 | . | + | + | + | + | . | . | . | + | + | + | . | + |
| 1.0–2.5 | + | + | + | + | + | + | . | + | + | + | + | . | + |
| 2.5–5.0 | + | + | + | 2.8 | 3.5 | 1.4 | + | 2.0 | 1.7 | + | + | . | 2.0 * |
| 5.0–10.0 | + | + | + | 3.5 | 3.9* | 1.5* | 3.0 | 1.5 | 1.3 | 1.3 | 1.0 | - | 2.1 * |
| 10.0–Median (50.0) | . | . | + | + | 3.3 * | -0.2* | 1.1* | 1.3* | 0.7 | -0.9 | - | - | 0.5 * |
| Median (50.0)–10.0 | . | . | + | 1.2 | 1.9 | -1.1* | 0.3* | 0.2 | 0.1 | 0.5 | . | . | -0.4 * |
| 10.0–5.0 | . | . | . | - | - | -1.1* | -0.2* | -0.2 | -0.0 | 0.8 | 2.2 | 1.2 | -0.7 * |
| 5.0–2.5 | . | . | . | - | - | -1.1* | -0.8 | -0.6 | 0.1 | 0.8 | 2.2 | 1.2 | -1.0 * |
| Upper Tail 2.5–1.0 | . | . | . | - | - | -0.7 | -2.2 | 0.1 | 0.6 | 1.8 | 2.2 | 1.2 | -0.9 |
| 1.0–0.5 | . | . | . | - | - | - | - | 2.8 | 2.8 | 2.8 | 2.2 | 1.2 | -1.4 |
| 0.5–0.0 | . | . | . | . | . | - | - | 1.2 | 1.2 | 1.2 | - | - | -2.1 |
| ALL | + | + | + | 2.6 | 2.5 | -0.7 | 0.5 | 0.7 | 0.6 | 0.5 | 0.7 | -0.9 | 0.0 |

Table a (b) is based on Table 4.a and Table 5.a (5.b).
See Text and Table 3 for the interpretation of this Table.
Entry in Tables is "." if both numerator and denominator were 0, entry is "+" if denominator was zero and it is "-" if numerator was zero.
*Percentage based on ten or more crash sections.

## b. Road Miles

Curvature Percentages (Lower Tail / Median / Upper Tail)

| Grade Percentages | 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | 10.0–50.0 | 50.0–10.0 | 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | . | . | . | . | . | . | . | + | + | + | + | . | + |
| 0.5–1.0 | . | + | + | + | + | . | . | + | + | + | + | . | + |
| 1.0–2.5 | + | + | + | + | + | + | . | + | + | + | + | . | + |
| 2.5–5.0 | + | + | + | 1.1 | 1.9 | 1.8 | 1.7 | 2.4 | 2.1 | + | + | . | 2.0* |
| 5.0–10.0 | + | + | + | 1.9 | 2.2* | 1.5 * | 1.9 | 0.7 | 0.8 | 0.2 | 1.4 | - | 1.5* |
| 10.0–Median (50.0) | . | . | + | + | 2.0* | -0.3 * | 1.0* | 0.7* | 0.6 | -1.1 | - | - | 0.4* |
| Median (50.0)–10.0 | . | . | + | 3.1 | 1.6 | -0.9 * | 0.7* | -0.6 | -0.7 | -0.7 | . | . | -0.2* |
| 10.0–5.0 | . | . | . | - | - | -1.0 * | -1.0 * | -0.7 | -1.4 | -0.9 | 0.5 | -0.5 | -1.1* |
| 5.0–2.5 | . | . | . | - | - | -1.2 * | -1.1 | -1.3 | -1.2 | -0.9 | 0.5 | -0.5 | -1.3* |
| Upper Tail 2.5–1.0 | . | . | . | - | - | -1.8 | -1.2 | -0.6 | -0.5 | 0.1 | 0.5 | -0.5 | -1.5 |
| 1.0–0.5 | . | . | . | - | - | - | - | 1.1 | 1.1 | 1.1 | 0.5 | -0.5 | -1.9 |
| 0.5–0.0 | . | . | . | . | . | - | . | -0.5 | -0.5 | -0.5 | - | - | -2.2 |
| ALL | + | + | + | 1.9* | 1.4* | -0.6 * | 0.6 * | 0.1 * | -0.2 * | -0.6 | -0.3 | -1.9 | 0.0 |

Table a (b) is based on Table 4.a and Table 5.a (5.b).
See Text and Table 3 for the interpretation of this Table.
Entry in Tables is "." if both numerator and denominator were 0, entry is "+" if denominator was zero and it is "-" if numerator was zero.
*Percentage based on ten or more crash sections.

