Safety Effects of Limited Sight Distance on Crest Vertical Curves

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The safety effects of limited sight distance at crest vertical curves on two-lane rural highways in Texas were examined. Two large data bases consisting of 222 study segments of approximately one-mile lengths representing nearly 1,500 accidents were assembled to evaluate the effects that stopping sight distance along crest vertical curves has on accident rates. It was found that the relationship between available sight distance on crest vertical curves on two-lane roadways and accidents is difficult to quantify, even when a large data base exists. The AASHTO stopping sight distance design model alone is not a good indicator of accident rates on two-lane roadways in Texas; thus, use of this model alone will not result in cost-effective project design. Where there are intersections within the limited sight distance sections of crest vertical curves, there is a statistically significant increase in accident rates. It can be inferred that other geometric conditions within limited sight distance sections of crest vertical curves could also cause a marked increase in accident rates. An example would be a sharp horizontal curve hidden by a crest vertical curve. The increase in accident rates because of intersections within limited sight distance sections of crest vertical curves was more pronounced on roadways with higher volumes, implying that a threshold volume level may be determined based on considerations of cost effectiveness.

This paper reports the results of an accident analysis on two-lane, two-way rural roads in Texas with 55 mph speed limits to determine the effect of crest vertical curve lengths on the number of accidents. The minimum design control for crest vertical curve length is the stopping sight distance. Stopping sight distance is calculated using basic principles of physics and the relationships among various design parameters. AASHTO defines stopping sight distance as the sum of two components: brake reaction distance (distance traveled from the instant of object detection to the instant the brakes are applied) and the braking distance (distance required for the vehicle to come to a complete stop). Crest vertical curves with stopping sight distance less than 450 ft are considered to have limited sight distance at 55 mph based on current AASHTO policy (*1*). In order to assess the cost effectiveness of reconstruction projects to upgrade vertical alignment, it is necessary to know the safety impacts of limited sight distance on crest vertical curves.

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PREVIOUS RESEARCH ON SAFETY AND STOPPING SIGHT DISTANCE

The vertical alignment of a highway is a balance of cost and safety. The effects of grade and stopping sight distance on accident rates on vertical curves have been analyzed in a number of studies. The results of the previous studies (*2–16*) appear to be inconclusive and inconsistent.

The difficulty of obtaining adequate data to evaluate the effects of limited sight distance on accident occurrence is surely a significant cause of the inconsistency of previous research. Several factors contribute to the difficulty. The extreme variability seen in accident rates, even under carefully controlled circumstances, makes the detection of any effect of limited sight distance extremely difficult. In addition, the availability of sites necessary to the design of meaningful comparison studies is limited because of the need to control for all elements at or near the stopping sight distance restriction.

If adequate controls are not used, the accident data recorded may reflect other geometric elements, such as intersections. This result is partially the result of the difficulty of defining adequately homogeneous sites. Additionally, it may be caused by accident data that are not recorded with enough precision to allow association between particular accidents and the short lengths of roadway that exhibit sight distance restrictions. This limitation sometimes necessitates the use of an overall segment accident rate instead of the rate associated exclusively with the short distance exhibiting the sight restriction as the measure of the effect of limited stopping sight distance. Because there may be relatively few sight restrictions relative to the length of roadway, an overall segment accident rate may dilute any effect of the stopping sight distance restrictions within the segment. And, as seen in the present study, the effects of sight distance restrictions may only be seen through their interaction with other geometric features, again making their detection more difficult. All these factors help to explain the inconsistencies seen in this review of the literature.

STUDY DESIGN

The initial study design was based on identifying the largest possible data base consisting of rural two-lane highways with and without limited sight distance. Potential study areas were identified in east and central Texas, where sufficient topographic relief was known to occur and limited sight distance segments were believed to exist.

Criteria were established for selecting potential study segments. The segment criteria included posted speed limit, proximity to signalized intersections, and segment length. The posted speed, including horizontal curves, had to be 55 mph or greater. The study segment could not be within one-half mile of a signalized intersection. The minimum segment length was set at one mile to eliminate short segments that might be overly affected by adjacent segments. These criteria were believed to be reasonable for controlling a number of factors (for example, horizontal curves and intersections) that could mask the effects of crest vertical curves. Specifically, horizontal curves and intersections are known contributing factors to accidents.

METHODOLOGY

In order to investigate the potential relationship between accident rate and limited sight distance caused by crest vertical curves, sections of highway with varying amounts of limited sight distance were identified and grouped by road type. Two general road types—two-lane with shoulders and two-lane without shoulders—produced sufficient lengths of roadway for analysis.

The initial selection of highway sections was restricted in an attempt to produce groups with segments as homogeneous as possible. The selection included only rural highways, and the geometry of each was carefully inspected to ensure conformity to predetermined standards as previously stated. Every segment was visited and videotaped.

Highway profiles were used to identify all vertical curves on the selected roadways and to characterize them by their length and K factor. Horizontal curves were also identified and the length and degree of curvature of each were recorded. Segments of approximately one mile in length were then defined on the sample roadways. These segments were used throughout the analysis as the experimental observations. The original roadway lengths were divided into these segments with the limitation that no vertical curve or horizontal curve was broken into two segments. Thus, the segment lengths were kept as close as possible to one mile while honoring this restriction.

The intersecting roads on each segment were counted and classified as numbered roads, county roads, or driveways, based on information available from the highway profiles. It was noted from actual observation of the sites that not all driveways were included on the plans.

The relative amounts of limited sight distance were calculated from the recorded data on crest vertical curves for all segments. Three criteria were used to define limited sight distance. AASHTO policy specifies a minimum stopping sight distance for a wide range of design speeds. The minimum values for 45 mph (325 ft), 55 mph (450 ft), and 65 mph (550 ft) were used to calculate limited sight distance. The AASHTO policy also specifies a desirable stopping sight distance. The desirable value for 55 mph, which is the posted speed on all roadways in this study, is 550 ft—or the minimum value for 65 mph.

The length of roadway that was calculated to be limited for each segment according to each criterion was translated into the percent of the road segment that was judged limited according to the various distance criteria. These measures of the relative amount of sight distance in the road segments were used to evaluate the effects of crest vertical curves on accident rates. In addition, the state numbered roads, county roads, and driveways on the segments were categorized according to whether they were within the limited sight distance portions of crest vertical curves based on the three criteria for stopping sight distance.

Texas accident data files, collected through the Texas Department of Public Safety and maintained by the Accident Analysis Division of the Texas Transportation Institute, provided the accident history for the selected highway sections. All accidents, with the exception of those reported by the driver, were considered in the calculation of accident rates.

Four years of accident data, 1984 through 1987, were summarized for the analysis. Several years of data were desirable because of the extreme variability in accident rates, even in a carefully selected, homogeneous sample. The rates become more stable over several years and the incidence of zero rates is practically eliminated, which simplifies the analysis. To avoid the possibility of changes in the condition of the selected roadways a longer time interval was not used. It was verified that no construction occurred on the selected sites during the four years of the study.

In addition, the computerized state roadway inventory files were used as the source of traffic volume for the analysis. If the annual average daily traffic (AADT) varied within the defined road segment, an average value was calculated. An average for the segment for the years considered in the analysis was then computed for use in adjusting accident rates for AADT. A match with the roadway inventory (RI) files also ensured the valid identification of the roadway segments using the method of milepoints within control sections.

The approximate one-mile segments served as the sampling unit for the analysis. Data from the three sources—highway profiles, accident data files, and roadway inventory files—were summarized by road segment and merged to produce the complete data set for analysis.

