Abridgment

Accident Analyses for Highway Curves

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The results of studies of accidents and roadway geometrics on two-lane rural highways are presented. The studies were a portion of federally sponsored research on the safety and operations of highway curves. A data base was assembled from geometry files of four states. Two sets of analyses were performed: (a) a multivariate analysis of the incremental accident effects of five basic geometric and traffic variables, and (b) a detailed study of the geometric and environmental characteristics of site populations with high- and low-accident rates. The study findings demonstrated that degree of curve, extent of roadside hazard, and pavement surface quality (i.e., available friction) have the greatest impact on safety of two-lane rural highway curves. Other notable effects were observed with shoulder width, roadway width, and length of curve.

The results of studies of accidents and roadway geometrics on two-lane rural highways, performed as a part of FHWA-sponsored research, are presented in this paper. Two separate accident analyses were undertaken: analysis of covariance was used to study the incremental accident effects of basic geometric and traffic variables, and discriminant analysis was applied to a detailed study of the geometry of sites that had either very high or very low accident rates.

CHARACTERIZATION OF ACCIDENTS

A data base of 3,557 sites from four states (Illinois, Florida, Ohio, and Texas) was used to perform the analyses. A series of constraints was applied to each state's geometric data base to create pure curve and tangent segments of 1 km in length with uniform geometry throughout. State accident records were used to produce a 3-yr history of accident experience at each site; the records included the following information: location, severity [fatal or injury versus property-damage-only (PDO) accidents], vehicle type, accident type, surface condition, light condition, and weather condition.

A total of 13,545 reported accidents occurred during the analysis period. A number of significant findings were derived from the characterization of the data.

Accident Types

The data in Table 1 give the proportion of accidents by number of vehicles involved and traffic volumes. Slightly more than half (54 percent) of the accidents on the selected analysis segments involved only one vehicle.

Accident Severity

A total of 5,390 accidents (41.5 percent) resulted in an injury or fatality. Single-vehicle run-off-the-road (ROR) accidents on curves were more likely to be severe when compared with multivehicle or other single-vehicle accidents. Regardless of roadway width or degree of curve, nearly half of all single-vehicle ROR accidents involved a personal injury or fatality. By contrast, 41 percent of multivehicle curve accidents and 29 percent of other single-vehicle accidents on curves were severe.

Surface Conditions

Approximately 27.5 percent of all accidents on curve segments occurred when the surface condition was reported as being wet or icy. It was rationalized from average climatology information that roadway pavements in the four states would be wet or icy approximately 10 to 12 percent of the time. Therefore, wet or icy surface conditions appear to almost triple the likelihood of an accident.

ANALYSIS OF ACCIDENTS

Initial analysis efforts focused on the incremental accident effects of five basic variables [average daily traffic (ADT), degree of curve, length of curve, roadway width, and shoulder width] by using the entire data base of 3,304 curve sites.

Analysis of covariance (AOCV) was used to study these incremental effects. This procedure provided a framework that considered both the direct effects of each variable and all of the potential interaction effects between variables. Preliminary analysis by using an AOCV framework, with accident rate as the dependent variable, indicated that all variables, except ADT, had a significant relation with accident rate. Subsequent analyses were conducted by using the following framework variables:

1. Covariates--degree of curve, length of curve (miles), road width (feet), and shoulder width (feet);
2. Factors--state: 1, 2, 3, 4; degree of curve: $\leq$ 1.999, 2.000 to 3.999, 4.000 to 6.999, $\geq$ 7.000; length of curve (miles): $\leq$ 0.1499, $\geq$ 0.1500; road width (feet): $\leq$ 21.999, $\geq$ 22.000; and shoulder width (feet): $\leq$ 5.999, $\geq$ 6.000; and
3. Dependent variables [accidents per million vehicle miles (MVM)]--total accident rate, single-vehicle accident rate, multivehicle accident rate, night accident rate, and fatal plus injury accident rate.

