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Evaluation of Crash Rates and Causal Factors for High-Risk Locations on Rural and Urban Two-Lane Highways in Virginia

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16. Abstract

Considerable efforts have been made in recent years to make highway travel safer. Traffic engineers continue to emphasize the identification of causal factors for crashes on individual sections and on different functional classes of highways as an area of emphasis. If precise causal factors and corresponding countermeasures can be identified, traffic engineers in the roadway design field would be able to use that information to make Virginia's highways safer. The purpose of this study was to identify causal factors of crashes on two-lane highways and corresponding effective countermeasures that should significantly reduce these crashes. The scope of the research was limited to two-lane highways in Virginia with data from 2001 through 2004.

The researchers identified 143 five- to ten-mile stretches of two-lane highways in Virginia that proportionally represented each of the counties in Virginia. Relevant data elements that included time of crash, road and weather conditions, driver action, and type of collision were extracted from the relevant police reports. Traffic volumes and speed data were obtained from VDOT publications. Global positioning system data collected for each site provided information on grading and curvature of the sites. Signing and speed limit data were also collected for each site. The final dataset consisted of nearly 10,000 crashes and more than 30 variables, grouped under different highway classifications (urban primary, urban secondary, rural primary, rural secondary) and collision type (rear-end, angle, head-on, sideswipe, run-off-the-road [ROR], deer, and other). Fault tree analysis was used to identify the associated causal factors, and generalized linear models were developed from which the significant causal factors were identified.

The results indicated that ROR crashes were the predominant type of crash, followed by rear-end, angle, and deer crashes. These crashes represented nearly 70% of all crashes. The significant causal factors for ROR crashes were found to be curvature and annual average daily traffic. One of the four recommendations is that a plan for correcting the geometric deficiencies of the significant causal factors at sites with high ROR crashes be developed and implemented.

The economic benefits of improving the radii at locations with predominantly ROR crashes were investigated using a sensitivity analysis on the benefit/cost ratios for different levels of improvements and expected crash reductions. In all cases, the ratio was higher than 1, with a range of 1.16 to 9.60.

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FINAL REPORT

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(A partnership of the Virginia Department of Transportation
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ABSTRACT

Considerable efforts have been made in recent years to make highway travel safer. Traffic engineers continue to emphasize the identification of causal factors for crashes on individual sections and on different functional classes of highways as an area of emphasis. If precise causal factors and corresponding countermeasures can be identified, traffic engineers in the roadway design field would be able to use that information to make Virginia's highways safer. The purpose of this study was to identify causal factors of crashes on two-lane highways and corresponding effective countermeasures that should significantly reduce these crashes. The scope of the research was limited to two-lane highways in Virginia with data from 2001 through 2004.

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INTRODUCTION

In Virginia in 2003, there were 94,770 crashes, including 726 fatal crashes that resulted in 799 total fatalities on highways under the jurisdiction of the Virginia Department of Transportation (VDOT) (VDOT, 2006). Considerable efforts have been made in recent years to make highway travel safer. However, the frequency and severity of crashes continue to be a subject of national concern. For example, Figure 1 indicates that in Virginia, crash rates (number of crashes per 100 million vehicle miles traveled [VMT]) continue to be high, despite the efforts being made to improve safety on these roads. Secondary roads show a significantly higher crash rates than the other road systems. Since two-lane roads comprise 99% of Virginia's secondary roads, two-lane secondary roads should be investigated to determine crash causal factors on these roads. Although two-lane primary roads have a lower crash rate than multilane primary roads (Figure 1), the fatality rates show that they are more dangerous. On all primary highways, there were 387 fatal crashes, resulting in 433 fatalities. These included 200 fatal crashes on multilane primary roads and 187 on two-lane primary roads. This indicates that 48.3% of these fatal crashes occurred on two-lane primary roads, and these roads account for only 34.7% of the annual VMT (AVMT) on all primary roads. It is therefore reasonable to conclude that in order to achieve overall safety on Virginia roads, some emphasis should be placed on both primary and secondary two-lane roads.

Traffic engineers continue to place increased effort on identifying the causal factors for crashes on individual sections and on different functional classes of highways. If precise causal factors and effective corresponding countermeasures can be identified for different types of crashes on different functional classes of highways, traffic engineers and professionals in the roadway design field would be able to use that information to make Virginia's highways safer.

However, effective countermeasures can be identified only if the causal factors of these crashes are known. This situation has created the impetus for further study to identify the causes of these crashes and to seek methods of reducing them. In addition, this study supports the American Association of State and Highway Transportation Officials (AASHTO) *Strategic Highway Safety Plan* (AASHTO, 2005). In 2003, with highway deaths approaching 43,000

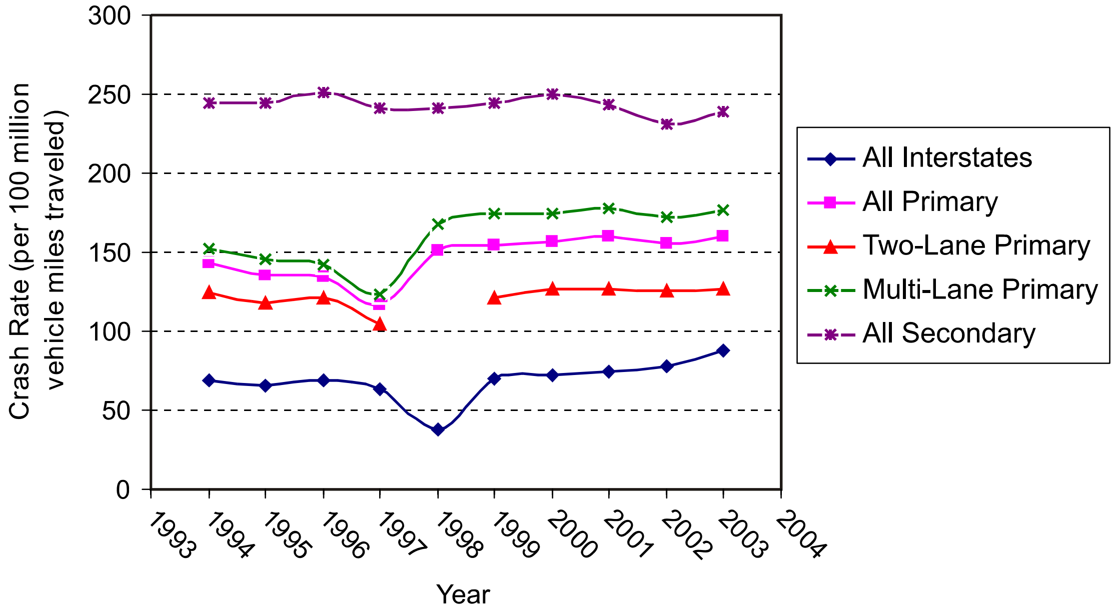

Figure 1. Crash Rates for Virginia's Highways (Data from 2003 VDOT Crash Database). *Crash rates are calculated as the number of crashes per 100 million vehicle miles traveled (VMT). For example, a highway that had 68 crashes in a given year and an annual VMT of 200 million would have an annual crash rate of 34 crashes per 100 million VMT.*

nationwide, the highway safety community restated its fatality reduction goal. State and federal safety and transportation officials are aiming to reduce the fatality rate from 1.5 to no more than 1.0 fatality per 100 million VMT (AASHTO, 2005). Although similar studies have been conducted, most of these are specific to the individual state in which the study was conducted, such as Texas or Georgia (Fitzpatrick and Brewer, 2004; Washington et al., 2002), and there is no evidence that the results of those studies are directly transferable to the types and severity of crashes in Virginia. In addition, many of the previous studies began by selecting a causal factor and then determining its effect on crash rates on different classifications of highways (Garber and Ehrhart, 2000; Persaud et al., 2000).

The high crash rates on Virginia secondary roads, which consist primarily of two-lane highways, and the over-representation of fatal crashes on two-lane primary roads in Virginia suggest that identifying and implementing effective crash countermeasures for these highways will result in an overall improvement of safety on Virginia highways. The results of this study will enhance the application of the proposed Federal Highway Administration (FHWA) methodology (FHWA, 2000) for prioritizing hazardous locations for remedial actions.

PURPOSE AND SCOPE

The purpose of this research was to identify causal factors of crashes on two-lane highways and corresponding effective countermeasures that would significantly reduce these crashes.

The scope was limited to two-lane highways in Virginia. The study identified stretches of two-lane highways with statistically high crash and fatality rates. Causal factors associated with the crashes at these sites were identified and several appropriate countermeasures were determined. It is expected that a second phase of the study will implement some of these countermeasures and evaluate their effectiveness in reducing crashes on two-lane highways.

METHODS

Eight steps comprised the methodology used to achieve the study objectives:

1. Conduct a literature review of publications related to the study.
2. Select sites with a high risk for crashes on two-lane highways throughout Virginia.
3. Collect crash data for the study sites.
4. Collect operational data for the study sites.
5. Analyze crash data for relevant crash variables.
6. Analyze geometric data for the study sites for use in the analysis.
7. Use fault tree analysis to determine the major crash causal factors.
8. Use generalized linear modeling (GLM) to develop models for predicting crash occurrence at the sites.

Site Selection

In order to determine causal factors for crashes on Virginia highways, representative sites with a high risk of crashes had to be selected. This study began with a list of 2,509 sites across Virginia. These sites consisted of rural and urban two-lane highways with most sites having a length between 7 and 10 mi. The mean length was 8.3 mi, and the standard deviation was 1.5 mi. VDOT's Central Office provided the initial list of sites. Each site was given an identifier number, and site information included route prefix and number, district, jurisdiction, and beginning and end node numbers. Beginning and end nodes usually corresponded to a cross street or intersection along the site. Along with the site list, Excel files containing average daily traffic (ADT) information and the crash document number for each crash (each crash report has an identification number that is usually referred to as the crash document number) for the years 2001 through 2004 for each site were provided by the database.

The initial list of sites was prohibitively extensive for the time and scope of this study. Beginning with the list of possible sites, several criteria were used to narrow the list to the final selected sites. First, sites for which no or incomplete ADT information was available were eliminated. Second, any sites that did not have any crashes for the data period were eliminated. Third, if the site list did not provide the beginning or end node, it was removed from consideration. These initial screening steps reduced the list of possible sites to 1,623.

In order to ensure that only sites with relatively high crash rates were included for analysis, the following procedure was used to narrow the site list further. From the list of 1,623 possible sites, 1,160 sites had more than 10 crashes during the 4-year data period, 932 sites had more than 15 crashes, and 752 sites had more than 20 crashes. The characteristics of the sites and crashes included in each list were examined. The three lists of sites were comparable in the distribution of site types, such as urban vs. rural and primary vs. secondary, and in the distribution of crash characteristics, such as major factor, time of day, and weather conditions. The researchers decided to use the list of sites with more than 15 crashes because this provided a sufficiently large number of sites for random selection while including sites with high crash rates. Therefore, at this point in the site selection, the possible sites numbered 932 sites.

The accuracy of the final results of this study was dependent on how accurately the selected sites represented Virginia roadways as a whole. In addition, as the researchers desired to analyze the sites across the state, and because there may be traffic characteristics that are unique to different areas in the state, the researchers considered each of VDOT's nine districts a unique unit (see Figure 2).