Other units of measurement were considered and rejected because of the inherent limitations of the data. If one could identify accident locations exactly on the roadway, their relative positions with respect to crest vertical curves could be known. This knowledge would allow a direct comparison between accident rates on crest vertical curves and on sections of roadway with flat vertical alignment. This method of comparison was rejected because the recorded accident locations were not believed to be precise. The somewhat arbitrary one-mile segment length was selected to generate as large a sample as possible without going beyond the known limitations of the data.

STATISTICAL METHODS

Multiple regression techniques were employed to investigate and measure the effects of limited sight distance on accident rates. Two types of accident rates were considered as dependent variables in the analysis: accidents per mile and accidents per million vehicle miles (MVM). In both cases, it is of prime importance to adequately model the effect of AADT on the rate before attempting to evaluate other potential effects. Without first adjusting for AADT, examination of the possible effects of limited sight distance is not meaningful. Multiple regression provides the methodology for making these simultaneous adjustments and the associated tests.

Certain assumptions must be met before the use of a least-squares regression analysis is valid. The first is that the observations on the dependent variable are independent. There is no reason to believe that the observations of accident rates for the different road segments in this analysis are not independent. Nevertheless, one could not use multiple observations from consecutive years and comply with this assumption. Thus, this requirement provides another reason to summarize the several years of accident data for each segment into a single observation.

Another assumption that must be met is that the dependent variable, in this case accident rate, is normally distributed with constant variance. The least-squares analysis is robust against deviations in the normality requirement; that is, if the assumption is not strictly met, the analysis is still valid. But, if the assumption of equal variance is not met, the analysis may be flawed.

Accident rates are generally believed to follow a Poisson distribution, not a normal distribution. Additionally, it is known that the Poisson distribution has a variance that is equal to its mean. In other words, as the accident rate increases, the variance increases. Therefore the assumption of equal variance is also violated.

Averaging the numbers of accidents over several years makes the distribution more nearly normal, and taking the logarithm of the rates prior to analysis helps to eliminate the problem of unequal variance or heteroscedasticity. Therefore, instead of accidents per mile a year and accidents per million vehicle miles, the analysis uses the logarithms of both these variables. In order to accommodate the few zero accident rates, the logarithm of the accident rate plus one was used. The adjustments are believed to make the analysis statistically valid.

A nominal significance level of 0.05 is used in interpreting the statistical analyses. This value means that there is only a 5 percent chance of making an error in stating that a given relationship is nonzero. The actual significance probabilities are reported in many cases to allow the reader further interpretation of the results. Also, due to the limited data available for some tests, results that approach significance ($0.05 < p < 0.10$) will be noted.

RESULTS

Two-Lane Roads with Shoulders

One hundred and sixty-eight road segments were defined from the group of two-lane roads with shoulders. Nine hundred and ninety accidents had occurred on these combined segments, the average annual accident rate per mile varying between 0.0 and 8.25. Averaged AADT values ranged between 943 and 9,075. Table 1 gives the frequency of road segments within specified AADT intervals.

TABLE 1 TWO-LANE ROADWAYS WITH SHOULDERS—FREQUENCY AND PERCENT OF SEGMENTS BY AADT

AADT	Freq	Percent
≤ 2000	15	8.9
2-2999	36	21.4
3-3999	45	26.8
4-4999	40	23.8
5-5999	21	12.5
≥ 6000	11	6.5
Total	168	100.0

Figure 1 provides a plot of accident rate per mile versus AADT. Several observations can be made from this graph. First, the strong relationship between accident rate and AADT is illustrated. Second, the increasing variance as the average accident rate increases can be seen. Last, the tremendous variation in accident rates for fixed AADT can be noted. It is the explanation of this variability that is attempted through the additional variables in the multiple regression analysis, including the measurements of limited sight distance.

The relative amounts of limited sight distance varied greatly depending on the criteria used to define adequate sight distance. The percentages of limited sight distance are summarized for the three criteria examined in Table 2. Only two road segments contained lengths with limited sight distance using the lowest criterion—325 ft stopping sight distance. Thus, no analyses could be performed based on sight distance of less than 325 ft because of the lack of data. That is to say, virtually all two-lane roadway segments with shoulders meet the AASHTO minimum criteria for 45 mph. The other two sight distance criteria yielded adequate numbers of segments for analysis, although the majority are not sight deficient by any of the three standards.

The effects of limited sight distance using the criterion of 450 ft, the minimum value for 55 mph, will be examined first. The terminology "percent limited stopping sight distance" will hereafter be used to indicate the percent of the roadway that has less than the specified stopping sight distance based on the current AASHTO driver eye height (3.5 ft) and object height (0.5 ft). Figure 2 examines the possible relationship between accident rate per mile and this measurement of limited sight distance. The percent of roadway with limited sight distance ranges as high as 35 percent, but very few segments have more than 20 percent limited sight distance. No strong relationship can be seen between the average accident rate and percent limited stopping sight distance. From Table 2 it can be seen that 134—or 80 percent—of the road segments have no limitation of sight distance according to this standard.

The relationship between percent limited stopping sight distance and AADT is illustrated in Figure 3. There is no association apparent in this figure. In other words, the sample data set is well balanced with respect to these two variables. The presence of limited stopping sight distance is not associated with only particular values of AADT, but is well represented across the full range—between 2,000 and 8,000 vehicles daily. This balance contributes to confidence in the analytical results.

Regression analyses were performed on the logarithms of accident rate per mile and accident rate per MVM. Included among the independent variables examined were AADT, the square of AADT, percent limited stopping sight distance,

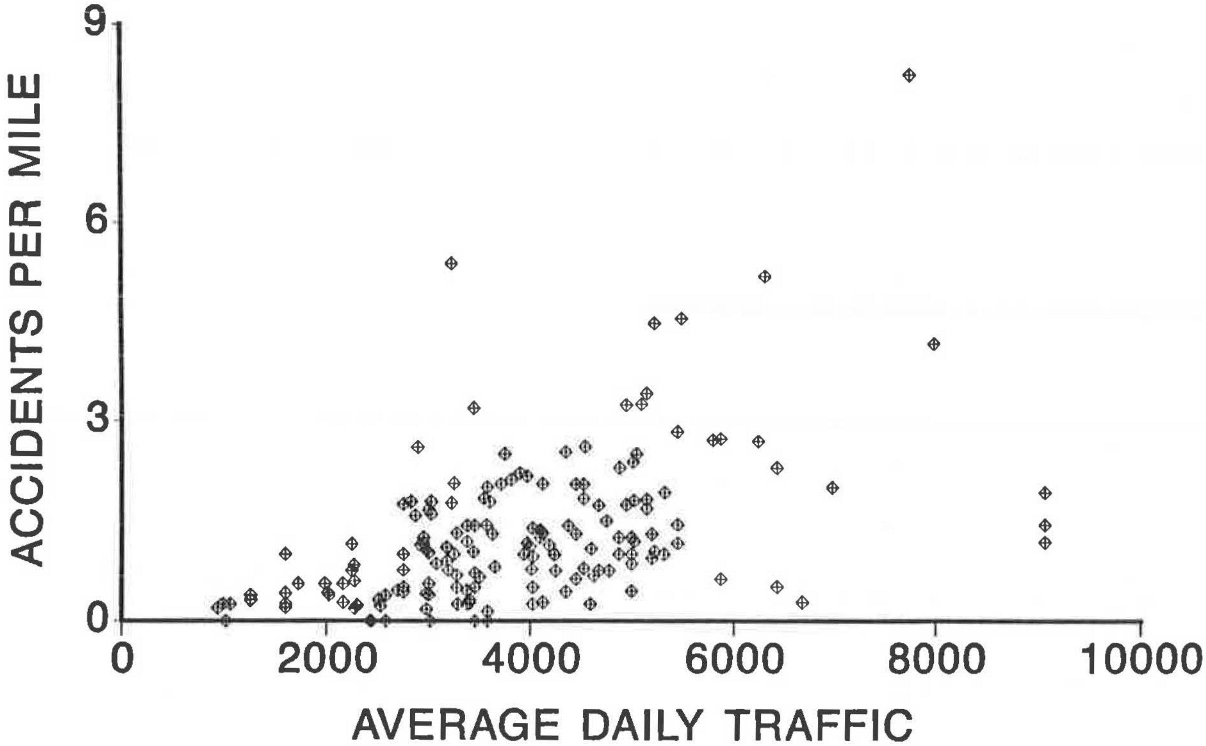

FIGURE 1 Accident rate per mile versus AADT, two-lane roads with shoulders.