The results of the analysis that used the framework variables were as follows:

1. The multiple R^2 was about 0.19 (the AOCV framework explained 19 percent of the variance) for all matrices where the total accident rate was the dependent variable, and much lower for all other dependent variables;
2. State, degree of curve, and their two-way intersections with other variables accounted for most of the explained variance; and
3. The raw regression coefficients for each of

Table 1. Percentage of reported accidents by number of vehicles involved and volume class.

Traffic Volume Class (ADT)	Percentage of Reported Accidents: Single Vehicle ROR	Single Vehicle Other	Multivehicle
≤2,099	42.5	23.9	33.6
2,100-3,099	41.4	22.4	36.2
3,100-4,899	35.2	19.7	45.1
4,900-9,999	28.6	14.7	56.7
≥10,000	14.9	8.2	76.9
All volumes	35.1	19.1	45.8

Note: ADT = average daily traffic, and ROR = run-off-the-road accident.

Table 2. AOCV results.

Covariate	Practical Range of Covariate	Regression Coefficient	Difference in Accident Rate (accidents/ MVM)
Degree of curve	1° to 20°	0.056	1.12
Length of curve	0.05 to 0.40 mile	-0.141	0.05
Width of traveled way	18 to 24 ft	-0.023	0.14
Shoulder width	0 to 10 ft	-0.057	0.57

the covariates were as follows: degree of curve = 0.056; length of curve (miles) = -0.141; road width (feet) = -0.023; and shoulder width (feet) = -0.057.

The regression coefficients are the best overall estimates of the incremental effects of each covariate. They indicate logical relations, with the possible exception of length of curve. But in reality longer curves are usually associated with lower degrees of curve.

No logical trends could be derived from the individual regression of the cells in the AOCV matrix. The overall regression coefficients derived in the second step of the analysis are therefore the best-available predictors of the incremental accident effects of each covariate. It is informative to determine the predicted incremental differences over the practical range of each covariate, as given by the data in Table 2.

Degree of curve appears to have a sizable effect on accident rate over the practical range of usage. The effects of the other covariates, however, appear to be relatively small.

Analysis of High- and Low-Accident Sites

The limited success of the AOCV prompted a second approach: an analysis procedure that maximized the potential for discovering any geometric or accident relations. Two distinct populations were selected from the curve data base. The populations were defined as accident outliers; i.e., the sites were selected on the basis of either a very high accident rate or a very low rate. Differences in the geometric characteristics of these high- and low-accident populations were then investigated.

This approach ensured the discovery of any safety or geometry relations that may exist because the study sites were selected on the basis of dissimilarities in their accident experience rather than differences in geometric or other features that would only be hypothesized as being related to accidents.

The sites were partitioned into three ADT classes (1,400 to 2,099, 2,100 to 3,099, and 3,100 to 4,899) to control for any effects of traffic volume. Sites that had accident rates at least twice the mean rate for that state's ADT class were designated as high-accident sites. For all but the highest ADT class, low-accident sites experienced no accidents over a 3-yr period. A total of 330 sites that had extreme accident histories was thus selected.

Field studies were performed at all 330 sites to further define their geometric and environmental character. The following information was collected: degree of curve; road width (on tangent and in curve); shoulder width (on tangent and in curve); superelevation in curve; superelevation transition length; superelevation distribution; characteristic of horizontal alignment upstream from the curve; sight distance to the curve; relative hazard of roadside (slopes, objects, and so on); pavement condition; pavement skid resistance; signing; pavement markings; and presence of driveways, structures, minor roads, and so on.

The formal analysis of the high- and low-accident sites used a statistical technique known as discriminant analysis, which is used to statistically distinguish between two or more populations. Data that describe the characteristics on which the populations are expected to differ are collected and analyzed. In this case the two populations were the high- and low-accident sites. The characteristics (or discriminating variables) were the geometric and environmental variables studied in the field.