TABLE 8 LOGARITHM OF THE RATIO OF THE BIVARIATE DISTRIBUTIONS OF CRASH AND RANDOM SEGMENTS IN GEORGIA BY CURVATURE AND GRADE PERCENTAGES: TRAVEL VOLUME VERSUS ROAD MILES

a. Travel Volume

| Grade Percentages | Curvature Percentages: Lower Tail 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | Median 10.0–50.0 | 50.0–10.0 | Upper Tail 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | . | . | . | . | . | . | + | + | + | . | . | . | + |
| 0.5–1.0 | . | . | . | . | . | + | + | 1.9 | 1.9 | - | . | . | 3.9 |
| 1.0–2.5 | . | . | . | . | . | 2.5 | 2.4 | 1.9 | 1.9 | - | . | . | 2.4* |
| 2.5–5.0 | . | . | . | . | . | 0.5 | 2.1* | 3.5 | 2.9 | - | . | . | 1.4* |
| 5.0–10.0 | . | . | . | . | + | 0.5* | 1.5* | 2.7 | 1.5 | 1.9 | + | + | 1.1* |
| 10.0–Median (50.0) | + | + | + | + * | 4.2* | -0.4* | 0.5* | 2.6* | 3.0 | 2.9 | 2.9 | . | 0.3* |
| Median (50.0)–10.0 | . | . | + | 4.9 | 3.8* | -1.2* | 0.1* | 2.1* | + | + | + | + | -0.4* |
| Upper Tail 10.0–5.0 | + | + | + | 3.2 | 2.4 | -0.8* | 0.0* | 1.2 | 1.7 | + | . | . | -0.1* |
| 5.0–2.5 | + | + | + | 4.2 | 2.7 | -1.5 | -0.2 | 2.5 | + | + | . | . | 0.1* |
| 2.5–1.0 | . | . | + | 2.9 | 3.9 | -1.7 | 0.9 | 0.3 | . | . | . | . | -0.1* |
| 1.0–2.5 | . | . | . | - | - | 2.5 | + | . | . | . | . | . | 2.3 |
| 2.5–0.0 | . | . | . | . | . | + | . | . | . | . | . | . | 99.9 |
| ALL | + | + | + * | 4.8* | 3.7* | -0.7* | 0.4* | 2.2* | 2.7* | 3.3* | 3.9* | + | 0.0 |

Table a (b) is based on Table 4.b and Table 6.a (6.b).
See Text and Table 3 for the interpretation of this Table.
Entry in Tables is "." if both numerator and denominator were 0, entry is "+" if denominator was zero and it is "-" if numerator was zero.
*Percentage based on ten or more crash sections.

b. Road Miles

| Grade Percentages | Curvature Percentages: Lower Tail 0.0–0.5 | 0.5–1.0 | 1.0–2.5 | 2.5–5.0 | 5.0–10.0 | Median 10.0–50.0 | 50.0–10.0 | Upper Tail 10.0–5.0 | 5.0–2.5 | 2.5–1.0 | 1.0–0.5 | 0.5–0.0 | All |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lower Tail 0.0–0.5 | . | . | . | . | . | . | + | + | + | . | . | . | + |
| 0.5–1.0 | . | . | . | . | . | . | + | -0.4 | -0.4 | - | . | . | 1.6 |
| 1.0–2.5 | . | . | . | . | . | 0.2 | 1.9 | -0.4 | -0.4 | - | . | . | 0.9* |
| 2.5–5.0 | . | . | . | . | . | 0.9 | 0.6* | 1.2 | 0.6 | - | . | . | 0.8* |
| 5.0–10.0 | . | . | . | . | + | 0.7* | 0.1* | 1.8 | 0.5 | -0.4 | + | + | 0.6* |
| 10.0–Median (50.0) | + | + | + | + * | 5.8* | -0.1* | 0.4* | 1.6* | 1.2 | 0.6 | 0.6 | . | 0.4* |
| Median (50.0)–10.0 | . | . | + | 2.6 | 2.2 | -1.1* | 0.2* | 1.4* | + | + | + | + | -0.3* |
| Upper Tail 10.0–5.0 | + | + | + | 0.9 | 1.0 | -1.0* | -0.1* | 0.7 | 3.4 | + | . | . | -0.4* |
| 5.0–2.5 | + | + | + | 1.9 | 1.8 | -1.5 | -1.2 | 1.5 | + | + | . | . | -0.4* |
| 2.5–1.0 | . | . | + | 0.6 | 1.6 | -1.6 | -1.0 | 0.4 | . | . | . | . | -0.7* |
| 1.0–0.5 | . | . | . | - | - | 0.6 | . | . | . | . | . | . | 0.0 |
| 0.5–0.0 | . | . | . | . | . | + | . | . | . | . | . | . | + |
| ALL | + | + | + * | 2.5* | 2.7* | -0.6* | 0.2* | 1.4* | 1.6* | 1.1* | 1.6* | + | 0.0 |

Table a (b) is based on Table 4.b and Table 6.a (6.b).
See Text and Table 3 for the interpretation of this Table.
Entry in Tables is "." if both numerator and denominator were 0, entry is "+" if denominator was zero and it is "-" if numerator was zero.
*Percentage is based on ten or more crash sections.

• Collect geometric data on crashes that have occurred at sites with adverse geometry. Prepare the local version of the ratio tables (cf. Tables 7 and 8) for estimating overinvolvement.

• Define types of candidate sites in terms of the extent of overinvolvement. These should include all sites with extremely adverse geometries such as those marked with a positive sign (+) in the ratio tables. It is probable that most states will have large numbers of sites with estimated overinvolvement rates in excess of 10 or more or even 50 or more.