TABLE 2 TWO-LANE ROADWAYS WITH SHOULDERS—FREQUENCY OF SEGMENTS BY THREE CRITERIA OF SIGHT DISTANCE

Percent Limited Distance	Minimum 325	Sight 450	Distance (ft) 550
0	166	134	101
1-10	1	16	13
11-20	1	12	32
21-30	0	4	12
31-40	0	2	7
41 +	0	0	3
Total	168	168	168

classification variables identifying the type of intersecting roads on the segment, and the number of intersecting roads within the limited sight distance sections of crest vertical curves. Interactions among these variables were also considered as potential contributors to the models.

Linear terms in the regression model become multiplicative factors when the results are transformed back to the original scale of the data. This results from the original logarithmic transformation of accident rates. Examples of predictive values are provided to aid in interpreting the results. Potential predictive factors are modeled as either continuous variables, such as AADT and percent limited distance, or as categorical variables, such as the types of intersecting roads on a segment.

The classification of segments according to the types of major intersections divided the road segments into four groups. Major intersections were initially placed in one of two categories designated numbered or county roads—and the cross-classification of these two types produced the four possible groups. For example, one group represents segments that contain a county road, but not a numbered road; another group, segments that contain both numbered and county roads. It can be seen throughout the results that this categorical factor contributes to explaining variability in the accident rates before considering the factors of major interest in this study.

The number of intersecting roads that are within the limited stopping sight distance sections of crest vertical curves is considered as a separate continuous variable. All intersections, including the less prominent ones designated as driveways, are counted in this calculation. Only a small percentage of total intersections satisfy the condition of being within a limited stopping sight distance section. In the two-lane-with-shoulder data set, only 19 of 299 roads—or 6 percent of the total intersections—are within sight-deficient curves using the sight distance criterion of 450 ft. Table 3 gives the full summary of available data on intersecting roads.

The results of the analysis of the logarithm of accidents per mile are presented in detail. The accident rate significantly depended on AADT, modeled by a quadratic relationship. The type of intersecting roads also contributed to explaining the variability in accident rates. Using the AASHTO minimum criterion for 55 mph of 450 ft, the variable for stopping sight distance, percent limited stopping sight distance, was not significantly associated with accidents per mile after adjustment for these two factors. The variable for the number of intersecting roads within limited stopping sight sections of

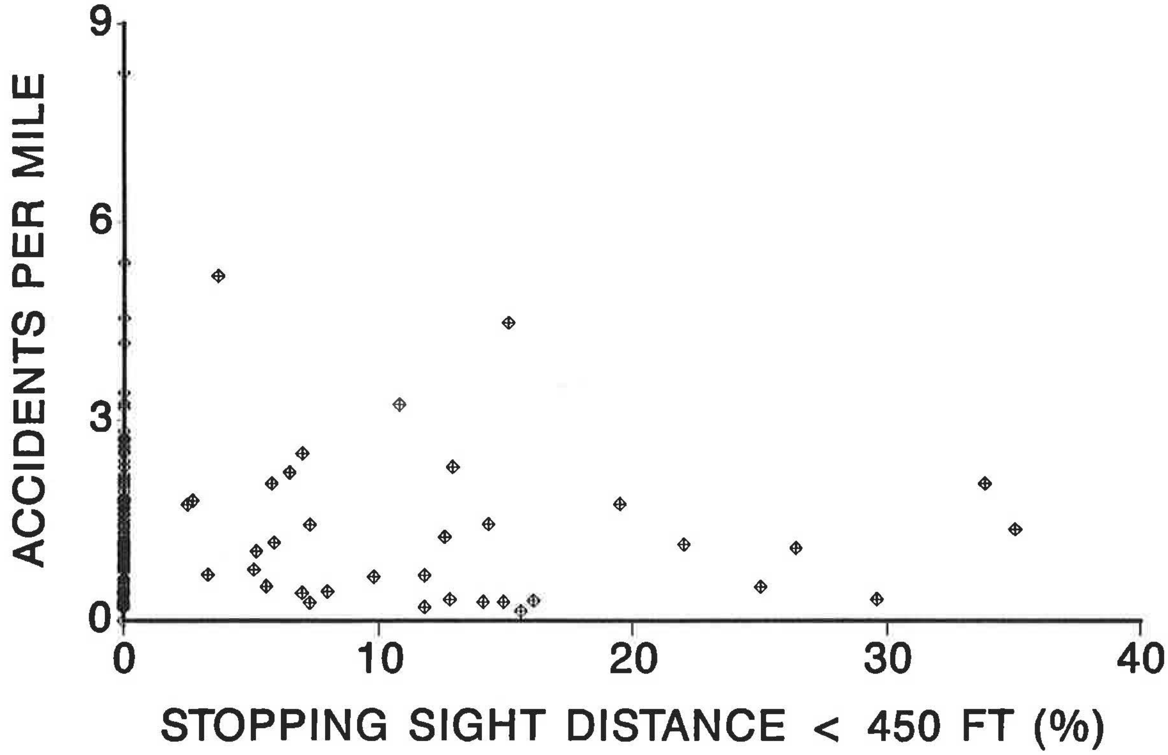

FIGURE 2 **Relationship of accident rate per mile and percentage of limited SSD, two-lane roads with shoulders.**