In order to represent each district properly in the analysis and research, the number of sites selected from each district was proportional to the number of miles of two-lane highways in the district. The total two-lane mileage in each district and that for two-lane secondary and primary roads separately were extracted from VDOT mileage tables (VDOT, 2005a). The researchers decided that 200 final sites should be selected; this number would allow for statistically significant results from the analysis and would still be manageable for data collection and analysis. The mileages, proportions, and resulting number of sites for each district are given in Table 1.

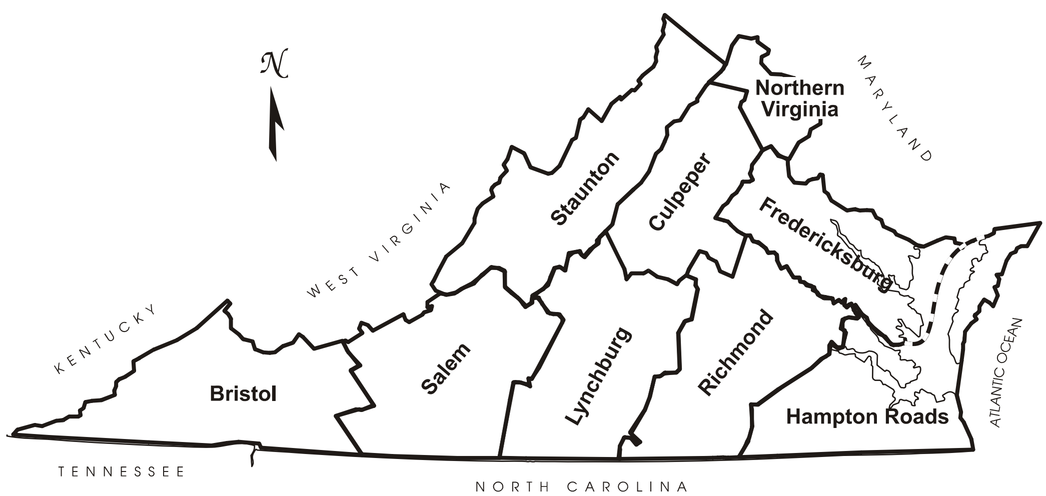

Figure 2. Virginia District Map

Table 1. Number of Sites Selected per Jurisdiction

Jurisdiction (District No.)	Two-Lane Mileage (mi)	Proportion of Miles (%)	No. of Sites
Bristol (1)	7029.9	13.3	27
Salem (2)	7877.3	14.9	30
Lynchburg (3)	6853.3	13.0	26
Richmond (4)	7206.3	13.7	27
Hampton Roads (5)	4428.6	8.4	17
Fredericksburg (6)	4849.2	9.2	18
Culpeper (7)	4495.0	8.5	17
Staunton (8)	5934.5	11.2	22
Northern Virginia (9)	4107.8	7.8	16
Total	52781.7	100	200

The researchers considered using annual average daily traffic (AADT) information for each district to determine the proportion of sites to be selected from the district. In this scenario, districts with highways with larger AADTs would have more selected sites than districts with low-AADT highways. The proportions were calculated, and they were based only on the AADT information given by VDOT's Central Office in the original list of 2,509 sites. However, the information on the sites did not include a complete record of AADT for all two-lane highways. It could have been the case that the smaller dataset was biased toward higher or lower AADT values; it could not be assumed with confidence that no bias existed. Therefore, using the mileage proportions introduced less bias because the mileage of two-lane highways in the entire state was known.

Once it was determined how many sites to select from each district, as shown in Table 1, a random number generator was used to select the sites from each district. The list of sites included those in the list of possible sites, 932, but was narrowed one final time. Speed data were obtained from VDOT's Central Office and the individual district offices. Because of the timing of the speed data extraction, the list of 932 sites was narrowed to those sites for which speed data were available.

Random numbers were generated for each district until the desired number of sites had been identified. In the case of the Bristol District, 27 sites should have been selected, but only 26 sites had speed data. Therefore, the random number generator was not implemented; all available 26 sites were included. In anticipation of the possibility that the researchers might have trouble collecting global positioning system (GPS) data at certain locations, the random number generator was also used to identify 4 back-up sites for each district. One site in each of the four categories (urban primary, urban secondary, rural primary, and rural secondary) was listed as a replacement to be used if needed in the field.

After the random number generator had pulled the appropriate number of sites for each district, the general characteristics of those sites were examined. The proportions of rural to urban and primary to secondary were examined; a representative distribution was desirable in order for the final analysis to provide significant and accurate results. In several cases, the selected sites for a given district were nearly all rural, with only a few urban sites. Based on the judgment of the researchers, the random number generator was employed a second time to ensure the final list of sites was reasonably representative of the district as a whole. The researchers initially included 200 sites in the final site list. This number was chosen because it was large enough to allow for significant analysis but manageable enough for the scope of this study. However, because of time constraints, especially in the operational data collection phase, only 144 sites were used in the analysis. Details for each district and the selected sites for the district are given in Appendix A.

Crash Data Collection

As stated previously, VDOT's Central Office provided a list of crash document numbers corresponding to each site. The FR300 police crash report is used to record details about the crash, such as driver information, location and time of the crash, weather and roadway conditions at the time of the crash, and driver actions. Each crash report is assigned a document number, which is used to access a copy of the police report in the VDOT database. The list of document numbers included all of the crashes that occurred along the site for the years 2001 through 2004. After determining the final list of sites for analysis, a simple query in VDOT's crash database provided all the elements from each police crash report. The elements pulled from the crash database for each crash document included crash date, crash hour, weather conditions, surface conditions, lighting conditions, and various other variables. A list of the variables and their codes is provided in Appendix B.

Operational Data Collection

Speed Data

VDOT's Central Office and individual districts provided speed data. The Central Office provided data from continuous count stations in an electronic format. The speed data provided by the individual district offices consisted of spot speed studies, which were conducted over a short period of time, most often a 24-hour period.

From the speed studies provided by either the continuous counts stations or individual jurisdictions, important speed elements were extracted. The 85th percentile speed was the operational speed investigated by the researchers. Since the 85th percentile speed is most often used in traffic engineering studies and jurisdictions commonly base speed limits on the 85th percentile speed, this speed was used in place of an average speed value.

For each continuous count station, VDOT's Central Office provided 4 years of data. From this dataset, the researchers extracted 1-week-long samples. Three samples were extracted for each year of data available, so that most sites had approximately 10 or 11 speed samples. The continuous count stations record data based on speed bins (0-5 mph, 5-10 mph, etc). The 85th percentile speed was obtained via a cumulative frequency distribution based on the midpoints of the speed bins.

For each site that did not have continuous count data available, the researchers obtained spot speed studies from the respective jurisdiction. Each site had at least one if not multiple speed studies during the period 2001 through 2004. The 85th percentile speed was extracted from these speed studies. Unlike the continuous count station data, the spot speed studies provided data over only a relatively short time frame. The speed data were still considered applicable for all years of the study based on the fact that speed data at the continuous count stations did not vary significantly from year to year.

Truck Percentage

The percentages of trucks in the vehicle stream were obtained in one of two ways. The speed data from the continuous count stations included vehicle classification data. In this case, the truck percentage was calculated as the ratio of the number of trucks recorded during the study period to the total number of vehicles recorded. For sites where continuous count data were not available, the truck percentages were extracted from VDOT traffic counts (VDOT, 2005b). As with the speed data, the continuous count station data did not reveal significant changes in the percentage of trucks in the traffic stream from year to year. Therefore, the truck percentage data published in 2005 were considered accurate for all years of the study.

AADT Data

VDOT's Central Office provided AADT information for the sites. AADT was available for the years 2001 through 2004 at several locations, or nodes, along each site. To determine the AADT for each site, the research team first ordered the nodes along the site, which would be the order a motorist would encounter when driving the site. Next, a weighted mean was used to determine a single value for the AADT for each year. For example, if 3 mi of the site has an AADT of 2,500 and the next 4 had an AADT of 3,500, the weighted mean would be approximately 3,070. In the analysis, these AADT values were linked to individual crashes at the site for that calendar year. In other words, all crashes along site 123 that occurred in 2002 would have the same AADT value.

GPS Data

The researchers drove each site, and a hand-held GPS device recorded location information. Longitude, latitude, and elevation were recorded every 1 second for the length of the site. The GPS files were then processed to extract the curvature and grade information for each site; the methodology to process the GPS data is discussed in subsequent sections. While driving each site, the researchers also collected information about the roadway environment. These data included whether there existed a school zone, an at-grade railroad crossing, a rescue squad, turning lanes, and a centerline and whether passing was allowed. As these variables may influence the occurrence of crashes, they were included in the crash analysis. Further, the number of advisory signs along the site and the posted speed limit were recorded. The number of major cross streets, stoplights, and stop signs were also noted.

Analysis of Crash Data

The research team assessed the crash elements to determine which would be relevant independent variables in the crash analysis. Several variables had a large number of categories in the police crash reports, as given in Appendix B. In such cases, the researchers determined that analysis would be more effective and manageable if these variables were regrouped into a smaller number of categories. These variables included weather, lighting, vehicle type, vehicle maneuver, and driver action. The crash database codes are linked to the new codes used for the statistical analysis in Tables 2 and 3.

In the analysis of vehicle type, the researchers were not concerned with the individual types of vehicles. Instead, the focus was on the comparative types of vehicles involved in a crash. For example, with similar difference in the speeds between vehicles, a crash involving two passenger cars will often result in a crash of lower severity than that involving a passenger car and a tractor-trailer. Therefore, the vehicle type codes were grouped according to similar vehicle sizes and weights. The analysis then considered whether the vehicles involved in a crash were similarly matched or were mismatched. Table 4 provides the vehicle categories and new codes used by the researchers.

When determining how to group the codes for the vehicle maneuver and driver action variables, the researchers implemented a histogram. The frequency of each code was determined and was used to form the number and composition of the new code groups. For example, Table 5 indicates that ROR left and ROR right crashes are each a unique category. The number of these types of crashes was large enough to warrant an exclusive group. Table 6 also shows the groups of driver actions used.

Table 2. Weather Conditions Codes

New Code	Database Code(s)	Description
0	1	Clear
1	2, 3, 4, 8	Cloudy, fog, mist, smoke, or dust
2	5, 6, 7	Raining, snowing, sleeting

Table 3. Lighting Conditions Codes

New Code	Database Code(s)	Description
0	1, 3	Dawn, dusk
1	2	Daylight
2	4	Darkness (highway lighted)
3	5	Darkness (highway not lighted)

Table 4. Vehicle Type Codes

New Code	Database Code(s)	Description
0	0	Not stated
1	1, 2, 3	Passenger car, truck, pickup, van
2	4, 5, 6, 7, 8, 12, 13	Straight truck, tractor-trailer, motor home, oversized vehicles, school bus, etc.
3	9, 10, 11	Bicycle, moped, motorcycle

Table 5. Vehicle Maneuver Codes

New Code	Database Code(s)	Description
1	1	Going straight ahead
2	2, 3, 4	Right, left, and U-turns
3	5	Slowing or stopping
4	6, 7	Starting from parked or traffic lane
5	8	Stopped in traffic lane
6	9	Run-off-the-road (right)
7	10	Run-off-the-road (left)
8	13, 14	Passing, changing lanes
9	11, 12, 15, 16	Other

Table 6. Driver Action Codes

New Code	Database Code(s)	Description
0	7, 13, 18, 19, 24-30, 33, 35-39	Other (see Table B.13 in Appendix B)
1	1	None
2	2	Exceeded speed limit
3	3	Exceeded safe speed but not speed limit
4	4, 5, 6	Overtaking on hill, curve, or intersection
5	8, 9, 10, 41, 42	Cutting in, improper passing or lane change, wrong side of road
6	11	Did not have right of way
7	12	Following too close
8	14, 15, 16, 17	Improper turning
9	20, 21, 22	Disregarded officer, stoplight, or stop sign
10	23	Driver inattention
11	31	Avoiding other vehicle
12	32	Avoiding animal
13	34	Hit and run
14	40, 43	Failure to maintain control, overcorrection

Analysis of Geometric Data

Data collected using the hand-held GPS were downloaded into the Pathfinder software. The list of coordinates was then exported into Excel for analysis.

