Geometric Design Element Groups and High-Volume Two-Lane Rural Highway Safety

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ABSTRACT

The complex relationships among several geometric design elements and accidents on two-lane rural roads were studied. Two data sets were used in modeling effects of traffic volume greater than 2,000 vehicles per day, driveway and intersectional conflict frequency, roadside obstacle characteristics and geometric design elements on total accident occurrence for a national data set, and off-road accident frequency and severity for a Michigan route data set. Geometric design elements were aggregated into bundles or groups that are actually found in the field as a result of design policies. Advanced multivariate techniques were used to study these interactions. It was found that accidents interact in such a complex way with traffic volume that use of the conventional vehicle mile exposure rate in modeling is less fruitful than treating average daily traffic (ADT) as an independent variable. For the prediction of accidents, the effects of ADT were found to be most important followed by driveway and intersection density and the geometric elements. The interactive effect of access point density with volume was also important, as was the interactive effect of access point density and geometric characteristics. Longitudinal alignment elements were found to dominate in off-road accident prediction for rural two-lane roads at ADT values of 4,000 vehicles per day or less, whereas roadside elements were of more importance at higher ADT values. No significant independent effects of cross-sectional elements were found in the total accident prediction. Off-road injury accident prediction on rural two-lane highways was more sensitive to roadside obstacle location and characteristics than total accident prediction. Simple categorical models developed from this research explained 63 percent of the total accident variance in the national data set and 54 percent of the off-road accident variance in the other.

Two-lane rural highway safety is an issue of pressing national concern. It has been identified as the highest priority research need in the area of responsibility of the TRB Committee on Geometric Design (1). These roads constitute approximately 4 million km or 63 percent of the highways in the United States and are the locations of about 50 percent of all highway fatalities (2). They have the highest accident rate of any class of rural highway, with fatal and injury vehicle mile exposure accident rates (VMER) consistently being 4 to 7 times higher than those on rural Interstate highways (3).

The geometric design elements of two-lane rural roads vary widely, just as do their use, frequency and character of intersectional and access conflict points, and physical condition. The cost of bringing them all up to current design standards is prohibitive, and the highway engineer must make choices from among many possible improvements and locations to achieve the greatest safety benefit from investments in highway modernization.

Despite many studies, the understanding of the effects of geometric design on safety has not been adequate to predict effectively the traffic accident response to individual geometric design element changes. The effects of a few dominant elements such as horizontal curvature have been identified. However, the obviously complex interactions among geometric elements are neither well known nor adequately understood.

The objectives of this research were to explore the interactive effects of geometric design elements on the occurrence and severity of accidents on two-lane rural roads and to identify some promising prediction models useful in engineering decisions. Attention is limited to highways with average daily traffic (ADT) values of 2,000 vehicles per day or greater. Groups of design elements frequently used together at the same time as a result of design policies, called bundles in this research, were formed and explored as alternatives to the individual elements.

PREVIOUS STUDIES

The relationships between geometric design elements and accidents have often been studied. Horizontal alignment particularly has been shown to be strongly related to accident experience by many researchers (4-8). Other single elements such as intersection and driveway density have also showed a safety relationship (5). On the other hand, the effects of lane and shoulder width have been found to differ (8,9). It has also been observed that combinations of elements are related to accident experience (5,9-11). For example, Kihlberg and Tharp (5) found that road segments with combinations of less-desirable values of curvature, grades, intersections, and roadside structures generated VMER as high as 6 times the rates on road segments with the best designs.

The effect of a single geometric element is difficult to identify because of the mixing or confounding of these elements in actual highway installations (8,12). This probably results in overstating the positive effect of better individual geometric improvements because higher-quality alignments are found more frequently with better cross-section geometric elements on high ADT facilities. Zegeer et al. (13) found lower VMER at higher volumes and noted that normally the higher-volume roads are much better built and are not as accident prone.

The interacting effects of the individual elements and the high correlations among these elements were clearly shown in Versace's early study (14), in which he used factor analysis (15) on the characteristics of approximately 1,400, 1-mile road segments in Oregon, 1,110 of which had an ADT of less than 3,000. A strong correlation among the various individual elements describing road segments was clear. Although he labeled them differently, his first factor captured horizontal and vertical alignment effects, the second factor captured the conflict effect of traffic volume and access point density, the third captured the cross-sectional elements, and the fourth was made up of the roadside elements.

The effect of traffic volume on accidents on these roads is somewhat better understood. On tangent sections of road, VMER has been reported not to increase with ADT (16). However, it was also been reported that there is a relationship between VMER and ADT (5,17). In one study the VMER of single-vehicle accidents decreased as volume increased, whereas the multivehicle VMER was unaffected by changes in traffic volume (18). When accident measures different than VMER are used, strong traffic volume effects are found. Among these, accidents per mile per year (MYER) has been occasionally used as an independent variable (11,14,18-21). Zegeer and Mayes (18), in a large study on two-lane highways in Kentucky, found that the MYER increased with ADT from 250 to 8,000. The VMER of single-vehicle accidents decreased as volume increased, whereas multivehicle VMERs were unaffected by changes in traffic volume.

Mathematical models relating accidents to geometric design elements have been constructed by several researchers (10,22-24). The best recorded fit was attained by a multiple linear interactive model developed by Dart and Mann (10) that explained 46 percent of the variation and considered the following variables: lane width, horizontal alignment, shoulder width, pavement cross slope, vertical alignment, percentage of continuous roadside obstructions, marginal obstruction per mile, traffic access points per mile, percentage of trucks, and traffic volume ratio at intersections.

Gupta and Jain (22) also developed a linear-regression model for VMER using the variables lane width and horizontal alignment as well as vertical clearance and sight-distance restriction. They found no significant effect for these geometric variables, and the regression equations obtained were not statistically significant with variance explanations of less than 5 percent. Snyder (23) reported that ADT, number of intersections, and driveway access density were the main VMER explanatory variables. He found no interaction among these variables in his additive model.

Roy Jorgensen Associates (24) analyzed relationships for rural two-lane highways. The variables included in their regression analysis, in addition to lane width, horizontal alignment, and shoulder width, were surface type, ADT, terrain, and section length. The regression models explained little of the variance of the data, generally less than 8 percent.

In a recent NCHRP study of clear roadside recovery areas, Graham and Harwood (9) identified three roadside design policies involving mixes of side slopes and roadside obstruction clearances. They accounted for differences in ADT and shoulder width and found a statistically significant relationship between design policy and the off-road accident VMER.

In Blackburn's analysis of the FHWA anti-skid resurfacing program data (25), no correlation was found between wet-pavement VMER and several geometric factors. An analysis of the same data set by advanced multivariate techniques by the authors of this paper (11) found that the effects of the geometric elements on MYER accident occurrence were highly interactive with ADT and that the patterns of interaction of these geometric elements varied over the range of ADT values.

METHODOLOGY

Two data sets containing information on traffic, geometric and environmental conditions, and accident experience on two-lane rural roads were analyzed. The first data set was developed from a file originally prepared and analyzed for the FHWA in a study that examined the safety effects of resurfacing rural highways (25). The file contained the accident history for a 1-year period and descriptive road information for a national sample of 428 before sites, which included test segments that were to be resurfaced and control sections that remained unchanged, and 378 test and control after sites. In this study this file is referred to as the FHWA Skid file.

The second source of data contains information on a set of selected 2-mile sections along Michigan two-lane rural state highways (20). The frequency and severity of off-road accidents covering a 4-year period are included in the file.

Both data files were filtered for this research. Because there is evidence that lower-volume two-lane rural roads exhibit accident experience quite different from that found on higher-volume roads (4,5, 11,20), cases with ADT lower than 2,000 vehicles per day were removed. The lower ADT sections are analyzed in a separate paper (26).

Segments in the FHWA Skid file with four lanes, speed limits less than 45 mph, density of access points exceeding 25 per mile, or with curbs were eliminated. Only segments with constant lane widths and shoulder treatment over their entire length were retained.

The lengths of the sections in the FHWA Skid file ranged from 1 to 25 miles. It has been shown that typical methods of selecting homogeneous segments for safety studies result in data sets in which accidents are correlated with segment length with high VMER found on short segments and lower VMER on long segments (5). After a study of these data, only those sites with a length between 3 and 9 miles were retained (11).