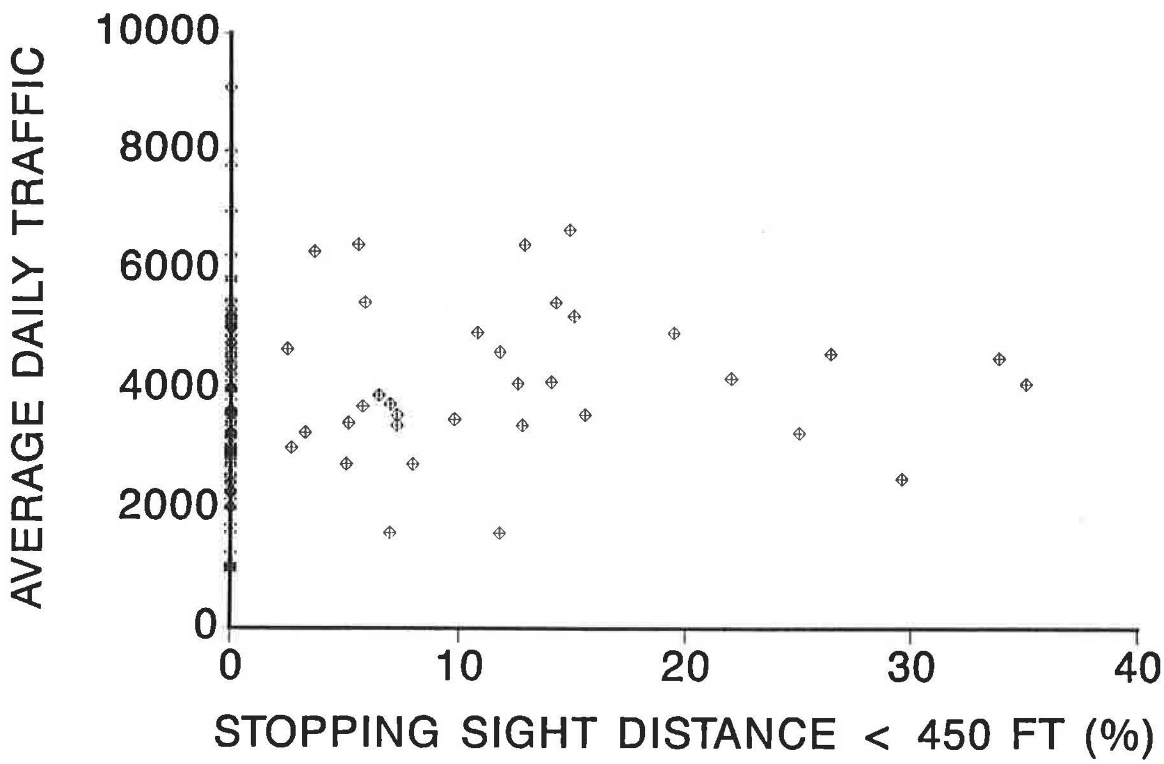

FIGURE 3 **Relationship between limited SSD and AADT, two-lane roads with shoulders.**

TABLE 3 INTERSECTIONS ON TWO-LANE ROADWAYS WITH SHOULDERS BY AVAILABLE SSD

Type of Intersection	Total	Number of Intersections Available SSD (Ft.)		
Road		<325	<450	<550
Numbered	53	0	4	5
County	221	0	9	22
Driveway	25	0	6	9
Total	299	0	19	36

TABLE 4 REGRESSION COEFFICIENTS FOR ANALYSIS OF MINIMUM CRITERION OF SIGHT DISTANCE FOR 55 MPH (450 FT) ON TWO-LANE ROADWAYS WITH SHOULDERS

	Dependent Variable: Accidents per mile	Logarithm of Accidents per mvm
Intercepts		
Neither County nor Numbered Roads	-0.1559	0.4065**
County Road, No Numbered Road	-0.1179	0.4258**
Numbered Road, No County Road	0.1624	0.6805**
Both County and Numbered Roads	0.1222	0.6255**
AADT	0.0002563**	0.00002317
AADT²	-0.0000000126+	----
Intersecting Roads within Influence of Restricted Sight Distance	-0.5452*	-0.4139*
Interaction of AADT and Intersection Roads	0.0001522*	0.0001169+

+ =p < .1
* =p < .05
** =p < .01

crest curves did have a significant effect when included in the model along with its interaction with AADT. The presence of the interaction with AADT yields a model with an increasing effect of the intersections as AADT increases.

Examination of the alternative dependent variable, logarithm of accidents per MVM, yielded similar results. The estimated coefficients from the two analyses are presented in Table 4. Note the negative coefficients associated with the number of curve-influenced intersecting roads within limited stopping sight distance sections. The effect of the negative coefficient is overshadowed, however, by the positive coefficient associated with the interaction of AADT with this factor. A slight negative effect on accident rates is seen at low AADT values, but an overwhelming positive effect of curve-influenced intersections is demonstrated at higher AADT values. These results are demonstrated in Table 5, which provides estimated values of accident rates from the model for accidents per mile. Note the slight decrease in accident rate as the number of intersections increases for AADT of 2,000. The effect is reversed, however, for the higher AADT values. The effects seen at the outer ranges of the data are extreme and should not be accepted casually. The more reliable estimates are associated with AADT values between 3,000 and 5,000 vehicles, which represent over half of the sample data. These estimates assume a county road, but no numbered road on the segment.

TABLE 5 ESTIMATED VALUES OF ACCIDENTS PER MILE ON TWO-LANE ROADWAYS WITH SHOULDERS

AADT	Number of Intersections Within Limited SSD Sections			
	0	1	2	3
2000	0.41	0.11	0.00	0
4000	1.02	1.16	1.30	1.45
6000	1.63	2.80	4.45	6.93

The plot of accident rate versus percent limited sight distance is repeated in Figure 4, with the sample points containing curve-influenced intersecting roads indicated. Note that the majority of such points are associated with higher accident rates. This result is what is being brought out by the regression analysis.

The same analyses were carried out using the more conservative measure of sight distance. The value of 550 ft, which is the minimum value in the AASHTO policy for 65 mph, was used to calculate the percent of limited sight distance. These analyses yielded essentially the same results as those for the 450-ft criterion for both accidents per mile and accidents per MVM. The effects of intersections within limited SSD sections were statistically significant ($p > 0.05$) in both these analyses.

Two-Lane Roads without Shoulders

A smaller sample of 54 approximately one-mile road segments was defined from the selection of two-lane roads without shoulders that was identified by the Texas State Department of Highways and Public Transportation district offices. The total number of accidents occurring on these segments was 464. Annual accident rates per mile varied between 0.0 and 7.19.

Examination of the distribution of AADT in this sample showed that there was very limited data available for AADT greater than 4,000 vehicles. Further, Table 6 provides the cross-classification of AADT and percent of limited sight distance using the AASHTO minimum criterion for 55 mph of 450 ft. The data illustrate extreme imbalance with respect to these two important variables. Only nine road segments are identified with AADT greater than 4,000, and each of these segments has little roadway with limited sight distance. Figure 5 provides the plot of the relationship and it can again be seen that the segments with the higher AADT values are

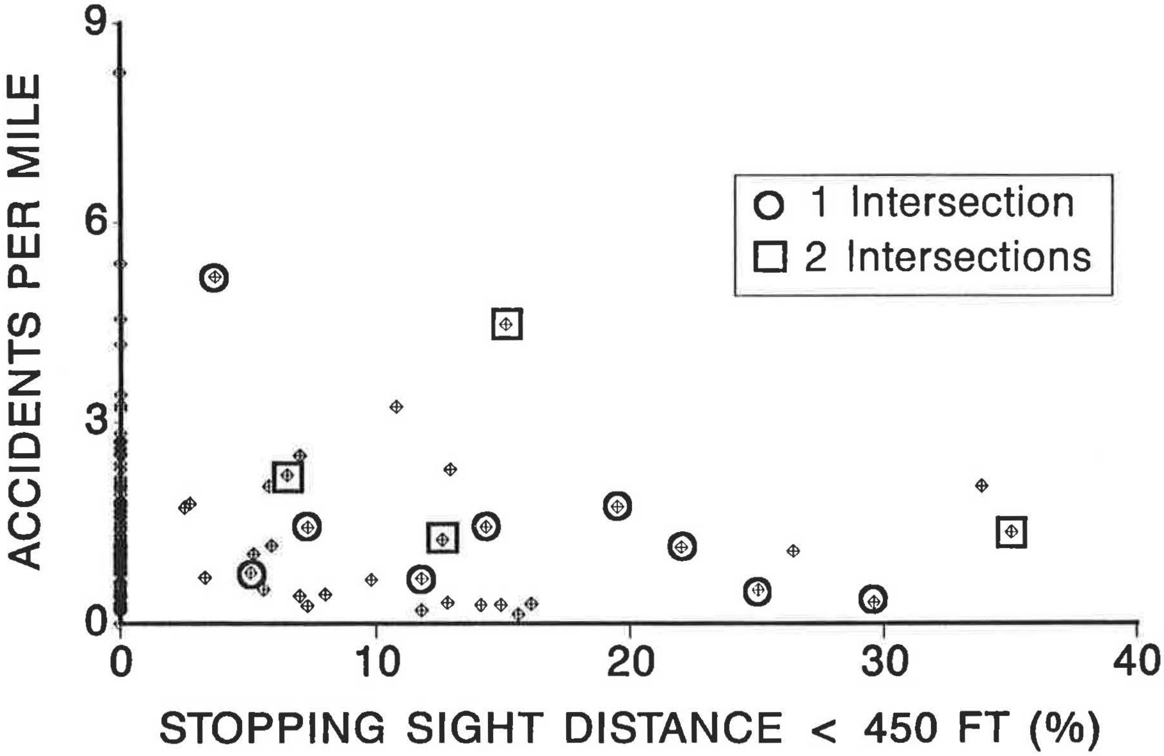

FIGURE 4 Relationship between limited SSD and accidents per mile with consideration of curve-influenced intersecting roads, two-lane roads with shoulders.