The grade along each segment was calculated using the *x*- and *y*-coordinate and the elevations. The change in longitude can be calculated using Equation 1, and the change in latitude was calculated using Equation 2 (The Math Forum, 1998). In both equations, the solution is given in units of linear feet.

$$\Delta longitude = \frac{\pi}{180^\circ}\left[\frac{a^2}{\sqrt{a^2 cos^2\vartheta + b^2 sin^2\vartheta}} + h\right] cos\vartheta \qquad \text{[Eq. 1]}$$

$$\Delta latitude = \frac{\pi}{180^\circ}\left[\frac{a^2 b^2}{\left(a^2 \cos^2 \vartheta + b^2 \sin^2 \vartheta\right)^{3/2}} + h\right] \qquad \text{[Eq. 2]}$$

where a = 6378137m (semi-major axis)
b = 6356752.3142m (semi-minor axis)
ϑ = geographical latitude (°)
h = height.

After x- and y-coordinates (i.e., longitude and latitude, respectively) were determined, the horizontal distance between any two points could be found using Equation 3.

$$\Delta\text{distance} = \sqrt{(\Delta longitude)^2 + (\Delta latitude)^2} \qquad \text{[Eq. 3]}$$

Next, the researchers graphed the cumulative distances versus the elevation for each site. Figure 3 shows an example of the grade for a site. This graph is essentially a profile of the roadway and allows the researchers to determine where changes in grades occurred along the site. Grade was calculated as the change in elevation divided by the horizontal distance between two points.

The latitude and longitude data collected using GPS were also used to analyze the horizontal alignment, or curvature, of each site. The curvature of a segment of roadway is simply the radius of the circle drawn by the curve in the road. For every site, the curves along that site were numbered. Then, the radius of curvature for each curve was calculated using the chord length and the middle ordinate of the chord. These measurements were taken in the GPS Pathfinder software. Figure 4 is an example of the plan view, or horizontal alignment, of a site as seen in the Pathfinder software. Figure 5 illustrates the chord length and middle ordinate measurements taken for each curve.

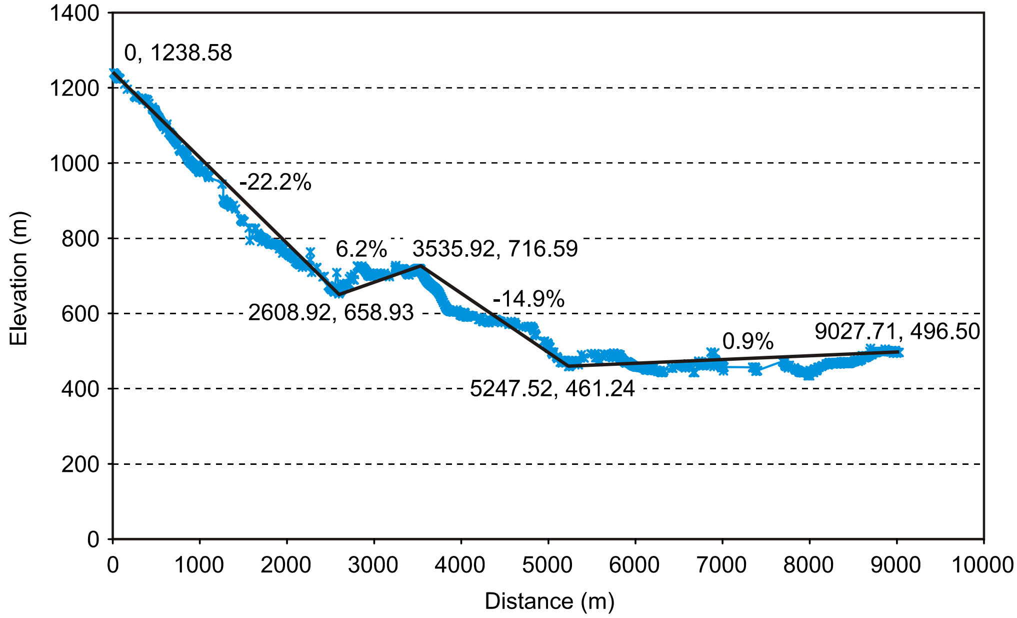

Figure 3. Grade Data for Site 2313

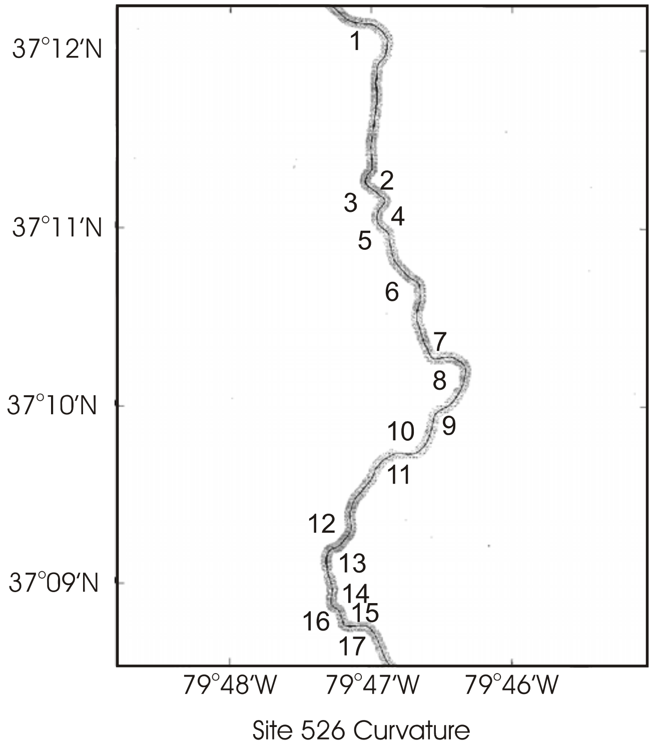

Figure 4. Horizontal Alignment of Site 526 in Pathfinder

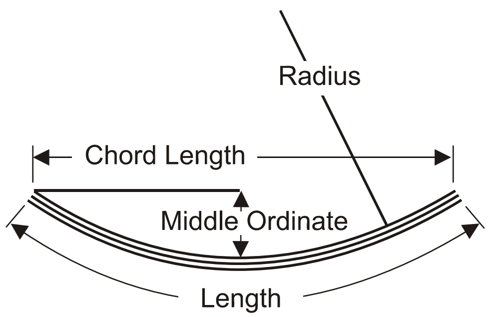

Figure 5. Diagram of Curve with Chord Length and Middle Ordinate

The chord length and middle ordinate for each curve were entered into an Excel file, and the radius of curvature was calculated. The radius of curvature was calculated using Equation 4 (The Math Forum, 1998).

$$R = \frac{c^2 + 4h^2}{8h} \qquad \text{[Eq. 4]}$$

where R = radius of curvature
c = length of chord
h = length of middle ordinate.

In cases where the roadway had a 90-degree angle, usually indicating the occurrence of a stop and an orthogonal right turn, the curve was classified as a dogleg. These curves were placed in a separate category for the crash analysis.

Fault Tree Analysis

The operational and crash data were combined into an Excel spreadsheet. The data for each crash and for each variable were placed into categories for analysis. For one set of variables, the category value was the same for every crash at that particular site. For example, the number of advisory signs along a segment was used for that category for every crash along the site. The cross-street density was calculated as the number of major cross streets along the site divided by the length of the site. The stoplight and stop sign densities were calculated in a similar manner. The speed differential is the difference of the posted speed limit and the operational speed (85th percentile speed). Negative values indicate speeding, and positive values indicate safe driving. Although the operational speed and speed limits provide valuable information about each site, the speed differential enhances the knowledge of the site characteristics and might be influential in determining crash occurrence.

Each variable was divided into categories for the analysis. This process allowed the researchers to determine how the variation in a variable affected crash occurrence. In many cases, the categories were self-evident, such as the presence or absence of turning lanes. Other variables, including AADT and lane width, were more challenging to classify. For these variables, a histogram was implemented to determine the distribution of the values. The researchers used these distributions to determine appropriate categories for each variable. The first set of variables and the corresponding categories are given in Table 7.

The second group of variables was crash specific. In other words, the variable was unique for each crash document and was not necessarily consistent for all crashes along that site. Those variables and their categories are given in Table 8.

Driver action and vehicle maneuver were two additional variables included in the analysis. The categorization of these variables was discussed previously. Tables 5 and 6 provide the variable information for vehicle maneuver and driver action, respectively.

For analysis, crashes were grouped according to highway classification and collision type. Since this research sought to identify causal factors and recommend countermeasures, the results would be most applicable if they were specific to roadway classification. Therefore, the analysis considered rural primary, rural secondary, urban primary, and urban secondary highways separately. Crashes along sites with these classifications were further divided by collision type. A histogram of the crashes by collision type identified the most common crash types. The six most prevalent collision types were ROR, rear-end, angle, deer crashes, sideswipe, and head-on. All other collision types were grouped into an “other” category.

Table 7. Fault Tree Variable Categories

Variable	Unit	Category					
		0	1	2	3	4	5
School zone		No	Yes				
Railroad crossing		No	Yes				
Rescue squad		No	Yes				
Advisory signs	No.	≤8	>8-17	>17			
Speed limit	mph	≤45	> 45				
No centerline		No	Yes				
Passing allowed		No	Yes				
Scenic byway		No	Yes				
Federal lands		No	Yes				
Turn lanes		No	Yes				
Cross-street density	No./mi	<2	≥2				
Stoplight density	No./mi	0	>0				
Stop sign density	No./mi	0	>0				
Curve density	No./mi	<2	>2-4	>4			
Curves with chevrons	No.	0	1-4	>4-14			
Lane width	ft	≤10	>10				
Shoulder width	ft	0-2	>2-5	>5-8			
AADT		0-2,000	2,001-5,000	5,001-10,000	>10,000		
Operational speed	mph	<45	45-49.9	50-54.9	55-59.9	≥60	
Grade	%	0-2	>2-6	>6-10	>10-14	>14	
Curvature (radius)	ft	Dogleg	<200	200-400	>400-700	>700-1,100	>1,100
Truck percentage	%	0-2	>2-6	>6-10	>10		
Speed differential	mph	≤–10	>–10 and ≤–5	>5 and < 0	0-5	>5-10	>10

AADT = average annual daily traffic.