The final sample in the file, hence referred to as the Michigan-FHWA Skid Data file, contained the 1-year accident history and descriptions of the geometric features of 152 rural two-lane road segments with lengths varying from 3 to 9 miles and ADT volumes in the range of 2,000 to 10,000 vehicles per day in 14 states. In the file there is a total of 3,224 accidents, with an average of 21.2 accidents per year per road segment and a MYER of 4.0 on about 800 miles of road.

The second data set, referred to as the Michigan State Route Data set, after filtering, contains a sample of 137, 2-mile sites with a 4-year accident experience of more than 1,300 off-road accidents, 514 of which involved injuries. Besides accident frequency and severity, the data include ADT and intersection information, geometric characteristics, and some data on roadside obstacles. A list of variables for each data set appears in the model summary tables (see Tables 1 and 6 presented later in this paper).

The driving theme in modeling complex phenomena is to simplify the model as much as possible while keeping the quality of prediction high. This was followed in this study by reducing the number of independent variables as much as possible while still retaining the effectiveness of the model as measured by variance explanation. The following analysis methodology was used.

1. There was a statistical examination of data to identify the variables that contribute most to

the explanation of variation of accident occurrence by using automatic interaction detection (AID) (27).

2. Factor analysis (15) was used to identify reasonable groups of correlated variables.

3. Interrelated roadside and geometric elements were grouped into reasonable bundles. The aggregation of geometric and roadside design element characteristics has been called a bundle in this research. This is a term adopted from economics, which signifies interrelated elements that are best treated as a group.

4. The ability of the bundles to explain the variation in accidents was determined and it was compared with the variation explanation of individual geometric design elements

5. The characteristics of the segments with the best and the worst accident experience were explored.

6. A promising illustrative categorical model was developed.

Highway accident data sets, like most large data sets of observations of complex real-world phenomena, are characterized by the absence of many combinations of factors in reality and the lack of a balanced experimental design in building the data file. Furthermore, the descriptive variables (predictors) are usually correlated, and some are categorical. Although some standard statistical analysis techniques are legitimate and helpful, many make use of the restrictive and unrealistic assumptions of linearity and additivity. Joint effects or interactions can be treated in multiple regression, but this process becomes extremely cumbersome if many higher-order interactions for all predictors are considered. Furthermore, interaction effects, as well as main effects, may be important only for certain subgroups. In regression and in the analysis of variance, the variance in the dependent variables accounted for by each predictor and each interaction effect is measured on the entire data set. Thus it is assumed that the same relationship holds over the entire range of variables, something that often is not true.

The primary statistical method selected for this study is AID (27), a convenient way of examining categorical data. The basis of the AID algorithm is an interactive scheme that searches for that dichotomous split level for an independent variable that gives the maximum improvement in the ability to predict values of the dependent variable through unexplained variance reduction. AID divides the data into mutually exclusive subgroups through a series of such splits, stopping when subgroups become too small or selected confidence limits are exceeded. Each observation becomes a member of one of these subgroups. The resulting subgroups have simple statistics (mean, variance) and can be mapped onto an AID branch diagram for study and presentation.

The smallest AID split used in this research has a minimum number of five segments in a group. Differences in accident means are statistically significant at the 90 percent confidence limit. In the figures presented in this paper, only differences in means of at least 30 percent are illustrated.

The first step in the study was to use the AID analysis to identify the main and interactive effects and to select variables that had little apparent effect on the variation of the MYER accident frequency.

Related bundles of design policies were then defined. An example of design bundling is found in a Michigan state highway data sample (20), in which shoulder width had two classes, ditch invert offset had three classes, ditch condition had three classes, percentage of section with horizontal curvature had three classes, and percentage of section with roadside obstacles closer than 14 ft from the edge of the road also had three classes. If all combinations of these five descriptors existed, there would be 162 different types of roads. The data set drawn to represent all possible combinations actually found in the state had only 58 different classes, and 14 of these groupings had more than half of the sections. This occurs because design policies at any time fix a set of standards that make up a bundle.

Factor analysis (15) was then used to identify groups of correlated variables. A physical interpretation of the results from the factor analysis was used in the AID analyses to complete the bundle definition process. A comparison of variation explanation by AID analyses was then made by using bundles in one case and the original variables that made up the bundles in the second.

The last step in the methodology was to use the AID branch diagrams to identify the most important variables and to examine the patterns of interactions. Main effects were easily identified, and the patterns of interactions were exposed. The sections with the most and the least accident experience were also studied to reveal the pattern of variable interactions within each group of accident experience. The patterns of variable interactions were then incorporated into a single categorical model.

ANALYSIS OF MICHIGAN-FHWA SKID DATA FILE

The variables and the results of the AID runs on the Michigan-FHWA Skid Data file are given in Table 1. The variables that make significant contributions to each model are identified and the variance explained is also presented. The first step in the analysis of this data set was the selection of the accident exposure figure of merit. Candidates were accident rate based on VMER [and vehicle miles of travel (VMT)]; total annual accidents per segment (SYER), regardless of segment length; and accident frequency based on annual length exposure (MYER).

Previous studies by the authors and others (5,11, 8,21) have shown that VMER, the most widely used exposure measure, usually requires further adjustment for ADT. This was confirmed for this data set by an AID analysis that used VMER as the dependent variable (model 1 in Table 1). Although 73.6 percent of the variation was explained by this AID, the first splits involved ADT (early splits are the most important in variance explanation), which indicated that the effect of ADT was still important even after being included in the dependent variable. If values of the VMER had adequately eliminated the effects of volume on accident experience, such as split would not have occurred.

The second exposure candidate for consideration was the total number of accidents per segment per year (SYER). An AID analysis (model 2 in Table 1) that used all the possible explanatory variables explained 81.9 percent of the variance but still showed length as one of the important variables in the AID splitting process.

The third candidate measure was MYER, accidents per mile per year. An AID analysis that used all the possible explanatory variables, including segment length with MYER as the dependent variable (model 3 in Table 1) and ADT in 26 categories, explained 72.9 percent of the variation, and the segment length did not appear in any of the major variance-explaining splits. Although the variance explanation was the highest for SYER, it is less appropriate for modeling and prediction purposes, and MYER was selected as the figure of merit for further analysis and modeling efforts. Tests of independence between

TABLE 1 Michigan-FHWA Skid AID Summary

Variable Name	Symbol	Model 1	2	3	4	5	6	6A	7[a]	8	9[b]	10	11[c]
Dependent variable													
Accidents per million vehicle miles	VMER	●											
Accidents per section per year	SYER		●										
Accidents per mile per year	MYER			●	●	●	●	●	●	●	●	●	●
Flow and location													
State	–	●	●	●	●								
Length	Len	●	●	●									
ADT	ADT	●	●	●	●	●	●	●	●	●	●	●	●
Overall intersection density	OID	●	○	●	●			●	○				
Overall access density	Acc Den	●	●	●	●		●		●	●	●	●	●
Legal speed limit	Sp Lim	○	○	○	○				○				
85th percentile speed	85% Sp	●	●	○	○				○				
Mean skid number at 85th percentile speed	Skid #	●	○	●	●				●				
Time	–	○	●	○	○				○				
Cross section													
Pavement type	Pv Typ	○	○	○	○				○				
Pavement width	Pv Wid	●	○	○	○				○	○			
Shoulder treatment	Sh Tr	○	○	○	○				○				
Percent length with shoulder narrower than 6 ft	%Sh < 6	○	○	○	○				●	●		●	
Alignment													
Percent no passing zone in both directions	PSR	●	●	●	●				●	●		●	
No. of curves per mile	NC	○	●	○	○				●				
Percent length on curves	PCL	●	●	○	○				●	●		●	
No. of sag curves per mile	NSC	○	○	○	○				○				
Percent length on significant grades	PSG	○	●	○	○				○				
Roadside hazard													
No. of obstacles within 10 ft	OB10	○	○	○	○				○	○			
Percent guardrail in both directions	PGR	○	●	●	●				○	●			
Bundles													
Cross section	Xs Bun										●		
Alignment	Al Bun										●		
Geometric	Geo Bun												●
Variation explained (%)		73.6	81.9	72.9	73.0	48.2	66.8	54.0	71.8	70.8	72.9	70.7	71.1

Note: ○ = variable did not appear in significant split, and ● = variable did appear in significant split.
[a]AID branch diagram shown in Figure 1.
[b]AID branch diagram shown in Figure 2.
[c]AID branch diagram shown in Figure 3.

accident density and segment length by the standard chi-square and Kullback statistic tests (28) indicated that the segments with lengths between 3 and 9 miles did not exhibit a significant section length bias at the 0.05 level, and hence this section length was selected.