TABLE 6 FREQUENCY BY AADT AND PERCENT LIMITED SIGHT DISTANCE (450 FT) ON TWO-LANE ROADWAYS WITHOUT SHOULDERS

Percent Limited Distance	AADT			
	<2000	2-3999	4-5999	≥6000
0	3	8	3	2
1-10	4	2	0	1
11-20	6	11	1	2
21-30	1	6	0	0
31-40	0	3	0	0
>40	0	1	0	0

indeed restricted to low values of percent limited stopping sight distance. The higher AADT roadways do not contain large amounts of crest vertical curves with limited stopping sight distance.

Because of the importance of accurately adjusting for AADT before evaluating the relationship between accident rates and limited sight distance, this group of road segments was split according to AADT values before proceeding with the analysis. This step was deemed necessary because of the strong imbalance between AADT and percent limited stopping sight distance. Given the extremely unbalanced sample data, it could not be ensured that the modeling of accident rate on AADT would be adequate, and thus the evaluation of the effect of limited sight distance could be biased. The analysis could be performed in two parts, eliminating the problems just outlined. Because of the scarcity of data for AADT greater than 4,000, only those segments with AADT less than 4,000 were analyzed in order to eliminate the potential bias caused by imbalance.

This study sample of two-lane roads without shoulders represents roads with considerably more limited sight distance sections than the previously analyzed roadways with shoulders. The available information on sight distance for each of the three criteria is shown in Table 7. These frequencies are restricted to those road segments with AADT of less than 4,000. Almost all segments have limited sight distance sections when the more conservative criteria are used to define the measurement. A small percentage are, in part, limited using the stopping sight distance criterion of 325 ft.

As in the previous data set, only a small percentage of the intersecting roads are within the limited stopping sight distance sections of crest curves. Table 8 gives the breakdown of the data available on intersections within limited stopping sight distance sections for the two-lane-without-shoulders data set.

The variable for limited sight distance using the criterion of 325 ft of required sight distance is examined first. Figures 6 and 7 present the accident rate per mile against AADT and percent limited stopping sight distance, respectively. The same observations that were made previously in examining the first data set (two-lane roads with shoulders) hold here as well. In Figure 7, note the limited data available for percent stopping sight distance. The range is from 0 to less than 15

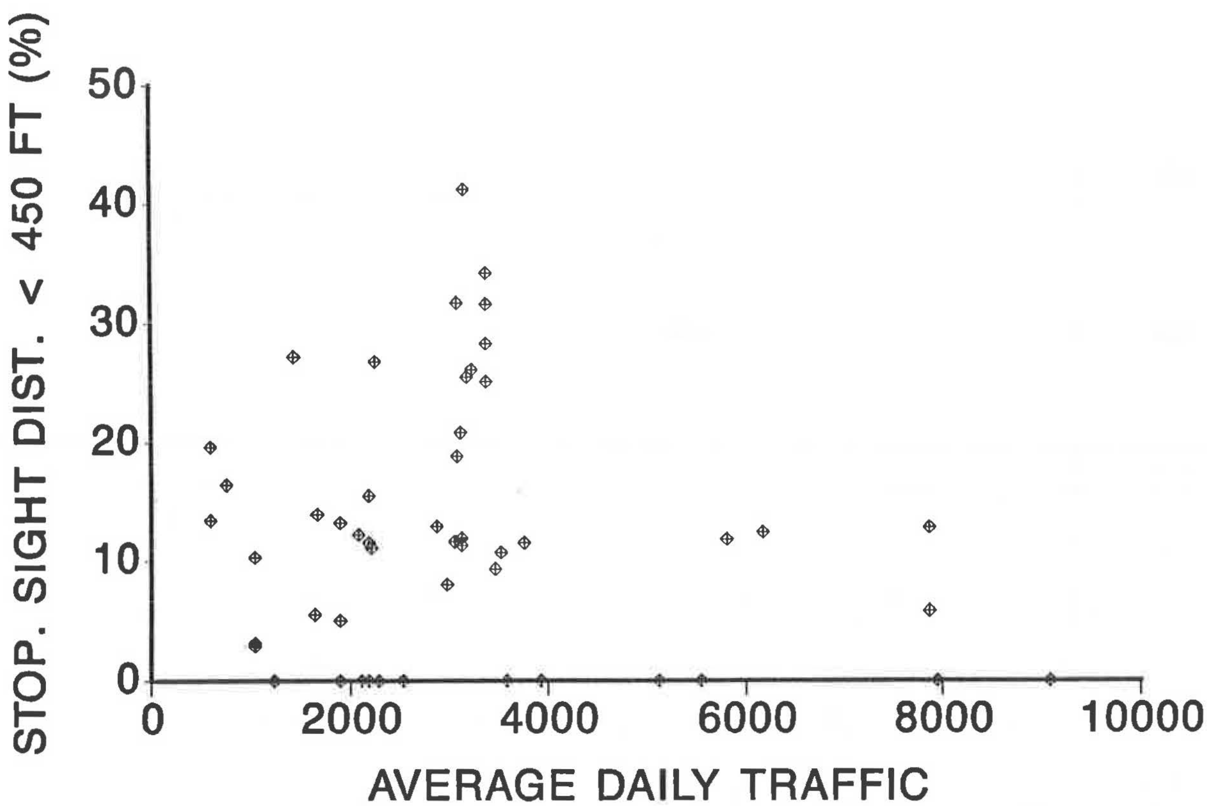

FIGURE 5 Relationship between AADT and limited SSD, two-lane roads without shoulders.

TABLE 7 FREQUENCY OF SEGMENTS BY THREE CRITERIA OF LIMITED SIGHT DISTANCE ON TWO-LANE ROADWAYS WITHOUT SHOULDERS

Percent Limited Distance	Minimum 325	Sight 450	Distance (ft) 550
0	33	11	1
1-10	9	6	2
11-20	3	17	18
21-30	0	7	10
31-40	0	3	8
41 +	0	1	6
Total	45	45	45

TABLE 8 INTERSECTIONS ON TWO-LANE ROADWAYS WITHOUT SHOULDERS BY AVAILABLE SSD

Type of Intersecting	Number of Intersections Total	Available SSD (ft)		
Road		<325	<450	<550
Numbered	13	0	3	7
County	72	0	4	9
Driveway	12	3	7	11
Total	97	3	14	27

percent. The number of intersections within limited stopping sight distance sections is indicated in this figure.

The regression analysis was performed in the same way as for the analysis of two-lane roads with shoulders. The results of the regression of the logarithm of accidents per mile as the dependent variable are presented in detail. Again, the only significant effect, after adjustment for presence of major intersections and AADT, was the number of intersections within the limited stopping sight distance sections of crest curves. The interaction of this factor and AADT was not significant ($p > 0.1$), indicating a clearly positive relationship with accident rate for all AADT values.