Table 8. Fault Tree Variable Categories

Variable	Category				
	0	1	2	3	4
Day of Week	Monday	Tues.-Thurs.	Fri.-Sun.		
Crash hour	1-5 A.M.	5.01-8 A.M.	8.01 A.M.-1 P.M.	1.01-6 P.M.	6.01 P.M.-1 A.M.
Surface type	Gravel	Bituminous	Asphalt		
Lane width	<10 ft	10-12 ft			
Left shoulder width	0-2 ft	>2-5 ft	>5-8 ft		
Right shoulder width	0-2 ft	>2-5 ft	>5-8 ft		
Surface condition	Dry	Not dry			
Road defect	No defect	Defect			
Safety belt	Unknown	None used	Belt used		
Vehicle type	Single vehicle	Matched type	Mismatched type		
Driver age	<25	25-40	>40-55	>55	
Driver sex	Male	Female			

A fault tree analysis was next implemented to gain a better understanding of the effects of variables and combinations of variables on crashes. A fault tree is a hierarchical model that is used to analyze risk. It provides a graphical representation of component failures and describes all interactions of the components. All events throughout a fault tree are determined by some combination of basic events. The top event in a fault tree, also known as the root of the tree, is the event that represents the most general statement of risk. For this study, the top event is the occurrence of a crash. A fault tree allows the researcher to determine the minimum cut set, which is the shortest chain of events that leads to the failure. Therefore, the minimum cut set would provide the sequence of variables that is most likely to lead to a crash. Basic events for this research included each independent variable discussed earlier. The probabilities for each variable occurrence were calculated from the dataset of crashes for all sites. A separate fault tree was developed for each highway classification (rural primary, rural secondary, urban primary, and urban secondary). In this way, the chain of events leading up to a crash is unique for each classification of highways. The crashes for each highway classification were further divided into collision types. The results observed were, therefore, specific to a particular crash type on a specific highway classification. As noted previously, the collision types considered were ROR, rear-end, angle, deer crashes, sideswipe, head-on, and other. Since crash severity is of concern in this study and because the causal factors of crashes may vary depending on crash severity, two fault trees were developed for each collision type: one for injury and fatal crashes and one for property-damage-only (PDO) crashes.

Fault tree analysis provides understanding about the nature of crashes through the identification of potential failures, the quantification of those failures, the identification of cause and effect relationships, and informed judgment about how, why, and with what frequency the systems fail (Garber and Joshua, 1990a,b). The symbols used in fault tree analysis are shown in Figure 6. They represent the events and logic gates that describe the possible outcomes of the top event. There are two kinds of logic gates used in fault tree analysis. The “And” gate is a logical operation that requires all input events to be true in order to produce the top event. On the other hand, the “Or” gate allows for the situation where the top event is true if one or more of the basic events are true. Since this study sought to identify any variables that influenced the occurrence of crashes, Or gates were primarily used in fault tree construction. A binary event is a basic variable for the fault tree. For example, the presence of passing lanes would constitute a binary event.

Figure 7 illustrates the structure of the initial fault tree used in this analysis. Because of the large number of variables included in the fault trees in this study, the fault trees are large and complex. As such, they are not easily displayed graphically in the report format**.** Figure 7 shows the first procedure of dividing the crashes by highway classification, severity, and then collision type. The binary event symbol indicates the location of the percentage of crashes for the subcategory. The fault tree was developed from the crash and operational data discussed earlier. The probability calculations were based on the subset of crashes for the particular highway classification and collision type. Figures 8 and 9 illustrate the two branches of the fault tree developed for each collision type and each highway classification.