AID analyses were then made. The first AID in this series (model 4) was carried out by using the 19 possible explanatory independent variables given in Table 1. The variation explained was 73.0 percent, and seven variables appeared in the significant splits. No cross-section variables were significant.

An AID MYER run that used only the 26 ADT classes (model 5) explained 48.2 percent of the variance. When only ADT and intersection density were used in an AID model, 54.0 percent of the variance was explained (model 6A). When both ADT and all access point density were considered (model 6), 66.8 percent of the variance was explained, and the important effect of driveway density in explaining total accident occurrence was revealed. The remaining explained variance of 6.2 percent of model 4 is attributable to the other four significant variables.

Factor analysis indicated that the state in which the segment was located--one of the four significant variables--was highly correlated with some design variables. Removing this variable decreased the variance explanation by only 1.2 percent (model 7). Figure 1 shows the AID branch diagram for this analysis. The first major splits occur at ADT levels of 4,500 and 8,000 vehicles per day. The next major contribution to variance explanation is from splits based on the percentage of length of the segment with no passing permitted (PSR). In the 4,500 to 8,000 vehicle per day category, segments where there was no passing for more than 65 percent of the length averaged 9.2 accidents per mile per year, whereas those with more passing opportunities had a MYER of 5.4. In the 2,000 to 4,5000 ADT category the split was at a PSR of 60 percent, and averages of 4.7 and 2.1, respectively, were recorded.

The further appearances of splits on ADT and access point density in the 2,000 to 4,500 vehicle per day group indicate the highly nonlinear and interactive effect of these variables on accident experience. Access density is important at both levels of ADT. No cross-section variables appear in the 13 groups formed. An AID analysis was run with eight explanatory variables (model 8), including ADT, access point density, and several alignment and cross-sectional variables identified by the factor analysis. The variation explained by the six significant variables was 70.8 percent, a small loss from model 7.

It was then decided to explore differences between the cross-section and longitudinal alignment design variable groups. The four significant geometric variables were than grouped into five classes in a cross-sectional bundle and six in an alignment bundle, as defined in Tables 2 and 3. At least 10 segments were included in each bundles class. The bundles were loosely ordered and numbered from best to worst in terms of combinations of the individual geometric elements. An AID analysis that used only four variables--ADT, access point density, the cross-sectional bundle, and the alignment bundle (model 9)--explained 72.9 percent of the variation, as good a performance as any previous MYER AID. The AID branch diagram is shown in Figure 2. These 13 categories gave a more than tenfold range in accident MYER. The worst segments, averaging 10.0 accidents per mile per year, were those six segments with an ADT of 8,000 or more vehicles per day. The lowest accident density, 0.9 accidents per mile per year, was found in the 11 sections with ADT in the

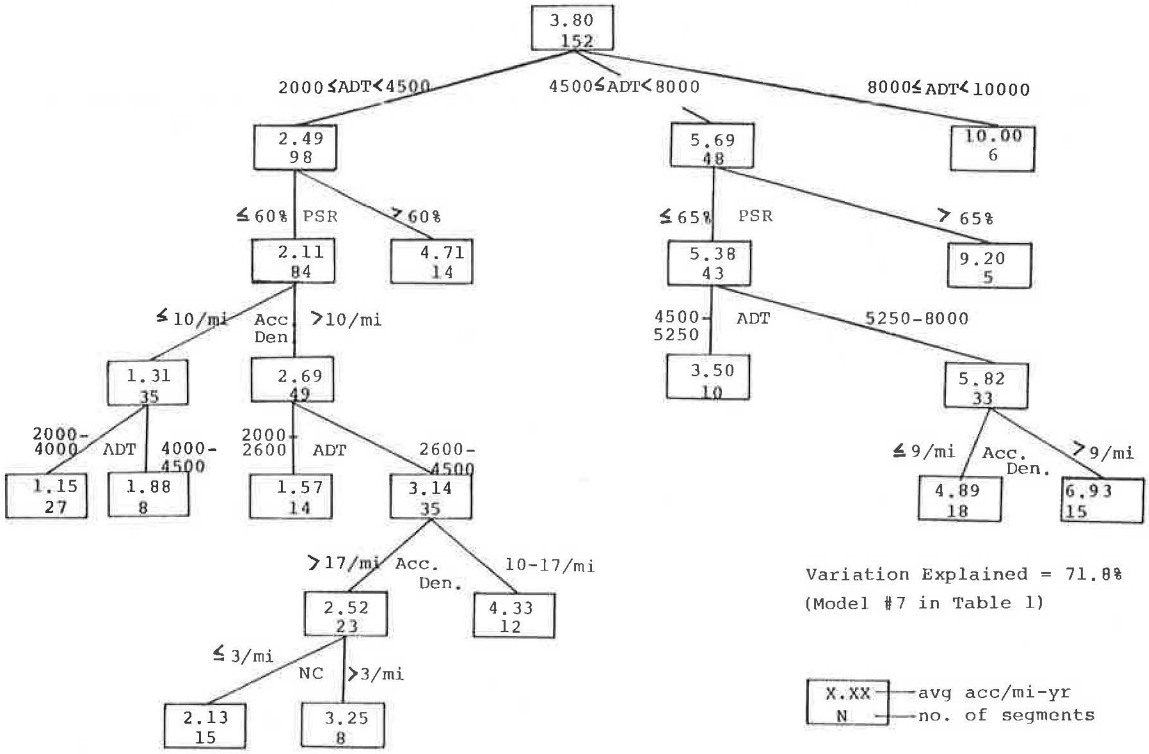

FIGURE 1 Michigan-FHWA Skid AID branch diagram using all variables except state.

TABLE 2 Definition of Cross-Section Bundles for Michigan-FHWA Skid Accident File

Bundle Designation	Shoulder < 6 ft (%)	Lane Width (ft)	Guardrail (%)	No. of Sections
Xs-1	≤50	–[a]	0	16
Xs-2	≤50	–[a]	>0	61
Xs-3	>50	≥12	0	23
Xs-4	>50	≥12	>0	23
Xs-5	>50	10-12	–[a]	29

[a]All.

TABLE 3 Definition of Alignment Bundles for Michigan-FHWA Skid Accident File

Bundle Designation	Nonpassing (%)	Curve Length (%)	No. of Sections
Al-1	0-20	0-25	30
Al-2	0-20	>25	20
Al-3	21-45	0-25	29
Al-4	21-45	>25	21
Al-5	>45	0-25	10
Al-6	>45	>25	42

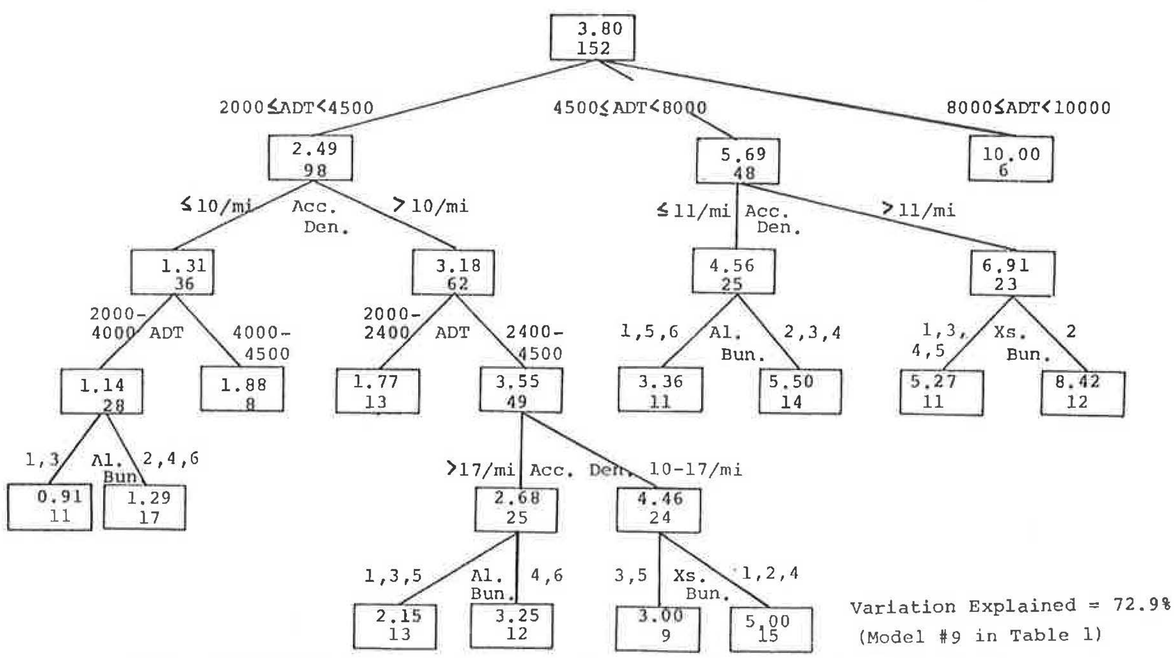

FIGURE 2 Michigan-FHWA Skid AID branch diagram using five cross-section and six alignment bundles.

range of 2,000 to 4,000 vehicles per day, with infrequent access points and alignments characterized by few curves and no passing restrictions.