• Identify individual candidate sites for improvement. This master list could include sites of single-vehicle crashes, not necessarily fatal ones only, with sufficiently adverse geometry as well as sites with adverse geometry but no crashes.

## SUMMARY AND RECOMMENDATIONS

Survey data on curvature and grade collected at crash and comparison sites in the states of New Mexico and Georgia were analyzed. The results showed that road sections with extreme geometry were far more common at the locations of fatal rollover crashes than at comparison sites. Numerical values for the extent of crash overinvolvement for sections with the most extremely adverse geometries could not be assigned because such sections were simply not found in the randomly chosen comparison samples, although 300 comparison sites had been surveyed in both states. However, such sites were overinvolved by a factor of 50 for some of the most extreme combinations of curvature and grade values in both states. The results also showed that the relative roles of extreme curvature and grade in causing fatal rollover crashes could vary between states, possibly because of differences in terrain or other factors. Specifically, although sharp left curves and steep downgrades were found to be more common at crash than at comparison sites in both states, the prevalence of steep downgrades at crash sites was greater in New Mexico than in Georgia. Because such differences in the relative roles of these factors are likely to be found in other states as well, no attempt was made to define an absolute priority scheme for hazard identification. Each state or geographic region should develop its own cost-effective set of priorities for hazard identification following the procedure outlined earlier.

Data for comparisons of bivariate curve-grade distributions at crash sites and at representative comparison sites may be available from construction plans or photologging surveys or could be routinely collected as part of existing state highway programs (e.g., maintenance or planning) that involve personnel already out in the field. The curvature and grade characteristics should be collected for known crash sites as well as for randomly selected sites representative of the state road system. Roadway sections included in the Highway Performance Monitoring System (HPMS) might be used to generate the bivariate distributions for representing the state's roadway system (*16*). However, because current data requirements for these sample sections do not allow for direct association of curve and grade on a specific roadway, the geometric data would have to be reanalyzed to construct the actual curve-grade bivariate distribution.

In addition to adverse vertical and horizontal alignments, inadequate superelevation was also shown to be associated with the incidence of fatal rollover crashes (*17*). This suggests that the bivariate curve-grade distribution recommended in the present paper for the identification of geometric hazards could be further improved by the incorporation of measures of superelevation deficiency. However, road sections with the most adverse vertical and horizontal alignments are extremely overinvolved in fatal rollover crashes and rate already high priorities for improvements regardless of their superelevation. In any case, the currently recommended design limits for superelevation rates preclude the adequate banking of curves 10 degrees or sharper for typical travel speeds (*17*). In states with primarily level terrain, very sharp curves are likely to be infrequent and, correspondingly, the role of superelevation is likely to be greater in causing fatal rollover crashes. Such states should appropriately modify the procedure recommended for hazard identification in this paper to include superelevation in their priority scheme from the outset. It is also recommended that all states collect data on superelevation deficiencies at the sites where curvature and grade are surveyed so that the current recommendations could be further refined in the future.

The present study has shown that extreme roadway geometry can raise the likelihood of fatal rollover crashes, and probably of all fatal single-vehicle crashes, by up to a factor of 50 or higher. Although the identification of specific measures for reducing the hazards at such sites was beyond the scope of this work, it is clear that improvements should be targeted to sites with such extreme risks.

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# Evaluation of Opportunity-Based Accident Rate Expressions

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**Recent development of opportunity-based accident rate expressions provides a potentially more sensitive set of indicators for use in safety studies. A comparison and evaluation of conventional versus opportunity-based accident rate expressions was undertaken for a set of 50 case study signalized intersections in Broward County, Florida. The effect of level of aggregation of the exposure data was examined, as well as differences in the rating of intersections by degree of hazard. It was found that hourly traffic volume counts may be necessary for reliable estimation of opportunity-based exposure levels and that the use of opportunity-based accident rate measures will yield significantly different hazard rankings compared with conventional accident rate expressions. Issues relating to exposure-based versus conflict-based opportunity expressions are also discussed.**

The use of accident rates is a commonplace but not necessarily unbiased method of analyzing hazardous roadway locations. Typically, an accident rate is defined as either the total number of accidents per million vehicle miles or the total number of accidents per million entering vehicles. The first measure would apply to roadway segments, whereas the second is used at specific locations such as intersections.

Although these rate expressions are easily calculated, because of aggregation effects, it is not clear that they accurately reflect the true degree of hazard. In both formulations, number of accidents is expressed as the sum of all accidents that have occurred at a given location over a specified time period. Locations such as intersections often have predominating types of accidents, the existence of which is not apparent because of this aggregation. In addition, the rate formula for intersections uses total entering vehicles and thus does not account for possible correlation between specific accident types and certain combinations of vehicular movements. Reality is therefore lost by the implied assumption that all entering vehicles have an equal probability of being involved in any type of accident.

Recent work by Council et al. (*1*) has resulted in the specification of a set of opportunity-based accident rate expressions that account for the correlation between accident type and vehicle movement. The opportunity-based accident rate differs from the conventional rate in that the number of opportunities

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