Discriminant analysis distinguishes between the populations being studied by forming a linear combination of the discriminating variables. The discriminant function is of the following form:

$$D = d_1Z_1 + d_2Z_2 + \ldots + d_pZ_p$$

where D is the score on the discriminating function, d's are weighting coefficients, and Z's are the standardized values of the discriminating variables. The best derived discriminant function was

$$\begin{aligned} D &= 0.071257(DC) + 2.9609(LC) + 0.10737(RR) \\ &= 0.035161(PR) - 0.14504(SW) - 1.54544 \end{aligned} \quad (1)$$

where

- D = discriminant function (nondimensional),
- DC = degree of curve,
- LC = length of curve (miles),
- RR = roadside rating (a measure of roadside hazard),
- PR = pavement rating (a measure of pavement skid resistance), and
- SW = shoulder width (ft).

Because a higher discriminant score indicates a higher likelihood that a site is a high-accident location, the variables appear to contribute to the expected results.

The relative discriminating power of the variables in Equation 1 is as follows:

Variable	Relative Discriminating Power
RR	2.11
SW	1.39
LC	1.39
DC	1.14
PR	1.00

Equation 1 correctly classifies 75.9 percent of the high-accident sites, 60.2 percent of the low-accident sites, and 69.1 percent of all sites.

Interpretation of Results

The discriminant analysis procedure predicts or classifies a site as being a high- or low-accident site based on the actual distributions of D values for the two groups of sites in the data base. The analysis procedure decides which classification is appropriate by calculating probabilities that each D score belongs to the high or low distribution.

The value of the discriminant analysis results is primarily in the ability to predict high-accident locations. Because the D score distributions of the high- and low-accident sites overlap considerably, it is probably more efficient to concentrate on sites that have relatively high probabilities of being high-accident sites.

The procedure enables analysis of any probability criterion level. Figure 1 shows the relation between D and P(H); i.e., the probability that a site is a high-accident site. Selection of any P(H) criterion level can be translated into a minimum D score (based on Equation 1) for analysis purposes.

A P(H) criterion of 80 percent was chosen for further study. As shown in Figure 2, with this criterion it appears that almost all sites that have high roadside hazards would qualify as high-accident sites. Likewise, almost all sites that have low roadside hazards would not qualify. The results are more mixed with moderate roadside hazards. Generally, moderate roadside hazards must be combined with either very sharp curvature or a combination of two variables that are moderate or worse.

In summary, hazardous roadside design appears to

Figure 1. Relations between D and P(H).

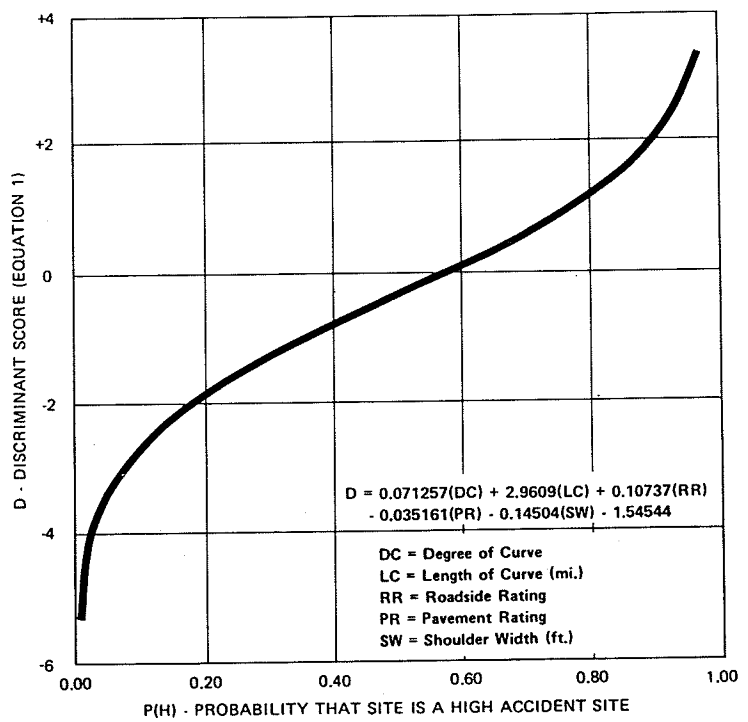

Figure 2. Probability that a highway curve site is a high-accident location.