Access density effects were important at all levels of ADT. For alignment bundles, only the best design had the lowest accident experience. For the cross-section variable, bundle sections with guardrail were worst, and there was a mixed effect of the shoulder width variable. The sections characterized by wider shoulders had a greater accident frequency in the higher ADT categories than at the lower ADT categories. This is an example of the dominating effect of ADT. Because wider shoulders are more often found on high-volume roads, the contribution of shoulder width to the variance explanation in accident frequency is believed to be actually another ADT effect that was not captured in the earlier split on ADT.

The next step was to combine the cross-sectional and alignment elements into one overall geometric bundle. An overall geometric bundle with six categories was created. The variables in the bundle are given in Table 4. The variables used were selected

TABLE 4 Definition of Geometric Bundles for Michigan-FHWA Skid Accident File

Bundle Designation	Nonpassing (%)	Curve Length (%)	Shoulder < 6 ft (%)	No. of Sections
Geo-1	0-20	0-25	-[a]	30
Geo-2	0-20	>25	-[a]	20
Geo-3	21-45	-[a]	≤50	31
Geo-4	21-45	-[a]	>50	19
Geo-5	>45	-[a]	≤50	30
Geo-6	>45	-[a]	>50	22

[a]All.

with the aid of the factor and AID analysis and include passing-restricted and horizontal curvature alignment variables and shoulder width from the cross-section elements.

An AID using just these three variables along with access density and ADT explained 70.7 percent of the variation (model 10). The AID for the geometric bundle (model 11) was then run. The variation explained is 71.1 percent, and the results are shown in Figure 3. The main divisions on ADT are the same as those seen in the earlier branch diagrams. In the 4,500 to 8,000 vehicle per day ADT category, those segments with access densities between 12 and 25 per mile with segments with no passing for more than 45 percent of the length and shoulders wider than 6 ft for more than 50 percent of the length averaged 9.6 accidents per mile per year. Those segments with an ADT from 2,000 to 4,000 vehicles per day, with access densities less than 10 per mile and geometric bundles characterized by better alignment, averaged 0.9 accidents per mile per year. Throughout the branch diagram, geometric bundle 2 (sections with more than 25 percent of the length on curves with few restrictions on passing) and geometric bundle 4 (sections with no passing on 21 to 45 percent of the length and more than half of the length with shoulders narrower than 6 ft) were associated with the higher accident experience in every category of ADT and access density.

A comparison of 51 sections with the most and least accident experience was then made: 17 sections with MYER of 8 or more against 34 sections with MYER of 1 or less. The sections with the worst accident record had the following statistically significant relative characteristics: higher ADT, more intersections and access points, more passing restrictions, more length with guardrails, higher 85th percentile speed, narrower lane width, and more roadside obstacles within 10 ft of the pavement edge.

Although there was no difference in the number of curves on the segments with highest and lowest accident experience, the segments with the highest accident experience had much shorter curves and more passing-restricted length.

The variables associated with speed, pavement width, and roadside obstacles did not appear in the significant splits in the AID analyses. Their effects are clearly dominated by other variables that did not show great explanatory power in this extreme value analysis, but did appear as strong predictors in the AID models. In formulating bundles, the percent length with shoulders narrower than 6 ft and percent length of curvature were added.

An illustrative categorical model developed from the Michigan-FHWA Skid Data file is given in Table 5. The results of the AID analyses and the six categories of geometric bundle were used to define the

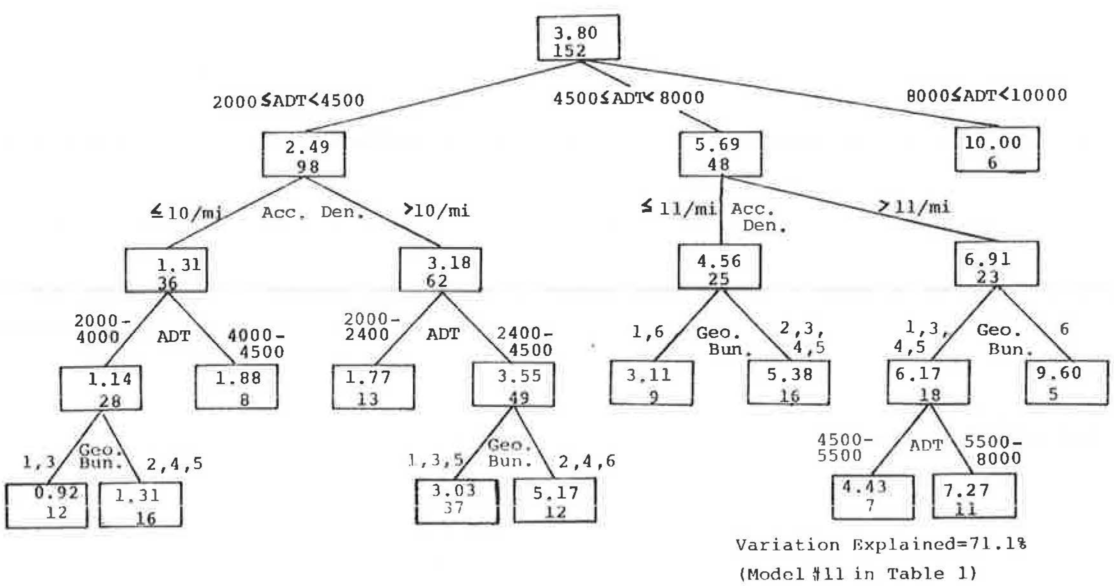

FIGURE 3 Michigan-FHWA Skid AID branch diagram using six geometric bundles.

TABLE 5 Cross-Classification Model for Michigan-FHWA Skid Accident File

ADT	Access Density (per mile)	No. of Accidents per Mile per Year by Geometric Bundle[a] Geo-1	Geo-2	Geo-3	Geo-4	Geo-5	Geo-6
2,000-2,500	≤5	0.86	1.38	0.86	0.86	1.38	0.86
	6-10	0.86	1.38	0.86	0.86	1.38	0.86
	11-16	1.29	2.34	1.29	1.29	2.34	1.29
	>16	1.29	2.34	1.29	1.29	2.34	1.29
2,500-4,000	≤5	1.18	1.18	1.18	1.18	1.18	1.18
	6-10	1.70	1.70	1.70	1.70	1.70	1.70
	11-16	3.30	7.50	3.30	7.50	3.43	7.50
	>16	2.38	2.83	2.38	2.83	3.43	2.83
4,000-7,000	≤5	5.89	5.89	5.89	5.89	5.89	5.89
	6-10	3.45	3.45	3.45	3.45	3.45	3.45
	11-16	6.60	6.53	6.53	6.60	6.60	8.60
	>16	5.00	6.53	6.53	5.00	5.00	8.60
7,000-8,000	-	6.80	7.71	9.00	6.80	6.80	9.00
8,000-10,000	-	10.00	10.00	10.00	10.00	10.00	10.00

[a]See Table 4 for geometric elements appearing in bundle.

divisions for the categories. This simple categorical model explains 63 percent of the variance in this data set.

MICHIGAN STATE ROUTE ACCIDENT DATA ANALYSIS

Two types of analysis were conducted on the Michigan State Route accident data set, the first being the total number of off-road accidents and the other the number of off-road injury accidents. The analysis procedure used was the same as for the national data set, and the salient results for the 11 AID runs made in the Michigan State Route data set (7 for total accidents, 4 for injury accidents) are given in Table 6.