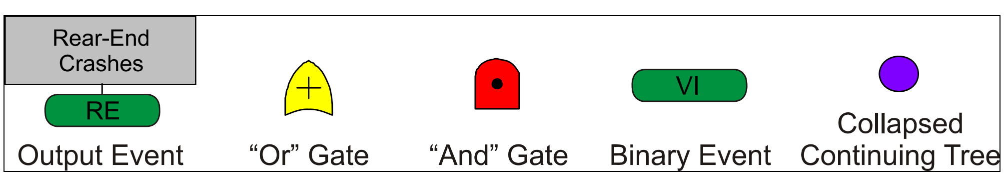

Figure 6. Symbols Used in Fault Tree Analysis

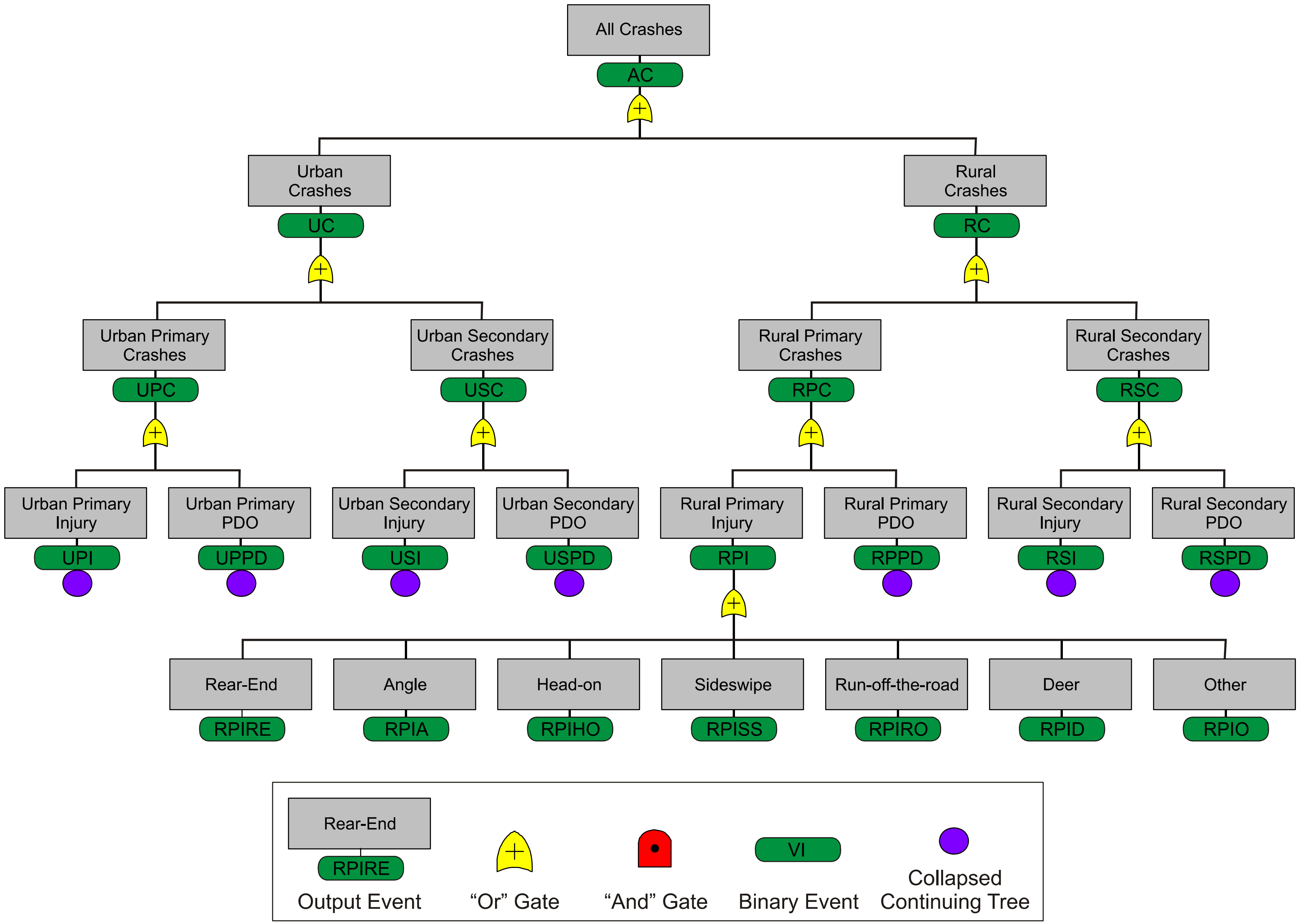

Figure 7. Initial Fault Tree

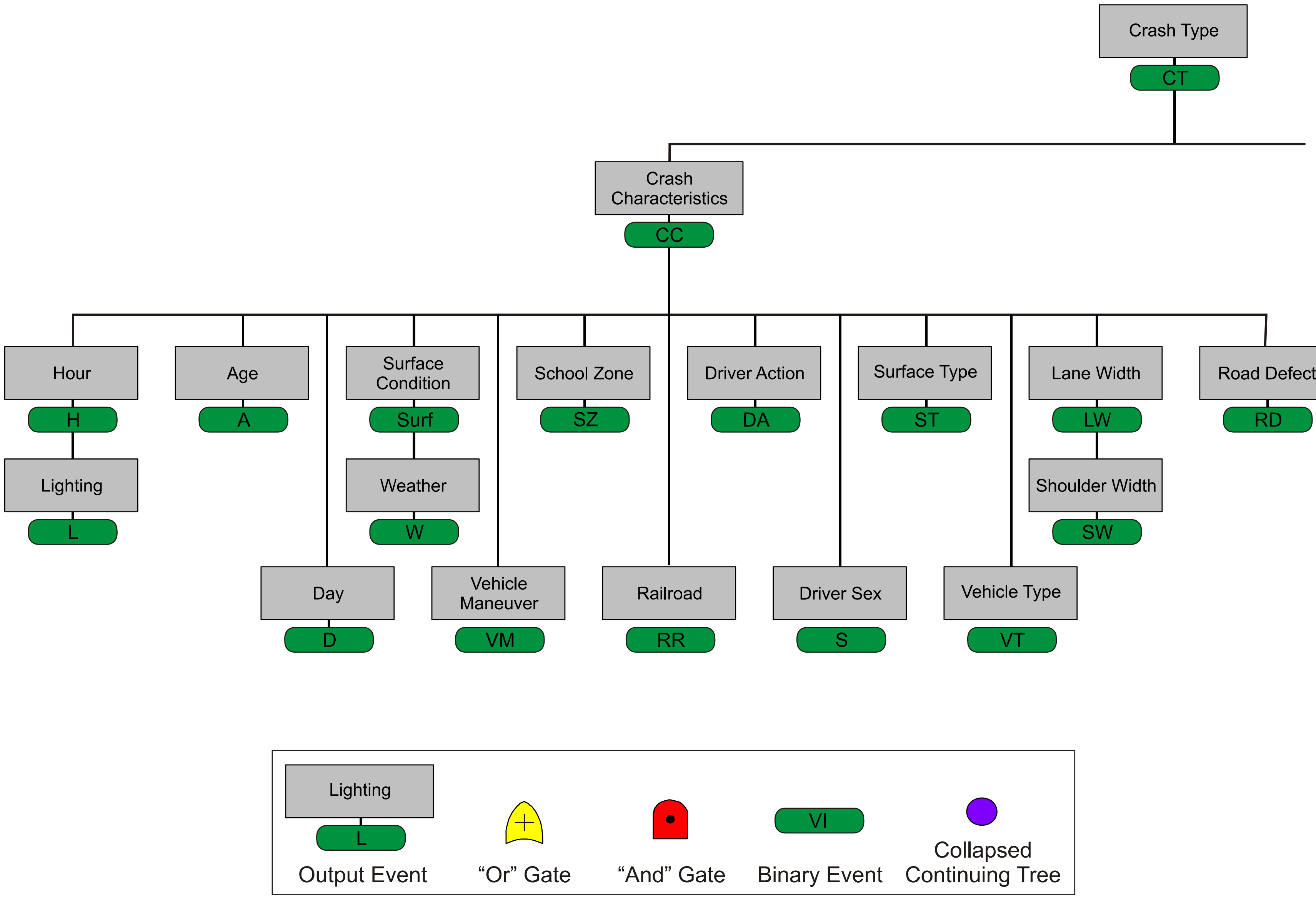

Figure 8. Crash Fault Tree, Crash Characteristics Branch

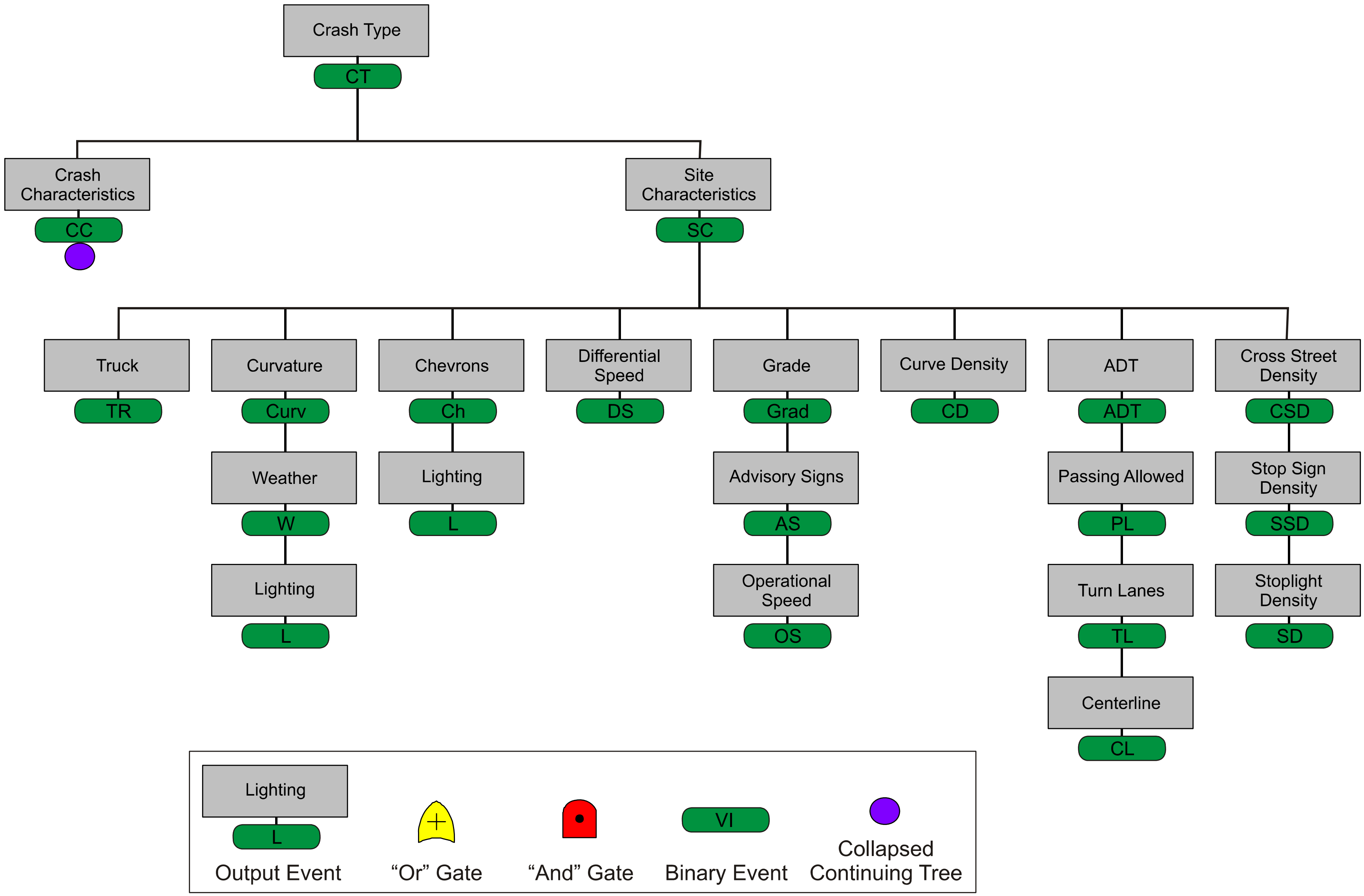

Figure 9. Crash Fault Tree, Traffic Characteristics Branch

Roadway, or traffic, characteristics are uniform along each site and include ADT, turning lanes, truck percentage, and others. Crash characteristics were obtained from individual police crash reports and, therefore, may vary for crashes along a specific site. These variables include weather and lighting conditions, lane and shoulder width, crash hour, and others. Although lane and shoulder widths may seem to be roadway characteristics, the length of the selected sites allows that the surface widths may change along the site. Therefore, the most accurate representation of the surface widths was on an individual crash basis. Interaction effects were also considered, especially between a given roadway characteristic and a crash characteristic. This organization allowed for a more complete knowledge of the sequence of events leading to crashes. For example, one branch of the fault tree considered curvature of the roadway in combination with weather and lighting conditions. The fault tree analysis, therefore, identified those variables that are associated with different types of crashes on different highway classifications.

Although analysis of variance (ANOVA) might have been implemented in the analysis, fault tree analysis offers a more complete picture of crash causes. ANOVA has the capacity to analyze main and interaction effects among independent variables. However, there are two key reasons why fault tree analysis was preferred over ANOVA. First, the procedure of considering each of the variables and the possible interactions between variables in ANOVA would have been time-consuming. Further, the use of fractional factorials would have been required, which again, although feasible, is time-consuming. Second, the fault tree software displays results graphically, in a manner similar to a decision tree. Each branch event on a fault tree represents a causal factor, and the minimal cut sets are shown in an easily understood and intuitive format.

Generalized Linear Modeling

The fault tree analysis provided the variables that were associated with the occurrence of different types of crashes. This information was then initially used to develop GLMs for each collision type for each highway classification using a significance level (α) of 10%. After the results of the fault tree were examined, it was determined that in the majority of the cases, the associated variables were the same for injury, fatal, and PDO crashes. Therefore, GLMs were developed for all crash severities, but for each of the seven crash types in each of the four highway classifications, for a total of 28 GLMs. In addition, because of the relatively fewer data points available for the urban sites, the initial effort of developing separate models for the different types of crashes did not produce any meaningful results. It was therefore decided that one model would be developed for all crash types on urban primary two-lane highways and one for urban secondary two-lane highways.

GLM provides a way to establish a quantitative relationship between the site and crash characteristics and the crash occurrence. Simple linear regression was not appropriate for this analysis because it assumes a normal distribution for the dependent variable, the number of crashes in this instance. However, the number of crashes does not necessarily follow the normal distribution. Instead, it may follow the Poisson or negative binomial distribution (Hauer, 1997; Persaud and Lord, 2000). For this analysis, the negative binomial and Poisson distributions were used in each of the models. GLM is an extension of traditional simple linear modeling, but it allows the dependent variable to follow any of the distributions in the exponential family. A logarithmic function was used to describe how crashes are related to the linear combination of variables. A typical GLM is given in Equation 5.

$$\begin{aligned} &Expected\ number\ of\ crashes(for\ a\ crash\ type) \\ &= \exp(\alpha + \beta_1 \times Main\ effect\ 1 + \beta_2 \times Main\ effect\ 2 + \beta_3 \times Main\ effect\ 3 \\ &\quad + \beta_4 \times Interaction\ effect\ 1 + \beta_5 \times Interaction\ effect\ 2) \end{aligned} \quad \text{[Eq. 5]}$$

where α = constant or intercept term
$\beta_1\ to\ \beta_5$ = coefficients or parameters for the main and interaction effects.

The GLMs were developed to estimate the number of crashes that should occur along a single site. Since this study sought to recommend countermeasures based on the causal factors, the models considered those factors that the fault tree analysis identified and that could be altered by the recommended countermeasures. For example, weather conditions may affect the occurrence of crashes, but this variable cannot be improved by the researchers or through countermeasures. On the other hand, sharp curvature or high operational speeds are variables for which countermeasures can reduce the likelihood of crash occurrence. The final set of factors incorporated in the models were those found to be significant at a level of significance of 10% and are not correlated with each other.

The researchers used 70% of the sites to build each model, leaving 30% of the sites to test the model developed. There were 52 rural secondary sites, for example, and 47 of those sites were randomly chosen to be included in model development. Although the statistical analysis software used for developing the models provided measures of goodness of fit for each model, the models were also validated by comparing the actual number of crashes with the number of crashes predicted by the model at the sites reserved for testing the model. A Wilcoxon rank-sum test, which is a non-parametric test, then was used to compare the actual and predicted crashes.

From the fault tree analysis and GLMs, the researchers were ultimately able to identify which variables had the most influence on the different types of collisions. The coefficients for each parameter, or variable, in the model indicated what effect the variable had on crash occurrence and how strong the effect was. This information was used to recommend countermeasures for each crash type in each highway classification. This final step led to the fulfillment of the goal of this study.

RESULTS AND DISCUSSION

Literature Review

Two-Lane Highway Research

Several states, including Georgia and Texas, have conducted studies similar to this study. The Texas study sought to identify common types of crashes on low-volume roadways, identify low-cost safety improvements, and evaluate the effectiveness of the selected improvements (Fitzpatrick and Brewer, 2004). The study included 50 sites over the period from 1995 through 2001. Since the Texas study most closely resembles this study, Table 9 is given as an illustration of the results of the Texas study. The introduction of countermeasures during this study resulted in over one-half of the sites showing a reduction in total crashes. A similar study in Georgia focused on two-lane rural highways (Washington et al., 2002). The Georgia study focused entirely on fatal crashes since a disproportionately high number of fatalities occurred on rural, two-lane highways. The researchers considered human, vehicle, environmental, and roadway factors at 150 sites in 1997. They found that nearly one-half of the crashes occurred at a horizontal curve requiring reduction in vehicle speed and approximately two-thirds of the crashes occurred on highways with lane widths at or below 11 ft. The recommendations included posting of advisory speed signs and widening of the roadway surfaces.

A study sponsored by FHWA had as its goal the prediction of safety performance on rural, two-lane highways (Harwood et al., 2000). Table 10 shows the distribution of the most common types of collision. These data guided the scope of the FHWA study and provided a reference for the crashes examined in this study. The study focused on accident modification factors, which considered lane and shoulder width, horizontal curves, grades, driveways, two-way left-turn lanes, and passing lanes. The researchers then developed an algorithm to predict safety performance and provided a calibration process that would adapt the algorithm to conditions on various other highways. Although the factors ignore interactions between safety effect variables, an empirical Bayes approach allows for comparison of actual and predicted crashes.

Table 9. Results of Texas Two-Lane Rural Highways Study

Treatment	Preventable Characteristics	% Reduction in Rate
Raised pavement markers, delineation	Wet surface or dark lighting conditions	76
Lane widening	Off-roadway or beyond shoulder crashes, or right-angle, sideswipe, or rear-end	-36
Safety treatment of fixed objects	Off-roadway or beyond shoulder crashes, and population category is rural or town <2,500	17
Flashers added on warning signs	Off-roadway or beyond shoulder crashes, or rear-end or sideswipe	100
Shoulders added or paved, resurfaced	Off-roadway or beyond shoulder crashes, or rear-end or sideswipe	-3
Chevrons on curve approaches	Crashes at curve	-112

A negative value for the percentage reduction in rate indicates an increase in crashes.
Source: Fitzpatrick and Brewer, 2004.

Table 10. Distribution of Crash Collision Types for FHWA Study

Collision Type	Percentage of Crashes on Rural, Two-Lane Highways
Collision with animal	30.9
Run-off-the-road	28.1
Rear-end collision	13.9
Angle collision	3.9

Source: Harwood et al., 2000.