Low Roadside Hazard (20)
High Pavement Skid Resistance (50)

Curve Length (mi.)	Shoulder Width (ft.)	Degree of Curve 1	3	6	12	20
Long (.30)	0	50	53	58	-	-
	4	37	39	45	-	-
	8	22	24	27	-	-
Moderate (.17)	0	42	45	50	-	-
	4	30	32	37	-	-
	8	18	20	23	-	-
Short (.05)	0	34	37	42	52	64
	4	23	25	30	38	52
	8	14	16	19	26	38

Moderate Roadside Hazard (35)
High Pavement Skid Resistance (50)

Curve Length (mi.)	Shoulder Width (ft.)	Degree of Curve 1	3	6	12	20
Long (.30)	0	86	87	88	-	-
	4	76	77	80	-	-
	8	66	67	70	-	-
Moderate (.17)	0	82	83	85	-	-
	4	69	71	74	-	-
	8	58	60	62	-	-
Short (.05)	0	74	76	78	85	91
	4	62	64	66	77	86
	8	50	52	54	65	79

High Roadside Hazard (50)
Moderate Pavement Skid Resistance (35)

Curve Length (mi.)	Shoulder Width (ft.)	Degree of Curve 1	3	6	12	20
Long (.30)	0	91	92	93	-	-
	4	85	89	90	-	-
	8	73	79	82	-	-
Moderate (.17)	0	87	89	90	-	-
	4	78	84	86	-	-
	8	66	72	75	-	-
Short (.05)	0	82	84	86	90	94
	4	71	76	79	84	89
	8	59	65	68	74	82

High Roadside Hazard (50)
Low Pavement Skid Resistance (20)

Curve Length (mi.)	Shoulder Width (ft.)	Degree of Curve 1	3	6	12	20
Long (.30)	0	97	97	98	-	-
	4	95	95	96	-	-
	8	92	92	93	-	-
Moderate (.17)	0	96	97	97	-	-
	4	94	95	95	-	-
	8	91	92	92	-	-
Short (.05)	0	96	97	97	98	99
	4	94	95	95	96	97
	8	91	92	92	93	94

Tabulated values are percent probabilities as given by Equation 1 and Figure 1.

be the largest contributor to high-accident experience at highway curves. Other less-prominent contributors are sharp curvature, narrow shoulders, low pavement skid resistance, and long curves.

APPLICATION OF RESULTS

For application at existing curves, Equation 1 indicates that improving roadside design, pavement skid resistance, and shoulder width may be valid countermeasures. The reduction of curvature may not be practical or productive because of high costs and the apparent trade-off between degree and length of curve for a given central angle. This study does not suggest that other design deficiencies, such as extremely unsatisfactory approach sight distances, extremely narrow lanes, extremely unsatisfactory transitions, and extreme shoulder slope breaks, might not be considered in an improvement program. Regardless, the discriminant analysis does provide guidance concerning the effects of roadsides, pavement surfaces, and shoulders.

Discussion

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Neuman, Glennon, and Saag have tackled a difficult problem in their paper. The TRB Committee on Operational Effects of Geometrics has been addressing this problem since they held their Workshop on Forgiving Roadways in July 1976.