Total Off-Road Accidents

The first total accident model (model 12) tested used only ADT as the explanatory variable for off-road accident frequency. It explained 39.7 percent of the variance. When the number of intersections

TABLE 6 AID Summary, Michigan State Route Data

Variable Name	Symbol	Model 12	13	14[a]	15	16[b]	17	18[c]	19[d]	20	21[e]	22
Dependent variable												
Total accidents per segment per year	TMYER	•	•	•	•	•	•	•				
Injury accidents per segment per year	IMYER								•	•	•	•
Flow and location												
Region within state	Region			•					•			
Terrain	Ter			○					•			
ADT	ADT	•	•	•	•	•	•	•	•	•	•	•
No. of intersections on curves	Int Cu			○					•			
No. of intersections on tangents	Int Ta			•					○			
Total no. of intersections	Int Tot		•	•					•			
Cross section												
Pavement width (ft)	Pv Wid			○	•				○			
Shoulder width (ft)	Sh Wid			•	•				•			
Shoulder treatment	Sh Tr			○					○			
Ditch offset (ft)	Dit Off			•	•				•			•
Ditch condition	Dit Con			○	○		○		○	○		
Alignment												
Percent passing sight-distance restriction	PSR			•	•		•		•	○		
No. of curves in segment	NC			•					•			•
Percent of segment curved	PCL			•	•		•		•	•		
Roadside hazard												
Cumulative percent of exposure length with obstacles within 6 ft of surface	OBJ6			○					○			
Cumulative percent of exposure length with obstacles within 10 ft of surface	OBJ10			•					○			
Cumulative percent of exposure length with obstacles within 14 ft of surface	OBJ14			•	○				•	•		•
Cumulative percent of exposure length with obstacles within 20 ft of surface	OBJ20			○					○			
Cumulative percent of exposure length with obstacles within 30 ft of surface	OBJ30			•					•			
Bundles												
Cross section	Xs Bun					•						
Alignment	Al Bun					•						
Overall geometric	Geo Bun							•		•		
Variation explained (%)		39.7	43.8	70.7	66.3	60.5	60.3	57.1	62.3	52.8	55.0	58.6

Note: ○ = variable did not appear in significant split, and • = variable did appear in significant split.

[a]AID branch diagram shown in Figure 4.

[b]AID branch diagram shown in Figure 5.

[c]AID branch diagram shown in Figure 6.

[d]AID branch diagram shown in Figure 7.

[e]AID branch diagram shown in Figure 8.

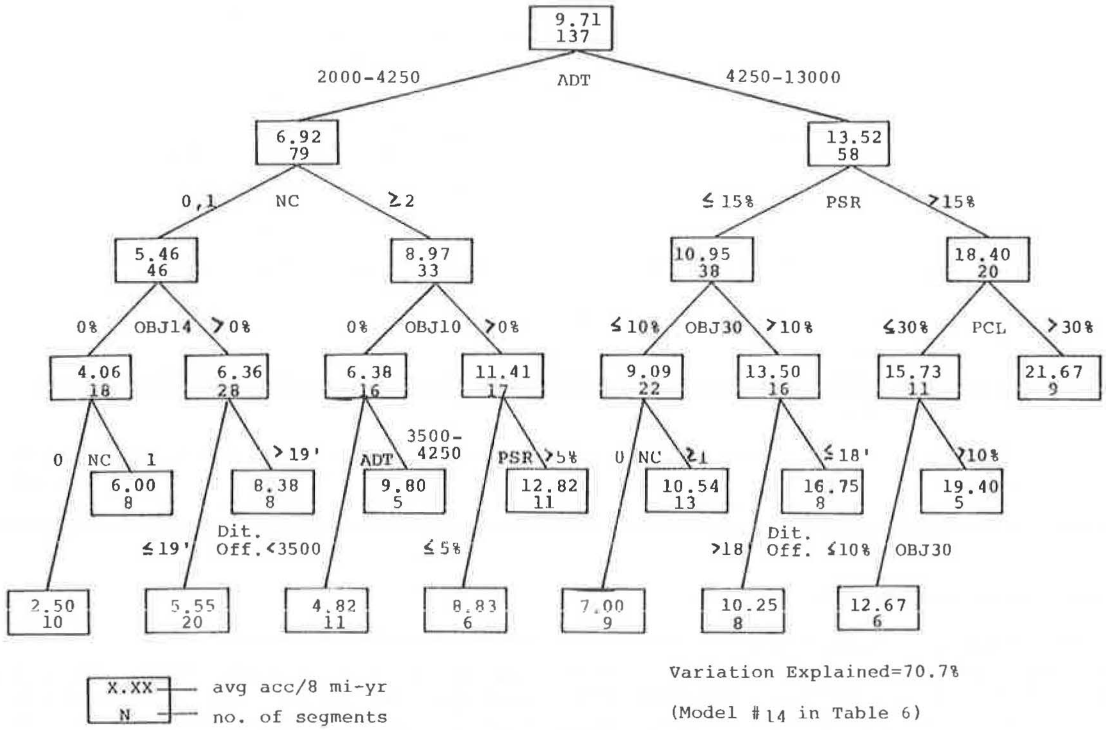

FIGURE 4 Michigan State Route total off-road accidents AID branch diagram using all variables.

TABLE 7 Definition of Cross-Section Bundles for Michigan State Route Data: Total Off-Road Accidents

Bundle Designation	Pavement Width (ft)	Shoulder Width (ft)	Ditch Offset (ft)	Ditch Condition	No. of Sections
Xs-1	24	9-10	>15	Excellent and good	11
Xs-2	20-22	9-10	-[a]	-[a]	10
Xs-3	22-24	7-8	-[a]	Excellent and good	62
Xs-4	20	7-8	>15	-[a]	20
Xs-5	22-24	7-8	≤18	Bad	18
Xs-6	20	7-8	≤15	Good and bad	16

[a]All.

was added (model 13), the variance explanation increased only to 43.8 percent.

Figure 4 presents the AID for all 19 variables (model 14) in the list given in Table 6. The variance explanation was 70.7 percent, and 12 of the variables were significant. Following a split at 4,250 vehicles per day, ADT appeared only once in the next 13 most important splits. Alignment variables appeared in six of the splits and are more important than the roadside obstacle clearance variable. Virtually every final group had at least one alignment and one roadside obstacle clearance variable. Only the highest accident group had no representation of roadside variables.

TABLE 8 Definition of Alignment Bundles for Michigan State Route Data: Total Off-Road Accidents

Bundle Designation	OBJ14 (%)	Curve Length (%)	Sight Restriction (%)	No. of Sections
Al-1	0	0-30	-[a]	23
Al-2	0	>30	-[a]	23
Al-3	>0	0	-[a]	26
Al-4	>0	1-30	0	4
Al-5	>0	1-30	>0	14
Al-6	>0	1-30	0-20	24
Al-7	>0	>30	>20	23

[a]All.

The variables in the six cross-section element bundles and the seven alignment element bundles, which were formed after factor analysis, are given in Tables 7 and 8. Again, the bundles are numbered by generally decreasing geometric quality. Figure 5 presents an AID analysis using only ADT and the alignment and cross-section bundles as variables (model 16). It gave an explained variance of 60.5 percent. At volumes less than 4,250 vehicles per day the alignment bundle was more important, whereas the cross-section bundle was more important at the higher volumes. In the first split for each type of bundle, accident experience increases with decreasing bundle quality.

The AID results for cells with at least 15 sections were used to create a categorical model for the alignment bundles with splits of ADT at 3,500 and 4,500 vehicles per day. The results are given in Table 9, and the effect of unsatisfactory alignments on off-road accidents is clear.