A study of two-lane rural roads in Minnesota and Washington sought to create statistical models to predict crash occurrence (Vogt and Bared, 1998). The researchers relied on a wealth of operational data, such as traffic data, horizontal and vertical alignments, posted speed, and truck percentage. Combined with crash data for the years 1985 through 1989 in Minnesota and 1993 through 1995 in Washington, negative binomial models were developed. The study found that crashes along the highway segments depended significantly on most of the variables collected.

A before-and-after study conducted in California focused on the relationship between shoulder width and crash rates (Rinde, 1977). The researcher considered three shoulder widths, and all three widths showed a reduction in crash rates after widening. The reduction in crashes was statistically significant for two of the three widths, although the researcher acknowledged that reductions could also have been attributable to improved signing, striping, and the new roadway surface. A Kentucky-based study focused on the effect of lane and shoulder widths on crashes along rural, two-lane roads (Zegeer et al., 1980). The researchers first determined that ROR and opposite direction crashes were the only two crash types to be positively affected by lane and shoulder widths. Results revealed that highways with wide lanes had crash rates 10% to 39% lower than narrow-lane surfaces. The researchers used 1-mi segments with a total of 17,000 crashes. They acknowledged that results were not significant for the shoulder width variable because of the small sample size (70% of sites had no shoulders), and the research methodology did not account for confounding factors. A study of two-lane rural roads in Illinois also focused on the effect of road- and shoulder-widening projects (Benekohal and Hashmi, 1990). The before-and-after study evaluated the cost-effectiveness of the roadside improvements, where the cost savings was based on crash reductions. The developed models estimated an annual cost savings of $609,300 for ROR crashes and more than $2 million for related crashes.

Causal Factor and Countermeasure Research

A different group of studies focused on a single causal factor for several types of highways. A recent Virginia study investigated the effect of speed characteristics on crashes (Garber and Ehrhart, 2000). The researchers identified the speed, flow, and geometric characteristics (grade, lane width, shoulder width) that affected crashes on different classifications of highways. A study conducted by Texas Tech University sought to determine the effect of shoulder treatments on single-vehicle ROR crashes (Wray and Nicodemus, 1996). The research considered several classifications of highways and concluded that depressed shoulder treatments were more effective than raised treatments. Numerous studies offer research on a variety of countermeasures and causal factors. The research presented here gives an illustration of the available literature.

Methodological and Research References

The available body of literature contains several sources that provide guidance on conducting analysis of two-lane highways. An article in *Transportation Research Record* details a 10-year study conducted at the University of Karlsruhe in Germany (Lamm et al., 2002). The study developed, tested, and applied three quantitative safety criteria to improve safety on rural two-lane highways. These criteria were design consistency, operating speed consistency, and driving dynamic consistency. This research was expanded, and the results were then published in a full-length book (Lamm et al., 2007). In addition to examining highway design safety criteria, the authors provided an extensive review of case studies implementing the safety criteria. This collection of methodological data was a valuable tool for guiding this study. A study that developed procedures for identifying high-crash locations and prioritizing safety improvements recommended focusing on ADT, rural versus urban designation, number of lanes, and functional classifier as significant variables (Agent, 2003). Various other references guided the methodology of this research, and they are discussed where appropriate in the "Methods" section. The recommended countermeasures are also referenced the literature, and those sources are discussed in the "Results and Discussion" section.

A statement in a report by the Texas Transportation Institute justifies the methodology for many other studies, including this one. The authors wrote: "experience suggests that although it is impossible to predict when and where on the network a vehicle crash will occur, it is, however, quite predictable as to how many crashes will occur on the entire network in a large area for a relatively long period of time" (Fitzpatrick et al., 2001).

Fault Tree Analysis Results

The results obtained for the initial fault tree illustrated in Figure 7 are shown in Figure 10. The major crash type on the two-lane primary roads was ROR crashes. They accounted for more than 30% of the injury and fatal crashes, followed by rear-end crashes, which accounted for about 20%. Each subsequent fault tree provided the sequence of events most likely to lead to a specific type of crash, as illustrated in Figures 8 and 9. The results showed some consistency for collision types across highway classifications. However, the variables found to be associated with crashes did vary from urban highways to rural highways. The distinctions of primary and secondary had less effect on the associated variables than the division of urban and rural. The detailed results of the fault tree analysis are provided in Appendix C.

ROR crashes were of utmost concern due to the over-representation in collision type, especially along rural highways. The grade, operational speed, lane width, and whether passing was allowed were associated variables for all four highway classifications. The shoulder width and curvature were also associated with either injury or PDO or both injury and PDO crashes for three of the four classifications.

Lane width, ADT, the presence of turn lanes, and operating speed were associated with rear-end crashes for all four highway classifications. In addition, the presence of stoplights and the presence of stop signs were associated with rear-end crashes on rural and urban primary streets. For angle crashes, the associated variables for all four highway classifications included ADT, operating speed, and lane width.

For head-on crashes in all highway classifications, curvature, grade, operating speed, ADT, whether passing was allowed, and lane width were associated variables. The associated variables were consistent across the highway classifications, perhaps because of the small sample

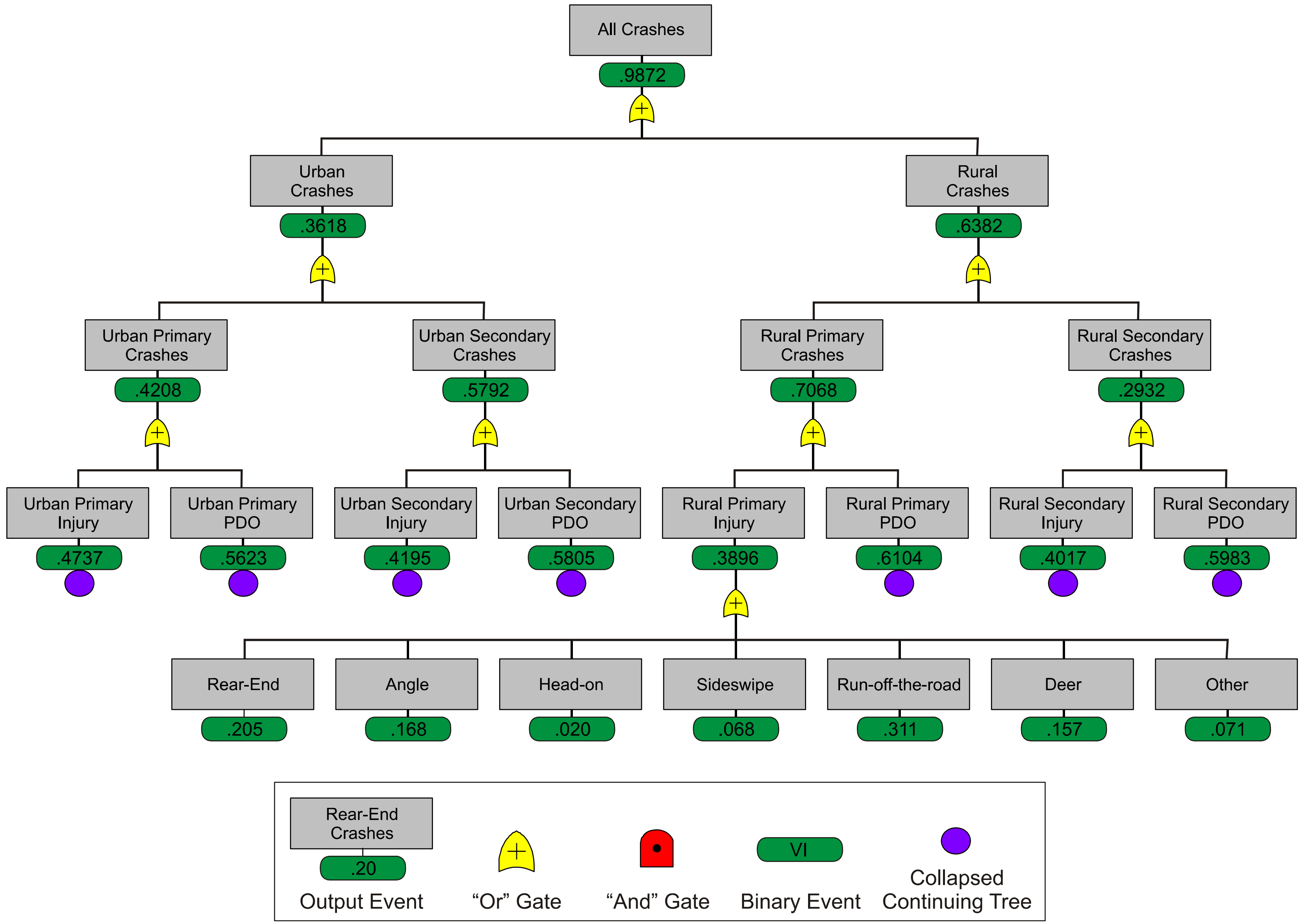

Figure 10. Results of Initial Fault Tree

of head-on crashes as shown in Figure 10. For all four highway classifications, curvature, grade, operational speed, lane width, and ADT were associated with injury or PDO deer crashes or both injury and PDO deer crashes.

The results for sideswipe crashes were similarly consistent across highway classifications. ADT, whether passing was allowed, grade, operating speed, curvature, and lane width were all associated with sideswipe crashes. The presence of chevrons was also associated with sideswipe crashes on rural sites, and truck percentage was associated with the sideswipe crashes on urban sites.

Any crashes that were not among the six collision types previously discussed were analyzed as a group. These “other” crashes showed associated variables of grade, operational speed, ADT, curvature, lane width, and whether passing is allowed. Chevrons, advisory signs, percentage of trucks, and curve density were associated variables in one or more of the highway classifications. The results of these fault trees provided guidance for the recommended countermeasures.

GLM Results

GLMs using the negative binomial and Poisson distributions were developed for each collision type in each highway classification. The results for the GLMs based on the negative binomial and the Poisson distributions were similar. Since the models based on the former gave slightly better results, they are given in Appendix D. The models obtained for the rural two-lane highways did not include the length of the site as an independent variable. The reason was that there was little variation among these lengths, with the mean being about 8.6 mi and with a standard variation of ±1.53 mi. The models for the rural sites are therefore appropriate for sites of between 8 and 10 mi long. The expression given in Equation 6 for ROR crashes on rural primary highways is an example of the models obtained. The predicted number of crashes is the number of crashes one would expect over the 4-year study period. Tables 11 and 12 show the *p* values obtained for each of the causal factors used in the different models. Table 13 shows an example of how the predicted number of crashes for an average length of 8.6 mi over 4 years can be determined using the models developed.

$$\text{ROR crashes} = \exp(2.5757 + 0.0002 \cdot \text{AADT} + 0.7659 \cdot \text{Passing allowed} - 0.0014 \cdot \text{Curvature}) \quad \text{[Eq. 6]}$$

Table 11. *p* Values of Coefficients in Crash Models (GML) for Rural Primary Two-lane Highways

Rural Primary	Passing Lanes (Y/N)	Turn Lanes (Y/N)	Cross-street Density (No./mi)	Stoplights (No./mi)	Curves w/ Chevrons	Operational Speed (85th)	Weighted Curvature	Weighted Mean Grade	AADT	Speed Differential	Shoulder Width
Rear-End		0.0003	< 0.0001	0.002				0.085	< 0.0001		
Angle				0.0524					< 0.0001		0.035
Head-on	0.047					0.0492			< 0.0001		
Sideswipe	0.0198						0.0075		< 0.0001		
ROR	0.0005					0.0798	< 0.0001		< 0.0001		
Deer	0.0011					0.0581	0.0944		< 0.0001	0.042	
Other					0.0006		0.0109		< 0.0001		

Table12. *p* Values of Coefficients in Crash Models (GML) for Rural Secondary Two-lane Highways

Rural Secondary	Advisory Signs (No.)	No Centerline (Y/N)	Passing Lanes (Y/N)	Turn Lanes (Y/N)	Curves w/ Chevrons	Operational Speed (85th)	Weighted Curvature	Weighted Mean Grade	AADT	Lane Width
Rear-End	0.0034	0.0486		0.0536	0.0526				< 0.0001	
Angle					0.0006	0.0027	0.0635	0.0827	< 0.0001	0.0488
Head-on			0.0504						0.0794	0.0827
Sideswipe					0.0576				0.0002	0.0672
ROR				0.0889			0.0787		< 0.0001	
Deer							0.0153		< 0.0001	
Other								0.0219	< 0.0001	

Table 13. GLM Results for Run-Off-the-Road Crashes on Rural Primary Highways and Application for Site 337

Parameter	Estimate	Parameter Value for Site 337	Value of Term in Model
Intercept	2.5757	--	2.575
AADT	0.0002	1891	0.3782
Passing allowed	0.7659	1	0.7659
Curvature	-0.0014	1093	-1.53
Sum			2.294
Predicted crashes			exp(2.1891) = 9

The estimated coefficient (β_i) of each variable, provided in the Statistical Analysis Software (SAS) results, was used for the variable in the model. The sign, negative or positive, indicates the effect of the variable on crashes. A negative coefficient signifies the factor reduces crashes, a positive coefficient signifies the factor increases crashes. Based on this principle and the negative binomial GLMs, the following conclusions can be drawn.