It is not surprising that roadside hazards appear to be the largest contributor to high accident experience on highway curves. Based on the material presented in the paper, it is assumed that the analyses were based strictly on reported accidents. There is the belief that a majority of the ROR accidents go unreported, but those people who are unlucky enough to hit a roadside obstacle on leaving the roadway end up a statistic. On the other hand, this conclusion substantiates other research results that indicate that the removal of roadside obstacles on the outside of horizontal curves may be one of the most cost-effective safety projects that could be implemented.

Therefore, a more detailed description of how the roadside rating factor and the pavement rating factor were determined should have been included in this paper so that the research could be duplicated in the future.

In the multivariate analysis, the regression coefficients indicate that the accident rate increases as the degree of curvature increases, and decreases as the length of curve, road width, and shoulder width increase. The authors agreed that these appeared to be "logical relations, with the possible exception of length of curve." They go on to state "in reality, longer curves are usually associated with lower degrees of curves." They imply that lower degrees of curves are associated with safer roadways and, therefore, longer curves are safer. However, in the discriminate analysis it was determined that, by increasing the degrees of curve, lengths of curve, and roadside hazard ratings, the discriminate score increased, which meant that there was a higher likelihood of a high-accident location. The inclusion of length of curve as a variable to indicate a high-accident location appears to be contradictory to the rationale stated in the discussion of the multivariate analysis.

For future reference, a bibliography of research associated with this study would have been appreciated.

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Authors' Closure

We thank Mulinazzi for his comments on our paper. Further analysis of the discriminant analysis findings has verified that treatment of roadsides holds the greatest potential for cost-effective improvements to existing rural highways.

In responding to the comments and questions regarding the paper, it should be emphasized that the paper documents preliminary research results. The work was performed as part of a larger study of rural highway curve safety and operations. In attempting to complete the accident analysis and present it to TRB in an abridged form, certain points may not have been clear or complete. We appreciate the opportunity to clarify these points.

The study was indeed based on reported accidents. As in almost all studies of this nature, which rely on existing data bases, reported accidents are the safety-related variable of interest. What is important in trying to identify hazardous situations is that severe accidents (i.e., those that involve injuries and fatalities) be identified. For obvious reasons, such accidents tend to be reported.

In the interest of brevity, roadside and pavement rating factors were not covered in the paper. We agree that a description of these variables is required for duplication or separate analysis of the research.

ROADSIDE RATING FACTORS

Roadside rating factors were obtained from pictures and sketches of each of the sites observed in the field. The basis for the factors used is reported in NCHRP Report 148 (1). The model describes the likelihood of a severe accident as a function of roadside encroachment frequency, probability distributions for lateral displacement given a roadside encroachment, a measure of the hazard displacement given a roadside encroachment, and a measure of the hazard associated with the roadside. The roadside hazard is described by (a) a roadside slope break at a given distance, (b) a clear-zone width, (c) an obstacle coverage factor (i.e., a measure of the frequency of obstacles), and (d) severity indices for roadside slopes and obstacles.

The hazard ratings for various roadside configurations, assuming the average side slope break point is 10 ft from the edge of road, are given in Table 3.

PAVEMENT RATING FACTOR

Pavement rating factors were obtained from field crew observations of pavement surface roughness and depth of asperities. Pictures of the pavement were taken to verify the field crew's judgment. The rating scheme was developed to approximate the skid number at 60 mph.

LENGTH OF CURVE VERSUS ACCIDENT RATE

The relation between length of curve and accident

Table 3. Roadside hazard ratings.

Side Slope	Coverage Factor	Roadside Hazard Ratings by Lateral Clear Width (ft)						
		30	25	20	15	10	5	0
6:1 or flatter	90	24	28	32	34	42	46	47
	60	24	27	29	30	35	38	39
	40	24	27	27	27	32	34	34
	10	24	24	24	24	25	26	26
4:1	90	35	37	39	41	44	48	49
	60	35	36	38	39	40	43	44
	40	35	36	37	37	39	41	41
	10	35	35	35	35	36	37	37
3:1	90	41	42	42	43	44	48	49
	60	41	42	42	42	43	45	46
	40	41	42	42	41	41	44	45
	10	41	42	42	41	41	42	42
2:1 or steeper	90	53	53	53	53	45	49	50
	60	53	53	53	53	46	49	50
	40	53	53	53	53	48	50	50
	10	53	53	53	53	50	50	50