A combined geometric bundle variable was then created. The four geometric bundles used to explain total off-road accident variation are given in Table 10. Only bundle 4 is clearly made up of the worst levels of the three geometric elements selected. The AID explained 60.3 percent of the variance for the

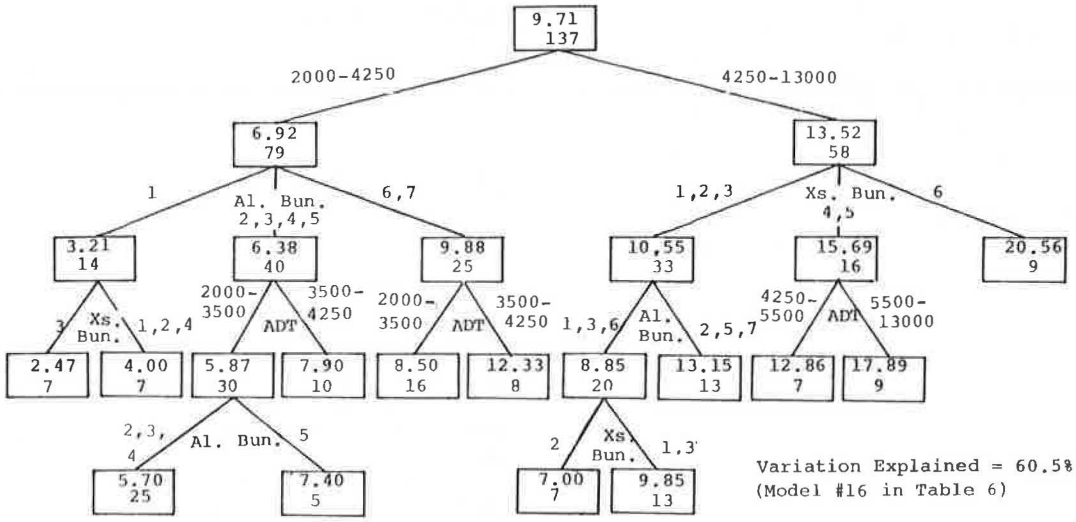

FIGURE 5 Michigan State Route total off-road accidents AID branch diagram using six cross-section and seven alignment bundles and ADT.

TABLE 9 Average Number of Total Off-Road Accidents for Michigan State Route Data

ADT	No. of Accidents per Mile per Year by Alignment Bundle[a]						
	Al-1	Al-2	Al-3	Al-4	Al-5	Al-6	Al-7
2,000-3,500	0.64	0.89	0.64	0.89	0.89	0.64	0.89
3,500-4,500	0.64	1.38	0.64	1.38	1.38	0.64	1.38
4,500-13,000	1.34	1.34	1.34	1.34	1.34	2.21	2.21

[a]See Table 8 for definitions.

TABLE 10 Definition of Geometric Bundles for Michigan State Route Data: Total Off-Road Accidents

Bundle Designation	Curve Length (%)	Sight Restriction (%)	Ditch Condition	No. of Sections
Geo-1	0	1-20	-[a]	26
Geo-2	-[a]	0	-[a]	42
Geo-3	>0	>0	Excellent and good	44
Geo-4	>0	>0	Bad	25

[a]All.

three variables used in the geometric bundle (model 17). Figure 6 presents the AID that used only the four geometric bundles and ADT (model 18). The variance explained by this simple model was 57.1 percent. Again, larger bundle numbers were associated with worse accident experience. Eleven classes give a range from 4.0 to 19.1 off-road accidents per section.

The 9 sections with the highest number of total accidents and the 24 with the fewest accidents were then compared. The worst accident sections had the following relative characteristics: higher ADT, more passing restriction length, more curves and length of curvature, narrower pavement width, narrower

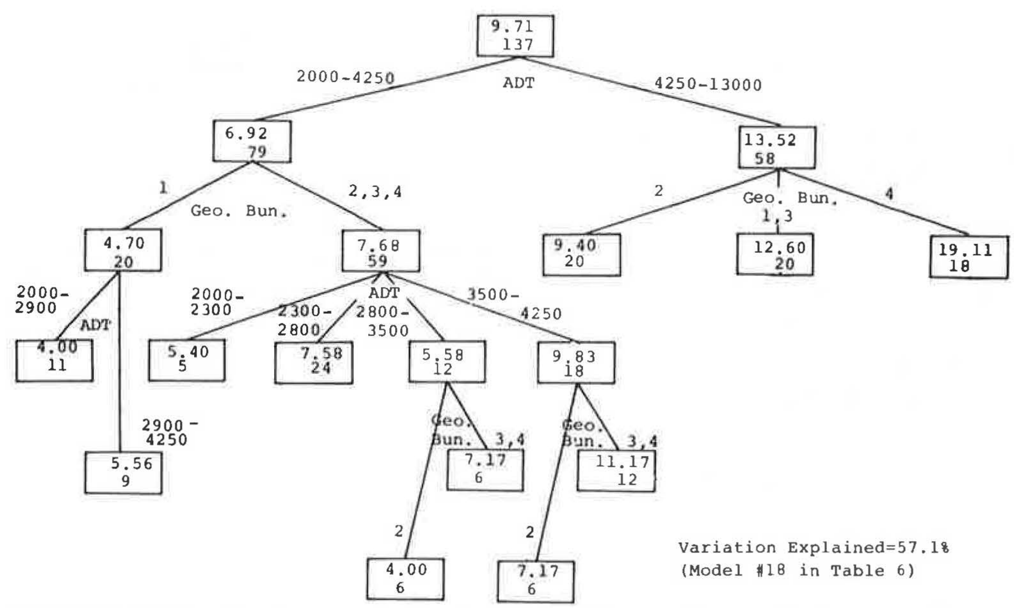

FIGURE 6 Michigan State Route total off-road accidents AID branch diagram using four geometric bundles and ADT.

shoulder width, and more roadside objects, particularly within 14 ft of the pavement edge.

All of these variables were significant in the AID analyses. The data in Table 11 present a categorical model for total off-road accidents developed from this data set by using only four geometric bundles and four levels of ADT. The variance explanation of this simple model is 53.8 percent.

TABLE 11 Cross-Classification Model for Michigan State Route Data: Total Off-Road Accidents

	No. of Accidents per Mile per Year by Geometric Bundle[a]			
ADT	Geo-1	Geo-2	Geo-3	Geo-4
2,000-2,800	0.51	1.01	0.88	0.51
2,800-4,250	0.68	0.68	1.10	1.58
4,250-7,000	1.47	1.16	1.47	2.20
7,000-13,000	1.38	1.38	2.57	2.57

[a]See Table 10 for geometric elements appearing in bundle.

Off-Road Injury Accidents

Figure 7 presents the AID for injury accident frequency for all 19 variables (model 19). The variance explained was 62.3 percent, and 13 variables were significant. In addition to ADT, the most significant predictors were roadside elements.

The data in Table 12 define the six bundles based on two roadside variable and one alignment variable identified to study injury accident variation. An AID run that used these three variables (model 20) explained 52.8 percent of the variance. As shown in Figure 8, the AID run for the six geometric bundles (model 21) used in injury accident prediction explained 55.0 percent of the variance. Again, as the bundle characteristics became worse, more injury accidents were recorded.

An AID (model 22) in which ADT was stratified at

TABLE 12 Definition of Geometric Bundles for Michigan State Route Data: Off-Road Injury Accidents

Bundle Designation	Curve Length (%)	OBJ14 (%)	Ditch Condition	No. of Sections
Geo-1	0	0-5	–[a]	41
Geo-2	1-30	>0	Excellent and good	9
Geo-3	1-30	>0	Bad	9
Geo-4	>0	0	–[a]	31
Geo-5	>30	>0	Excellent and good	28
Geo-6	>30	>0	Bad	19

[a]All.

four levels and in which ditch offset, objects within 14 ft, and number of curves were used as variables explained 58.6 percent of the variance. A categorical model for groups of six or more sections with meaningful differences is given in Table 13. The offset to the ditch was a better accident predictor than the 14-ft roadside object offset variable. The large effect of horizontal curves at lower volumes is also clear.

To further identify dominating variables, the 19 locations with the most injury accidents (eight or more) and the 33 segments with at most one injury accident were studied. As might be expected, those sections with the largest number of injury accidents had higher ADT, more passing restrictions, more and longer curves, narrower lanes and shoulder widths, closer ditch offsets, worse ditch conditions, and more obstacles closer to the road.

Pavement width and ditch condition did not appear in the AID analyses, their effect being better captured by other variables.