- *For rear-end crashes,* for rural primary highways, crashes decreased with turning lanes and increased with the presence of stoplights. For both rural primary and rural secondary highways, crashes increased with high ADT. For rural secondary highways, crashes tended to increase with a higher speed differential (the difference between the operating speed and the posted speed limit).

- *For angle crashes,* crashes increased with high ADT for both rural and primary roads and tended to decrease with the provision of chevrons for rural secondary roads.

- *For head-on crashes,* for both rural primary and secondary highways, crashes tended to increase with increasing AADT and tended to decrease with increasing lane widths. However, if passing was allowed, crashes tended to increase on rural secondary highways.

- *For sideswipe crashes,* on rural primary highways, crashes decreased with an increase in curvature, and for both primary and secondary rural highways, crashes increased as AADT increased and when passing was allowed.

- *For ROR crashes,* crashes increased with high ADT for rural two-lane highways and with the allowance of passing on rural primary highways. Crashes decreased with increased curvature for both rural and secondary roads.

- *For deer collision crashes,* crashes increased with increased ADT for both rural and primary roads and with allowing passing for rural primary roads.

- *For urban primary two-lane highways,* crashes tended to increase with increased AADT and increased length of the site but tended to decrease when passing was allowed.

- *For urban secondary highways,* increasing operational speed, AADT, cross-street density, and truck percentage will each tend to increase crashes and increasing curvature tends to decrease crashes.

- *For other crashes*, a sharp curvature tends to increase these crashes on rural primary highways and high ADT tends to increase them on both rural primary and secondary highways.

A Wilcoxon rank-sum test was implemented to test the validity of the models' predictions. For each model, the sites not used to develop the model (30% of the sites) were used to test the model. The researchers were then able to compare the predicted crashes at each site with the actual number of crashes. The non-parametric test showed no significant difference between the probability distributions of the predicted and the actual crashes based on a 95% confidence interval. The results of the test for rear-end crashes at rural primary sites are given in Table 14.

Table 14. Actual vs. Predicted Rear-End Crashes on Rural Primary Sites

Serial Number	Rear-End Crashes	Estimated Crashes
337	51	43.12
364	6	4.24
368	3	2.46
670	15.1	12.43
684	8.1	9.51
689	1.1	1.70
716	5	5.41
740	8.2	5.40
1046	2	6.18
1053	9	10.16
1057	4.1	2.98
1073	1	4.35
1090	22	43.59
1091	8	12.23
1096	4	1.90
1101	21	7.08
1830	31	15.55
2041	26	18.18
2336	15	16.28

Recommended Countermeasures

Using the results of the fault tree analysis and GLM, the major causal factors were identified. From those factors, countermeasures were identified and recommended for implementation. Table 15 provides the countermeasures by collision type, highway classification, and causal factor.

Table 15. Recommended Countermeasures by Collision Type, Highway Classification, and Causal Factor

Collision Type	Highway Classification(s)	Influencing Factor (Effect on Crashes) [a]	Countermeasure
Rear-end	Rural primary, urban secondary	Presence of turn lanes (-)	Add turn lanes at intersections
	Rural primary, urban primary	Stoplight density (+)	Provide advance warning signs at intersection approaches
Angle	Rural secondary, urban secondary	Increased shoulder width (-)	Add or improve shoulders
	Urban primary, urban secondary	Stop sign density (-)	Add stop signs where appropriate
Head-on	Rural secondary, urban primary	Steep grade (+)	Add advisory signs or realign
	Rural primary, rural secondary, urban primary	Passing allowed (+)	Add advisory signs or adjust passing segments
	Rural primary, rural secondary, urban secondary	Increased lane width (-)	Widen roadway; lane widths of at least 11ft, 12 ft preferable
Sideswipe	Rural primary, rural secondary, urban primary	Passing allowed (+)	Add advisory signs or adjust passing segments
	Rural primary, rural secondary, urban primary	Sharp curvature (+)	Add advisory signs and chevrons or realign
	Rural secondary	Steep grade (+)	Add advisory signs or realign
	Rural primary	High operating speed (+)	Reduce speed limit and/or increase speed enforcement
	Rural primary, rural secondary	Chevrons (-)	Add additional chevrons
Run-off-the-road	Rural primary, urban primary, urban secondary	Increased lane width (-)	Widen roadway
	Rural primary, rural secondary	Sharp curvature (+)	Add advisory signs and chevrons or realign
	Rural secondary, urban primary, urban secondary	Increased shoulder width (-)	Add or improve shoulders
	Rural primary, rural secondary	Passing allowed (+)	Add advisory signs or adjust passing segments
Deer	Urban primary	Sharp curvature (+)	Add advisory signs and chevrons or realign
	Rural primary, rural secondary, urban primary	High operating speed (+)	Reduce speed limit
Other	Rural primary, rural secondary	Sharp curvature (+)	Add advisory signs and chevrons or realign
	Rural primary, urban secondary	Increased lane width (-)	Widen roadway

[a]The sign of the parameter determines its effects on crashes. A negative sign indicates the variable reduces crashes and should therefore be implemented; a positive sign indicates the variable increase crashes and should be improved in order to reduce crashes.

From Table 15 it can be observed that several countermeasures are recommended multiple times for a specific highway classification to address different collision types. For example, increased lane width is recommended along urban secondary highways for head-on, ROR, and other crashes. Similarly, for head-on, sideswipe, and ROR crashes for rural primary and rural secondary highways, the researchers recommend adjustments to segments where passing is allowed. It should be noted that the recommended countermeasures are not necessarily an exhaustive list of countermeasures, as new technologies will probably lead to additional countermeasures. In order to have the greatest impact in reducing crashes, those countermeasures that would reduce multiple collision types should be implemented first. The countermeasures recommended here should be applied using the engineer’s personal knowledge and judgment. The engineering staff in each Virginia district are most familiar with the highways in their locality. The recommendations provide a list of possible countermeasures from which engineers can choose, based on the characteristics and crash history of a specific site.

CONCLUSIONS

- *Major causal factors associated with different crash types along roads with different highway classifications can be determined using fault tree techniques*. The necessary data are, however, required for the development of these trees. Depending on the level of analysis, extensive data may be required. For example if fault trees are to be developed for different severity levels (fatal, injury, and PDO) crashes, detailed data will be required for each severity level. Alternately, if the fault tree is to be developed for all severity levels combined, the data required will be less. In addition, the former requires adequate data for each severity level, and the latter requires adequate data for only all severity levels combined.

- *Each causal factor is not necessarily associated with only one type of crash*. The results obtained from the fault trees presented in Appendix C show, for example, that narrower lane widths are associated with rear-end, angle, and head-on crashes on rural primary roads. Although the fault tree analysis may identify several causal factors for a given crash type, it does not necessarily mean that all of the factors play a significant role in the occurrence of a crash. Further quantitative analysis is required to determine the significant causal factors, as was done in this study.

- *GLM can be an effective tool for identifying significant causal factors and quantifying the effects of these factors on crash occurrence.* The stochastic nature of crash occurrence requires modeling techniques that consider this phenomenon.

- *ROR is the predominant crash type on two-lane rural primary roads, followed by rear-end crashes.* The fault tree analysis shows that these two crash types account for more than 50% of the crashes on two-lane primary roads; the other five crash types considered account for less than 50% of the crashes.

- *Significant causal factors for ROR crashes on two-lane rural primary roads are the AADT, the radii of curves (curvature), and whether passing is allowed.* The models indicate that high AADT, low curvature, and passing allowed lead to increased ROR crashes.

- *Significant causal factors for rear-end crashes on two-lane primary roads are the AADT, the presence of turn lanes at intersections, whether passing is allowed, and the cross-street density along a stretch of the road.* The models developed indicate that high AADT, high cross-street density, and passing allowed lead to increased rear-end crashes whereas the presence of turn lanes at intersections lead to decreased rear-end crashes.

RECOMMENDATIONS

The following four recommendations are based on the results of this study. The research community is the audience for Recommendation 1 and VDOT's Traffic Engineering Division is the audience for Recommendations 2, 3, and 4. It should be emphasized again that in developing the models presented in this study, consideration was given to causal factors that could be changed by engineers. Other factors such as environmental and human factors were not investigated. The research team recognizes that these factors do have some effect on crash occurrence and, therefore, that implementing Recommendations 2, 3, and 4 will not lead to the elimination of ROR and rear-end crashes.

1. *This study should be repeated for the two-lane urban roads.* Although this research was sufficiently comprehensive for the rural roads, this cannot be said for the two-lane urban roads. Although the researchers made every effort to obtain adequate data for all road types, they were not successful in obtaining data for an adequate number of sites that would permit a detailed analysis as was done for the rural roads. The research team included all of the urban sites available to them, but the number of these sites was significantly lower than that for the rural roads and was less than adequate for the detailed analysis undertaken. Data at additional sites will improve the development of the crash prediction models for this type of road.

2. *A plan for correcting the geometric deficiencies associated with the significant causal factors at sites with a high number of ROR crashes should be developed and implemented.* The significant geometric causal factor for ROR crashes was found to be the curvature. Sites (see Appendix E) with a high number of ROR crashes with radii of curves that were lower than the minimum required (AASHTO, 2004) for the speed limit should be selected, and the radii of these curves increased to at least the minimum currently required.

3. *A plan for providing turn lanes at intersections at sites with a high number of rear-end crashes that do not have turn lanes should be developed and implemented.* A significant factor that will tend to reduce the number of rear-end crashes is the existence of turn lanes at intersections. Table F.1 of Appendix F gives the number of rear-end crashes that occurred at the study sites from 2001 through 2004.

4. *A plan for posting appropriate mandatory speed limits at sites for which the curvatures are currently inadequate for the existing posted speed limit should be developed and implemented. These mandatory speed limits will be based on the existing curvatures such that these curvatures are adequate for the mandatory speed limits posted.* It will take some time for Recommendation 2 to be implemented. In the meantime, by posting lower speed limits that reflect existing curvatures, it is likely that ROR crashes will decrease, as this study has shown that inadequate curvature tends to result in higher ROR crashes.