Figure 8 illustrates the relationship between accidents per mile and the percent limited sight distance using the 450-ft criterion. Indicated are the values associated with those segments containing intersecting roads within the limited stopping sight distance sections of curves. Again, it can be seen that the segments with the highest numbers of intersecting roads within limited stopping sight distance sections of crest vertical curves have some of the highest accident rates. Also, there appears to be a negative relationship between accident rate and the percent limited stopping sight distance.

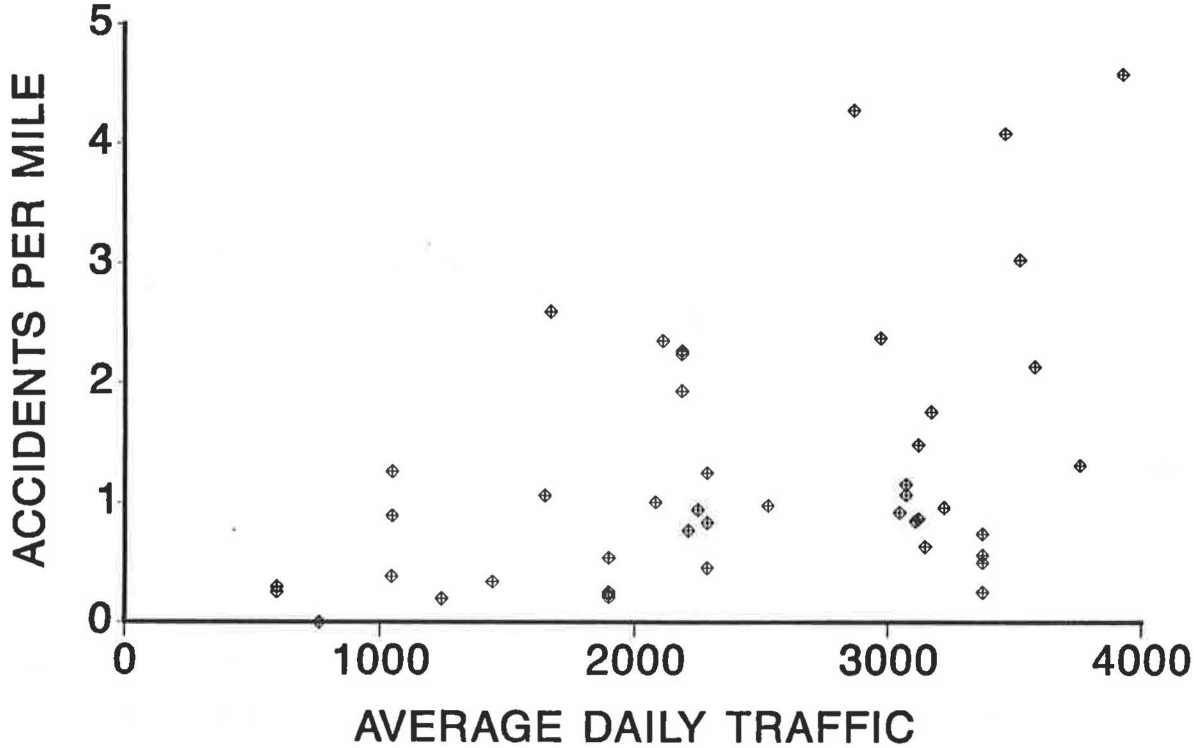

FIGURE 6 Relationship between AADT and accidents per mile with limited SSD, two-lane roads without shoulders.

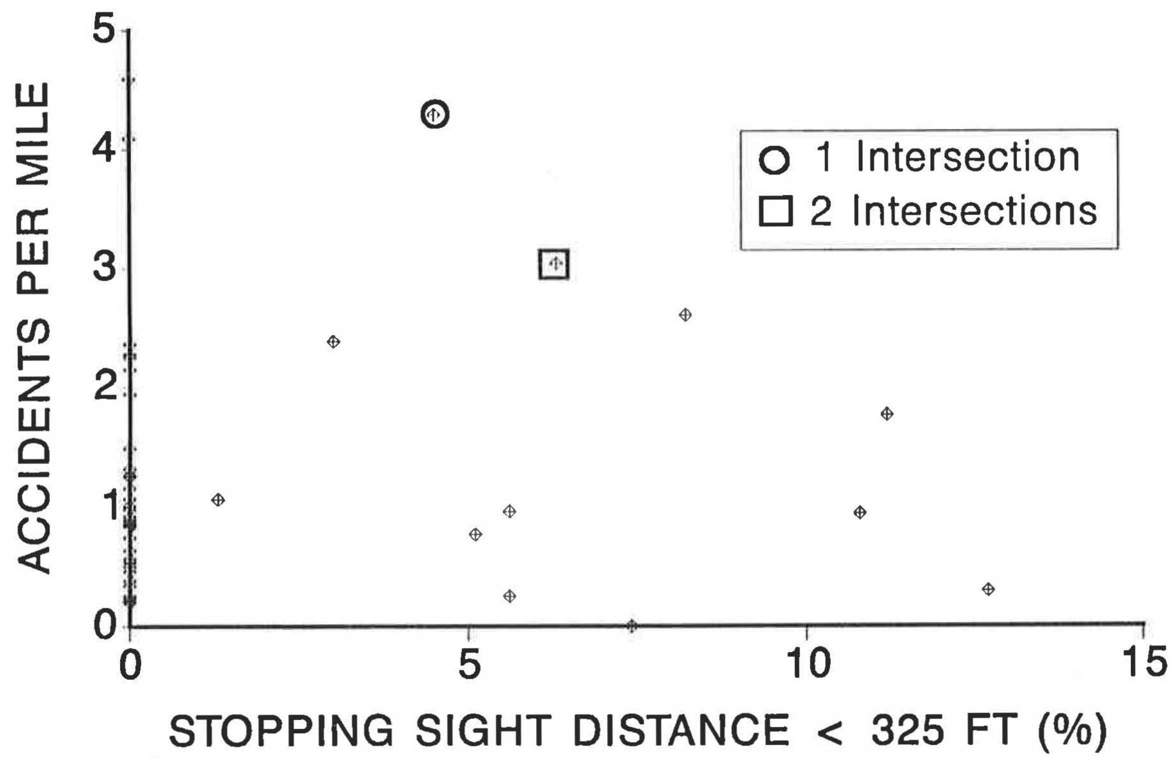

FIGURE 7 Relationship between limited SSD and accidents per mile with consideration of curve-influenced intersecting roads, two-lane roads without shoulders.