rate requires some clarification. The raw regression coefficients reported in the paper express the relation between the covariate and dependent variable for the entire data base. Because these coefficients do not reflect interactions between variables, they must be viewed with caution. In the case of curve length, the negative coefficient appears illogical unless one considers the strong correlation between curve length and degree of curve. In any event, as was discussed in the paper, the actual effect of this coefficient is negligible given the practical range of curve length.

REFERENCE

1. J.C. Glennon. Roadside Safety Improvement Programs on Freeways--A Cost-Effectiveness Priority Approach. NCHRP, Rept. 148, 1974, 64 pp.

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

Abridgment

Some Partial Consequences of Reduced Traffic Lane Widths on Urban Arterials

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When four-lane, urban, undivided arterials are newly built or reconstructed in place, traffic lane width becomes one of the major determinants of total right-of-way width. A particularly difficult problem arises when the urban corridor permits the construction of 10- or 11-ft-wide lanes, but not 12-ft-wide lanes. There are no guidelines for the roadway designer to indicate the trade-offs in traffic safety and operations as the width of a traffic lane is reduced below the 12-ft standard. The relationship of operating speed and accidents to a series of independent variables that characterize roadway design features and traffic volumes is investigated. It is concluded that both peak and off-peak operating speeds, as well as traffic accidents, are significantly related to traffic lane width on urban arterials. Specifically, operating speeds decrease and accidents increase as traffic lane width decreases. Operating speeds are also influenced by the posted speed limit, traffic volume, and total traffic lane width. Also, the number of accidents per year is related to the number of intersections per mile, the number of access trips to and from commercial driveways, average daily traffic, total traffic lane width, and changes in horizontal and vertical alignment. An example of the cost trade-offs between changes in traffic lane width and accidents and operating speeds is presented.

Traffic lane width is a key design element for the roadway; it influences right-of-way width, land costs, construction costs, levels of service, and traffic operational characteristics. In the past highway designers and traffic engineers have generally disregarded any lane width other than 12 ft, but because of current reductions in funding for improvements, there is increased interest in the feasibility and desirability of narrower traffic lanes.

The issue of lane width arises with restricted right-of-way width in urban corridors for new construction or reconstruction. It also arises with transportation system management (TSM) types of improvements in urban locations, where additional traffic lanes can be obtained by decreasing individual lane widths. Reducing lane widths, however, presents a dilemma. Although reduction in traffic lane width may result in reduced capital improvement cost, which may be the only way to accomplish the roadway improvement, such reduction does not meet most design standards and may result in permanent lowering of the roadway level of service.

It is clear that there are significant trade-offs involved when traffic lane widths are reduced to less than 12 ft. It is important that the decision maker know what these trade-offs are in order to evaluate the impact of a proposed reduction in lane width. Neither the technical research literature nor the design manuals provide guidelines to the decision maker for determining these trade-offs. This question of trade-offs is addressed in this paper. The scope of the investigation was limited to four-lane, undivided, urban arterial highways. Finally, it should be emphasized that no departure from current roadway standards for traffic lane widths is suggested in this paper.

LITERATURE REVIEW

The research literature on traffic lane width indicates that investigators have concentrated their efforts on rural, two-lane highways (1-5). When the effect of traffic lane width relative to highway speeds has been studied, the results have been inconsistent (6,7). When total traffic lane width was investigated relative to accident rates, the results were also inconsistent (1,8,9). Because traffic lane width should be investigated as a part of the total roadway system, it is appropriate to note the research results for certain other roadway design elements relative to measures of accident exposure. Investigators have reported that, as the number of urban intersections, access points, commercial