SUMMARY AND CONCLUSIONS

A national data set of two-lane rural total accident experience from 14 states involving 152 segments

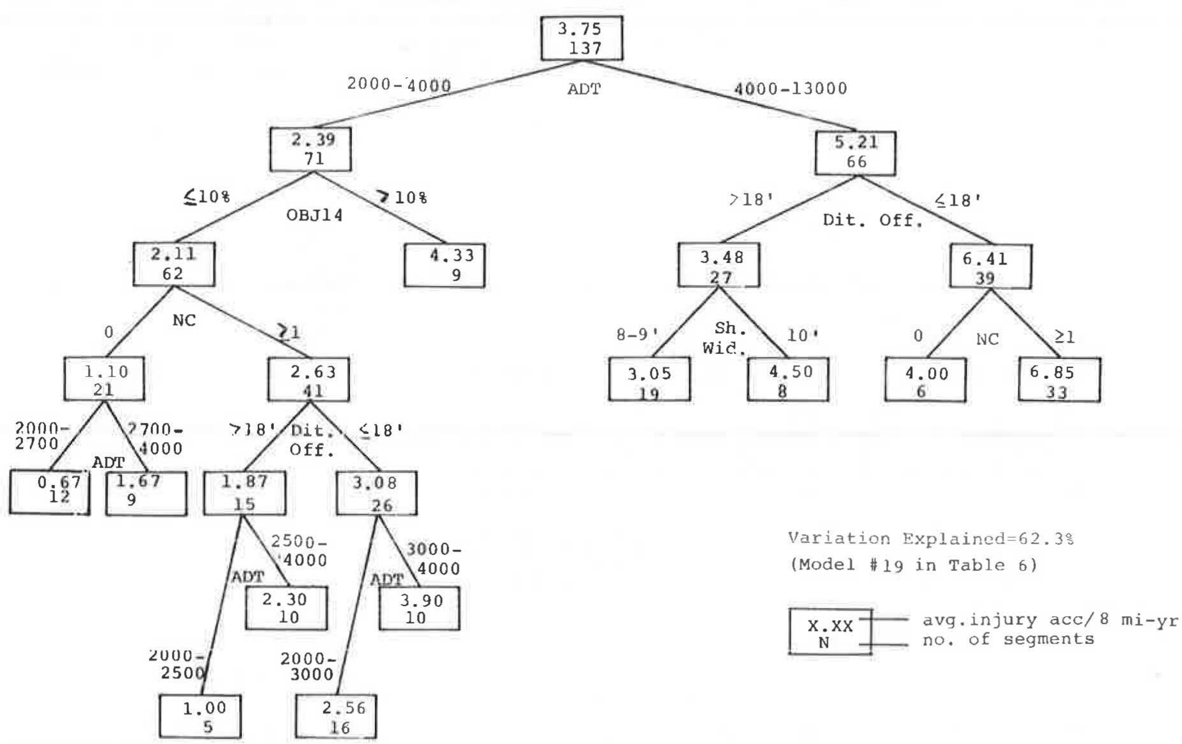

FIGURE 7 Michigan State Route off-road injury accidents AID branch diagram using all variables.

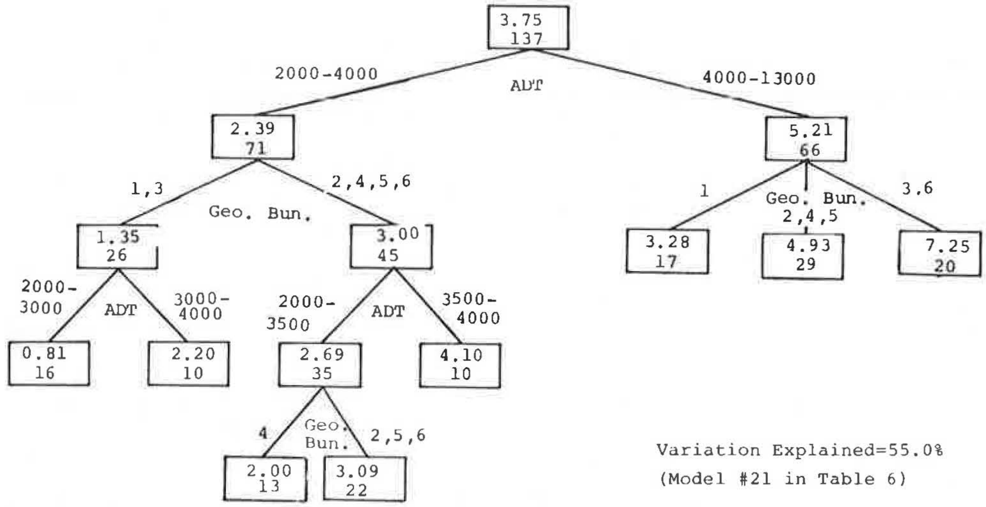

FIGURE 8 Michigan State Route off-road injury accidents AID branch diagram using six geometric bundles and ADT.

TABLE 13 Average Number of Off-Road Injury Accidents per Mile per Year for Michigan State Routes

ADT	No. of Curves per Mile	No. of Accidents per Mile per Year by Ditch Offset			
		⩾ 19 ft	18 ft	16–17 ft	⩽ 15 ft
2,000–3,000	0	0.10	0.10	0.10	0.10
	⩾0.5	0.25	0.25	0.25	0.48
3,000–5,000	0	0.28	0.28	0.28	0.28
	⩾0.5	0.41	0.66	0.66	0.66
5,000–7,000	0	0.44	0.71	0.71	0.71
	⩾0.5	0.44	0.71	0.71	0.71
7,000–13,000	0	0.54	0.54	0.98	0.98
	⩾0.5	0.54	0.54	0.98	0.98

totaling 800 miles in length and recording 3,224 accidents in a year was studied. In addition, 137, 2-mile sections of state highway in Michigan with 1,300 off-road accidents, 514 of which were injury-producing accidents, were analyzed by using advanced multivariate techniques.

The results of this research support previous findings that traffic volume is the most important single factor in the frequency of accidents for two-lane rural roads with ADT values from 2,000 to 13,000 vehicles per day. In AID analysis ADT alone predicted accidents per mile per year with explanations of 48 percent for all accidents in the Michigan-FHWA Skid data and 40 percent for off-road accidents in the Michigan State Route data.

In the Michigan-FHWA Skid data, access point and intersection frequency had an effect second only in importance to ADT. Including these elements increased the variance explanation from 48 to 67 percent. On the other hand, intersections were not found to be of much additional importance for the Michigan State Route off-road accident set, most of which are single-vehicle accidents. Intersection frequency improved variance explanation only slightly, from 40 to 44 percent. Including access and intersection density increased the variance explanation to 67 percent. The addition of seven significant geometric variables to the flow and intersection variables explained 72 percent of the variation in the skid data set, an increase of only 5 percent. The addition of eight significant geometric elements increased the variance explanation in the Michigan State Route data to 71 percent.

Groups of geometric and roadside design element values, found together in clusters because of design policies and traffic demand, form bundles to which accident occurrence is as responsive as it is to the individual elements of road design, and bundles of geometric elements showed as much variance explanatory ability as did the individual elements. Replacing the geometric elements by six bundles developed with the aid of factor analyses also explained 72 percent of the variance in the Michigan-FHWA Skid data. For off-road accidents, ADT and four geometric bundles explained 57 percent of the variance. In the case of off-road injury accidents, a geometric bundle variable and ADT explained 55 percent of the variance, whereas 12 significant variables explained 62 percent.

Accidents interact in such a complex way with traffic volume that using the conventional vehicle mile exposure rate, in which ADT enters into the exposure, requires particular care in specifying a mathematical model structure. In statistical studies this blunts the effect of this most important variables. This was particularly evident in the prediction of off-road accidents. Once the road segment groups were divided at an ADT of approximately 4,000 vehicles per day, the further effect of ADT on accident prediction was negligible. This study has again demonstrated that use of an annual section length exposure measure, such as accidents per mile per year, permits ADT to be treated as a classification or an independent regression variable.

Longitudinal alignment elements dominate in off-road accident prediction for rural two-lane roads at ADT values of 4,000 vehicles per day or less, whereas roadside elements are of more importance at higher ADT values. Nevertheless, the best predictive models at all ADT levels had representation from both types of variables. In total accident occurrence, the effect of a longitudinal alignment bundle was much stronger than the independent effect of the horizontal alignment elements. The cross-sectional elements were found to be highly correlated with state of location and ADT, and their effects could only be noted if the state variable was removed, which indicates that they are strongly related to the operating policy of the state.

Off-road injury accident prediction on rural two-lane highways is sensitive to horizontal curvature at ADT values less than 4,250. It is also more sensitive to roadside obstacle location and characteristics than is total off-road accident prediction.

Comparisons of the sections with the best and the worst accident records also identified several of the variables with the greatest explanatory power revealed by the other analyses. However, this simple comparison also signaled other differences as significant that have been shown to be not as important in explaining variation as other variables. Of particular interest is the absence of a strong independent safety effect of pavement or shoulder width. The independent effects of the pavement and shoulder width are clearly dominated by other factors such as state operating policy and traffic volume.

The categorical models that were developed explained 63 percent of the variation in total accident density in the Michigan-FHWA Skid data and 54 percent of the off-road accident variance in the Michigan State Route data set. This is much better than has been done by other models that have been reviewed. Furthermore, because the models are based on relatively unbiased data sets, they are not only descriptive of the particular data set but capture some of the underlying causal structure and can be used for prediction after further verification.