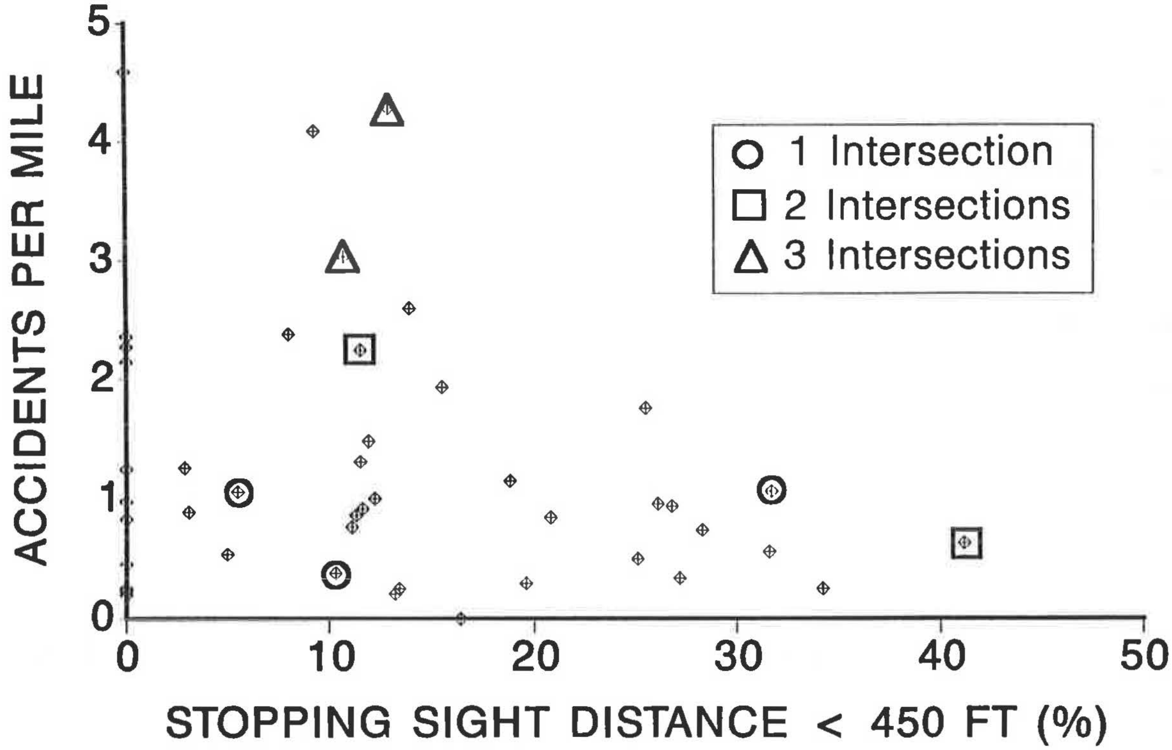

FIGURE 8 Relationship between accidents per mile with limited SSD with consideration of curve-influenced intersecting roads, two-lane roads with shoulders.

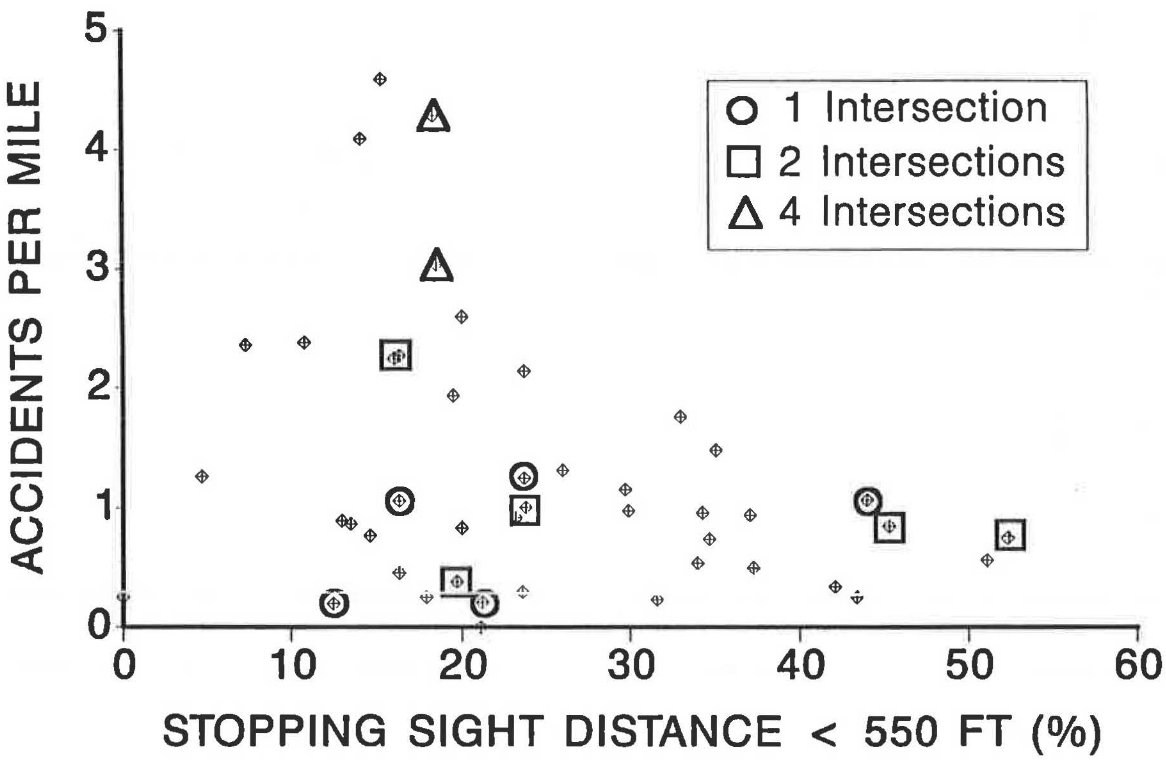

FIGURE 9 Relationship between limited SSD and accidents per mile with consideration of curve-influenced intersecting roads, two-lane roads without shoulders.

The regression analysis produced ambiguous results. The effect of the number of intersecting roads within limited stopping sight distance sections on the accident rate was positive and significant, but accompanying this effect was a significant negative relationship between accident rate and the percent of the roadway with limited sight distance.

The effect of percent limited sight distance using the most conservative standard of 550 ft was finally examined. The results of that analysis repeated the negative association between accident rate and percent limited stopping sight distance. Again, the percent limited distance was highly significant, with a negative coefficient. Figure 9 presents the results. The effect of the number of intersecting roads within limited stopping sight distance sections of crest curves was not significant (p = 0.15).

The coefficients from these three analyses are given in Table 9 for comparison. Special notice can be made of the relative sizes of the coefficients estimating the effect of the number of intersecting roads within limited stopping sight distance sections of crest curves. It is of interest that these coefficients are reduced by roughly one-half as the criterion for measuring limitations in sight distance becomes more conservative. For example, the coefficient of 0.36 for the 325-ft criterion is reduced to 0.17 when the "minimum" AASHTO criterion for 55 mph (450 ft) is used. And the size of the corresponding coefficient for the 550-ft criterion was 0.07, which was found to be nonsignificant (p = 0.15) and thus is not included in Table 9.

Both the models for the AASHTO minimum standard for 55 mph and the minimum for 45 mph contain significant coefficients for the effect of intersections within limited stopping sight distance sections, using the adopted significance level of 0.05. And the effect, if added to the model developed for 550 ft required sight distance, approached significance (p = 0.15). Nevertheless, the negative relationship between accident rates and percent limited sight distance remains for the 450- and 550-ft standards. The effect is clearly negative for stopping sight distance of 550 ft. And the effect sometimes overwhelms the positive effect of the intersections, yielding estimated accident rates that decrease for increasing percent limited distance with a stopping sight distance of 450 ft. Examples of this relationship are given in Table 10. The estimates assume the presence of a county road, but no numbered road.

TABLE 9 REGRESSION COEFFICIENTS FROM THE ANALYSIS OF LOGARITHM OF ACCIDENTS PER MILE ON TWO-LANE ROADWAYS WITHOUT SHOULDERS

	Sight Distance Criterion (ft) 325	450	550
Intercepts			
Neither County nor Numbered Roads	0.0986	-0.2404	0.3624+
County Road, No Numbered Road	0.3428*	-0.1079	0.4436**
Both County and Numbered Roads	0.4586+	-0.0655	0.5145*
AADT	0.0001645*	0.0004043**	0.0002929**
Percent Limited Sight Distance	------	0.02223	-0.01715**
Interaction of AADT and Percent Limited Sight Distance	------	-0.00001354*	-------
Intersecting Roads within Influence of Restricted Sight Distance	0.3592*	0.1741*	------

+ =p < .1
* =p < .05
** =p < .01

TABLE 10 ESTIMATED ACCIDENTS PER MILE FOR SSD CRITERION—450 FEET ON TWO-LANE ROADWAYS WITHOUT SHOULDERS

Percent Limited Stopping Sight Distance	Number of Intersections Within Limited SSD Sections 0	1	2	3
0	1.02	-	-	-
20	0.83	1.18	1.59	2.08
40	0.66	0.98	1.35	1.80
0	3.52	-	-	-
20	1.39	1.84	2.38	3.03
40	0.26	0.50	0.79	1.13

Examination of accidents per MVM, which was an additional dependent variable for analysis, did not significantly alter any results already obtained using the accident rate per mile.

In an attempt to understand the conflicting relationships modeled in this analysis, the values that seem to have the most influence on the negative relationship between accident rate and percent limited distance were examined. It was discovered that most of the segments that contain large relative amounts of limited stopping sight distance were from one area, all belonging to the same roadway section. Figure 10 identifies these points.

All the analyses for logarithm of accidents per mile, a dependent variable, were repeated, omitting this section of roadway. Many effects were no longer significant, which may be partly attributed to the reduction in the size of the data set. The coefficients and their significance levels for the adopted models for the three criteria were already presented in Table 4. Those results can be compared with these modified analyses. For the 325-ft criterion, the variable for intersections within limited stopping sight distance sections became insignificant (p = 0.12), leaving only the types of major intersections and AADT in the model. In the analysis of the 450-ft criterion, the negative relationship between accident rate and percent limited stopping sight distance was dropped from the model because of nonsignificance, leaving only the positive relationship with intersections within limited stopping sight distance sections. The resulting model, therefore, clearly predicts an increase in accident rate as the number of intersections within limited stopping sight distance sections increases. The model for the 550-ft stopping sight distance criterion remained unchanged, although the significance level was reduced (p = 0.04).

Another method of adjusting for differences that are known to exist among roadways, but for which we have no quantifiable measurements, was used. A constant term was introduced into the model for each different roadway, distin-

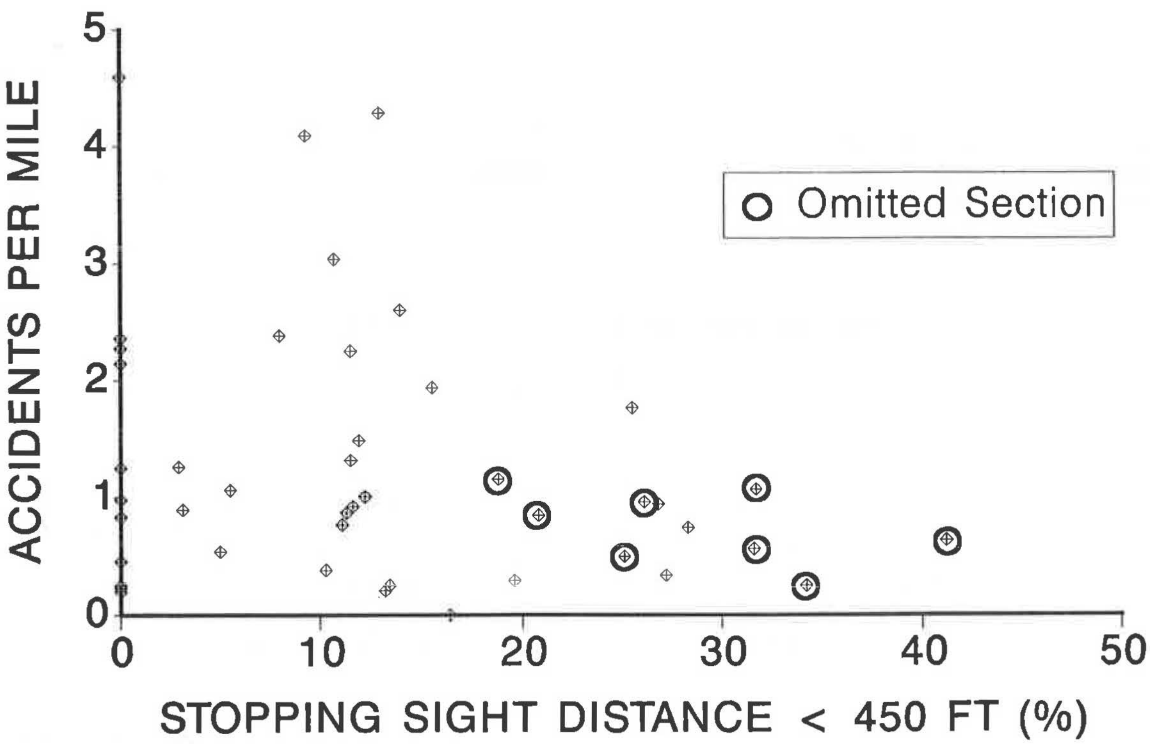

FIGURE 10 Relationship between limited SSD and accidents per mile, two-lane roads without shoulders.

guished by its control number. This method allowed an individual constant adjustment of the accident rate in each case. Again, some effects disappeared after incorporating this adjustment. Nonetheless, the positive effect of intersecting roads within limited stopping sight distance sections of crest curves based on the 325-ft criterion increased in its effect. The coefficient increased to 0.41, compared with 0.36 previously, with a significance probability of 0.01. All effects related to stopping sight distance (the relative amounts and the number of intersections within limited stopping sight distance sections) were no longer significant ($p > 0.05$) in the analyses of the 450- and 550-ft criteria.

These results are more meaningful when compared with similar analyses on the previous data set. The two-lane roads without shoulders were subjected to the same adjustment for different roadways for comparison. In the analysis of that data set, no changes in the models resulted. The models remained remarkably consistent in terms of the sizes of the coefficients as well. The limited data available for the analysis of two-lane roads without shoulders makes the ambiguous results open to question. The consistency of the analytical results of the larger sample of two-lane roads with shoulders can be interpreted with more confidence.

SUMMARY AND CONCLUSIONS

Two large data bases consisting of 222 study segments of approximately one-mile lengths representing nearly 1,500 accidents were assembled to evaluate the effects that stopping sight distance along crest vertical curves has on accident rates. The study sites were carefully screened to control for other geometric and operational conditions that could affect accident rates. All study segments were two-lane roadways. The roadways had 55 mph posted speeds and were located in rural areas of east and central Texas. The study segments with sight distance limitations generally had modest limitations; that is, sight distance limitations were generally less than the AASHTO minimum requirement for 55 mph design, but they were generally better than the AASHTO minimum requirements for a 45 mph design. The following are the most significant findings:

1. The relationship between available sight distance on crest vertical curves on two-lane roadways and accidents is difficult to quantify even when a large data base exists.
2. The AASHTO stopping sight distance design model alone is not a good indicator of accident rates on two-lane rural roadways in Texas. Thus, adherence to the model alone in designing projects will not result in cost-effective projects.
3. Where there are intersections within the limited sight distance sections of crest vertical curves, there is a statistically significant increase in accident rates.
4. It can be inferred that other geometric conditions within limited sight distance sections of crest vertical curves could also cause a marked increase in accident rates. An example would be a sharp horizontal curve hidden by a crest vertical curve.
5. The increase in accident rates because of intersections within limited sight distance sections of crest vertical curves is more pronounced on roadways with higher volumes, implying that a threshold volume level may be determined based on considerations of cost effectiveness.

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