This research has confirmed the existence of strong interactive effects among the road and traffic descriptors used in accident prediction. This necessitates the use of many combinations of variables in effective modeling. Creating geometric design bundles is a promising way of limiting and organizing the number of such combinations. These data sets illustrate the danger in basing decisions to improve a given element on simple comparisons when it really is the joint effect of the differences in several such elements that is responsible for observed accident differences. It is also recommended that engineers making decisions on safety improvements study the safety of the geometric element bundles that have been installed in their jurisdictions as an aid in determining the location and magnitude of safety improvements.

As high-quality data files with many more accidents become available, it is recommended that this study be repeated to test and refine the conclusions that were found in this research.

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1. Research Problem Statements: Operation and Maintenance of Transportation Facilities. Transportation Research Circular 210. TRB, National Research Council, Washington, D.C., Sept. 1979.
2. D.I. Davis. Shoulder Improvements on Two-Lane Roads. In Transportation Research Record 737, TRB, National Research Council, Washington, D.C., 1979, pp. 59-60.
3. Fatal and Injury Accident Rates on Federal-Aid and Other Highway Systems, 1976. FHWA, U.S. Department of Transportation, Sept. 1978.
4. M.S. Raff. Interstate Highway-Accident Study. Bull. 74. HRB, National Research Council, Washington, D.C., 1953, pp. 18-45.
5. J.K. Kihlberg and K.J. Tharp. Accident Rates as Related to Design Elements of Rural Highways. NCHRP Report 47. HRB, National Research Council, Washington, D.C., 1968, 173 pp.
6. P.H. Wright and L.S. Robertson. Georgia Study Shows Road Curvature is Factor in Fixed Object Crashes. Traffic Safety, Vol. 76, No. 6, 1976, pp. 19-36.
7. K.R. Agent and R.C. Deen. Relationship Between Roadway Geometrics and Accidents. In Transportation Research Record 541, TRB, National Research Council, Washington, D.C., 1975, pp. 1-11.
8. P.A. McBean. The Influence of Road Geometry at a Sample of Accident Sites. TRRL Report 1063. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1982.
9. J.L. Graham and D.W. Harwood. Effectiveness of Clear Recovery Zones. NCHRP Report 247. TRB, National Research Council, Washington, D.C., 1982, 68 pp.
10. O.K. Dart, Jr., and L. Mann, Jr. Relationship of Rural Highway Geometry to Accident Rates in Louisiana. In Highway Research Record 312, HRB, National Research Council, Washington, D.C., 1970, pp. 1-16.
11. D.E. Cleveland, L.P. Kostyniuk, K.L. Ting, C.P. Green, T. Chirachavala, P. Landau, K. Riegel, and M. Pohlman. Advanced Accident Causal Models. Department of Civil Engineering, University of Michigan, Ann Arbor, 1981.
12. E.A. Rinde. Accident Rate Versus Shoulder Width. California Department of Transportation, Sacramento, 1977.
13. C.V. Zegeer, R.C. Deen, and J.G. Mayes. Effect of Lane and Shoulder Widths on Accident Reductions on Rural, Two-Lane Roads. In Transportation Research Record 806, TRB, National Research Council, Washington, D.C., 1981, pp. 33-43.
14. J. Versace. Factor Analysis of Roadway and Accident Data. Bull. 240. HRB, National Research Council, Washington, D.C., 1960, pp. 24-32.
15. H.H. Harman. Modern Factor Analysis. University of Chicago Press, Chicago, 1967.
16. D.M. Baldwin. The Relationship of Highway Design to Traffic Accident Experience. Papers and Discussions, AASHO 32nd Annual Convention, 1946, pp. 103-109.
17. P. Shannon and A. Stanley. Pavement Width Standards for Rural Two-Lane Highways. In Transportation Research Record 685, TRB, National Research Council, Washington, D.C., 1978, pp. 20-23.
18. C.V. Zegeer and J.G. Mayes. Cost Effectiveness of Lane and Shoulder Widening of Rural, Two-Lane Roads in Kentucky. Res. Report 524. Division of Research, Bureau of Highways, Kentucky Department of Transportation, Lexington, 1979.
19. C.E. Billion and W.R. Stohner. A Detailed Study of Accidents as Related to Highway Shoulders in New York State. Proc., HRB, National Research Council, Washington, D.C., Vol. 36, 1957, pp. 497-508.
20. D.E. Cleveland and R. Kitamura. Macroscopic Modeling of Two-Lane Rural Roadside Accidents. In Transportation Research Record 681, TRB, National Research Council, Washington, D.C., 1978, pp. 53-62.
21. J. Bakke. A Statistical Study of Which Geometric Features Contribute to Highway Accidents. Minnesota Department of Transportation, St. Paul, 1982.
22. R.C. Gupta and R. Jain. Effect of Certain Geometric Design Characteristics of Highways on Accident Rates for Two-Lane Roads in Connecticut. Department of Civil Engineering, University of Connecticut, Storrs, 1973.
23. J.C. Snyder. Environmental Determinants of Traffic Accidents: An Alternate Model. In

Transportation Research Record 486, TRB, National Research Council, Washington, D.C., 1974, pp. 11-18.
24. Roy Jorgensen Associates, Inc. Cost and Safety Effectiveness of Highway Design Elements. NCHRP Report 197. TRB, National Research Council, Washington, D.C., 1978, 237 pp.
25. R.R. Blackburn et al. Effectiveness of Alternative Skid Reduction Measures--Volume 1: Evaluation of Accident Rate-Skid Number Relationships. Midwest Research Institute, Kansas City, Mo., Nov. 1978.
26. D.E. Cleveland, L.P. Kostyniuk, and K.L. Ting. Design and Safety on Moderate-Volume Two-Lane Roads. ASCE, Journal of Transportation Engineering (in preparation).
27. J.A. Sonquist, E.L. Baker, and J.N. Morgan. Searching for Structure. Institute for Social Research, University of Michigan, Ann Arbor, 1973.
28. S. Kullback. Information Theory and Statistics. Wiley, New York, 1959.

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Driving Dynamic Considerations: A Comparison of German and American Friction Coefficients for Highway Design

RUEDIGER LAMM

ABSTRACT

One of the main safety goals in developing new German Guidelines for the Design of Rural Highways was to overcome previous driving dynamic deficiencies and to enhance traffic safety by increasing friction supply wherever possible. The objectives of this paper are to discuss the German approach in determining new tangential and side friction factors with respect to design speed and to compare these values with those currently in use in the United States. The comparison showed that for design speeds greater than 80 km/h (50 mph), the maximum allowable tangential and side friction factors used in the United States are definitely higher than the German values. Accordingly, the computations for minimum stopping-sight distances and minimum radii of curve showed for all investigated cases and driving dynamic models smaller values in the United States than in Germany. Therefore, there is no doubt that, on the one hand, the American rural highway design is more economic but, on the other hand, the German values provide higher friction supply in critical driving situations. Finally, a preliminary study between road sections conducted according to the new German design guidelines and those with old horizontal and vertical alignment showed, on average, a 1.67 times lower accident rate for the redesigned road sections. This result is confirmed by a new research report for the Minister of Transportation of the Federal Republic of Germany, which will soon be published.

In the 1960s and the early 1970s the number of fatal traffic accidents and the number of heavy injuries increased in an unconscionable way in the Federal Republic of Germany. Many of these fatal accidents occurred on two-lane rural roads when the original design speed was exceeded by a substantial amount. Therefore, the demand for developing and introducing new guidelines, especially for two-lane rural highways, became more urgent. The main objective for the responsible Committee for Highway Design of the German Research Association for Road Engineering was to enhance traffic safety wherever possible.

The following driving dynamic considerations represent one main safety goal of the German Guidelines for the Design of Rural Highways (1,2). Other goals, which are directed to achieve operational consistency and to improve driving safety and comfort through a more uniform and balanced design of highway alignment, will be addressed in another publication.

One of the cardinal rules in horizontal alignment design is that friction supply should be greater than friction demand. With the revision of the German Guidelines for the Design of Rural Highways in the early 1970s, one of the main objectives was to check the conditions of friction between wheels and road. For example, a comparison between the guidelines used in the United States, the Federal Republic of Germany, and other countries had shown that there were enormous differences between the selection of allowable side friction factors and, result-