SUGGESTIONS FOR IMPLEMENTING RECOMMENDATION 2

In order to implement Recommendation 2, it is first necessary to identify the specific location(s) within each study site that has a high number of crashes or a high crash rate compared with those for other locations within the study site. Crash rates may be used if AADTs are significantly different within the segment. This is necessary as the average length of a study site was 8 mi, within which specific locations may exist that have deficient characteristics for which the effective countermeasures should be applied. This is best done by selecting 1-mi sections within each segment (study site), as shown in Figures 11 and 12. Figures 11 and 12 show examples for Site 2048 on Route 55, using number of crashes and crash rates, respectively. It can be seen that the specific locations that should be considered in the prioritization process are at mile markers 39.59 to 40.09, 43.59 to 44.09, and 36.59 to 38.59.

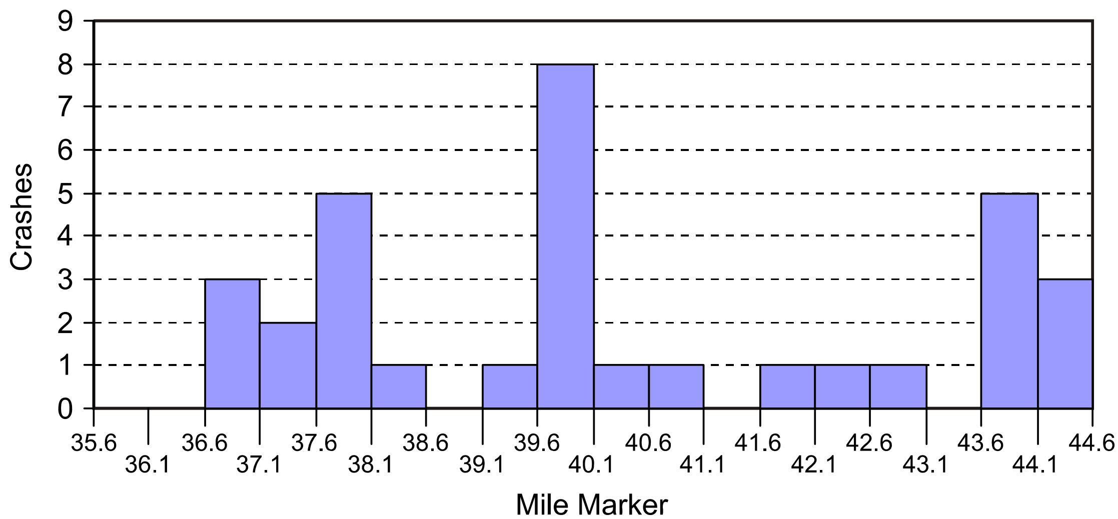

Figure 11. Half-Mile Crash Distribution at Site 2058 on Route 55

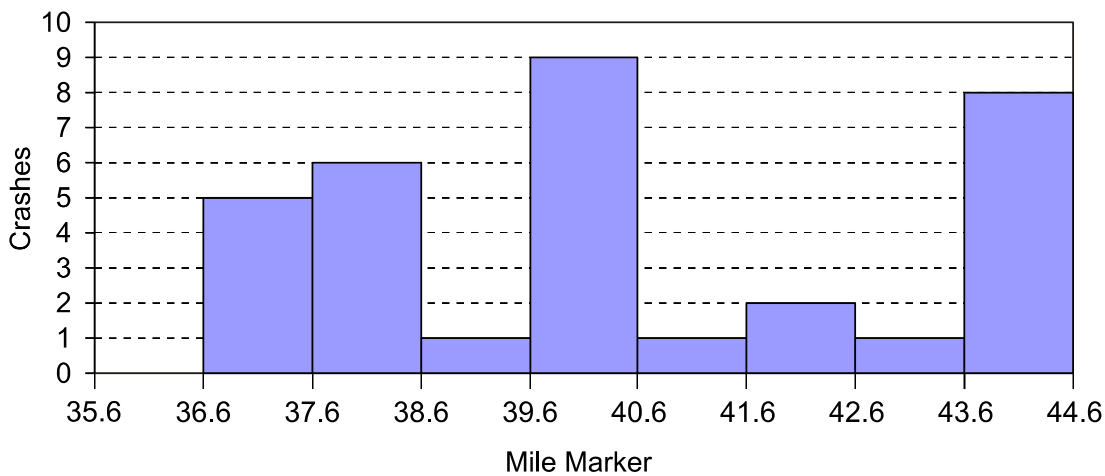

Figure 12. One-Mile Crash Distribution at Site 2048 on Route 55

The specific locations identified should then be prioritized using the safety performance functions now being developed by the Virginia Transportation research Council for two-lane highways. In addition, the expected reduction in a specific crash type at a location as a result of implementing an appropriate countermeasure can be determined by using the models developed in this study.

COSTS AND BENEFITS ASSESSMENT

The benefits and costs associated with Recommendation 2 are presented to illustrate the effectiveness of implementing the recommendation for eliminating ROR crashes. These crashes were selected as they are the predominant type of crashes on two-lane primary roads. It is therefore likely that significant benefits will be accrued from implementing Recommendation 2.

In order to estimate the potential benefits and costs of implementing Recommendation 2, a sensitivity study of the data for a selected number of sites was conducted, as shown in Table 16. For each site, the expected number of ROR crashes was computed for the existing AADTs and two increments of 5% each, with the curvatures in each case being the existing curvature, the minimum required (AASHTO, 2004), and the mean of the existing and the minimum required. The results shown in Table16 indicate that the reduction in ROR crashes increases with increasing curvature and with AADT for high AADTs (higher than 7,000). When the curvatures are increased to the minimum required for a site, ROR crashes decrease about 21% for low-volume roads (AADT < 1,500) and increase about 41% for high-volume roads (AADT > 7,000). The total number of injury and fatal ROR crashes on rural primary roads can be calculated from Figure 10 as 539 (9872 x 0.6382 x 0.7068 x 0.3896 x 0.311). A conservative assumption that an average reduction in these crashes of 30% will occur by implementing Recommendation 2 will result in the elimination of about 162 ROR fatal and injury crashes on two-lane primary roads over a period of 4 years, i.e., an average of about 41 such crashes every

Table 16. Results of Sensitivity Tests on Crash Reduction

Site Characteristics	Speed Limit (mph)	Evaluated Radius of Curvature	Radius of Curvature (ft)	AADT[1]	AADT[2]	AADT[3]	ROR Rural Primary Crashes[1]	ROR Rural Primary Crashes[2]	ROR Rural Primary Crashes[3]
Site 332: Passing Allowed, Rural Primary	45	Actual	450	1209	1269	1333	19	19	20
		Median[4]	526				17	17	18
		Minimum[5]	602				15	16	16
Site 338: Passing Allowed, Rural Primary	55	Actual	453	2025	2126	2233	22	23	23
		Median[4]	708				16	16	16
		Minimum[5]	964				11	11	11
Site 2046: Passing Allowed, Rural Primary	55	Actual	548	7689	8073	8477	61	66	72
		Median[4]	756				46	49	53
		Minimum[5]	964				34	37	40

AADT = annual average daily traffic, ROR = run-off-the-road crashes.
[1]Actual.
[2]5% increase.
[3]5% increase of 2.
[4]Median between actual and minimum.
[5]AASHTO, 2004.

year. FHWA estimates that the average cost of a single-vehicle crash, which is predominant in ROR crashes at 50 mph or greater, is $32,393 in 2001 dollars. Assuming an inflation rate of 3% per annum, the average cost in 2008 dollars is about $39,839. Applying this rate to the number of estimated crashes eliminated gives a savings of about $1.6 million per year.

Estimating the real rehabilitation cost for improving curvatures is not easy as this depends on the specific characteristics, such as land use, at each site. However, based on a discussion with VDOT construction engineers, an estimated average cost of $100,000 per site is assumed reasonable. The data on curvature at the rural primary roads show that 30 of the 67 sites have curvatures less than the minimum required and should, therefore, be improved (see Appendix E). The estimated total rehabilitation cost is therefore $3 million. Assuming a life span of each rehabilitation work of 10 years (although the savings attributable to crash reduction will continue for many more years) and an interest rate of 4%, it can be shown that the annual equivalent cost for the rehabilitation is $369,900. This gives a benefit/cost (B/C) ratio of 4.42. Table 17 shows the results of a sensitivity test of the impact of the assumption of percentage crash reduction and assumed construction cost on the B/C ratio. These results show that in all cases the B/C ratio is higher than 1.

Table 17. Results for Benefit/Cost (B/C) Ratio Using Different Percentages of Crash Reduction and Construction Costs

Crash Reduction (%)	No. of Crashes Eliminated/Yr	Average Construction Cost/Site ($)	Total Construction Cost (M$)	Discounted Annual Construction Cost (M$)	Annual Benefit (M$)	B/C Ratio
20	27	75,000	2.25	0.278	1.076	3.87
		200,000	6.00	0.740	1.076	1.45
		250,000	7.50	0.924	1.076	1.16
40	54	75,000	2.25	0.278	2.151	7.74
		200,000	6.00	0.740	2.151	2.91
		250,000	7.50	0.924	2.151	2.32
50	67	75,000	2.25	0.278	2.669	9.60
		200,000	6.00	0.740	2.669	3.61
		250,000	7.50	0.924	2.669	2.88

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APPENDIX A

SITE SELECTION

Table A.1 lists pertinent information for each of the selected sites.

Table A.1. Selected Sites

Site Number	District[a]	Rural/Urban	Route Prefix	Route Number	Jurisdiction (County)	Begin Milepost	End Milepost
2	1	R	10	606	Bland	0	9.85
54	1	R	25	607	Dickenson	1.69	7.86
60	1	R	25	637	Dickenson	0	9.37
77	1	R	38	607	Grayson	0	7.72
123	1	R	83	615	Russell	2.18	11.69
185	1	R	86	600	Smyth	7.86	15.67
225	1	R	92	650	Tazewell	0	7.51
264	1	R	97	640	Wise	0	8.96
303	1	R	SR	16	Smyth	26.21	31.9
312	1	R	SR	42	Bland	38.05	47.52
323	1	R	SR	67	Tazewell	15.45	22.36
332	1	R	SR	72	Dickenson	41.51	49.19
337	1	R	SR	80	Russell	23.88	33.32
338	1	R	SR	80	Buchanan	35.12	45.04
345	1	R	SR	91	Washington	3.31	12.92
346	1	R	SR	91	Washington	17.35	22.78
352	1	R	SR	94	Wythe	19.34	28.39
356	1	R	US	11	Smyth	46.98	56.47
357	1	R	US	11	Wythe	56.47	66.38
358	1	R	US	21	Grayson	5.5	11.41
364	1	R	US	52	Bland	58.13	67.96
368	1	R	US	58	Washington	88.91	94.03
377	1	R	US	460	Buchanan	0	9.65
379	1	R	C4US	23	Wise	5.74	13.7
459	2	R	17	670	Carroll	1.5	10.75
461	2	R	17	683	Carroll	0	9.94
486	2	R	31	610	Floyd	0	9.6
526	2	R	33	634	Franklin	0	9.03
539	2	R	33	674	Franklin	0	6.24
540	2	R	33	678	Franklin	0	6.61
577	2	R	44	610	Henry	0	9.46
588	2	R	44	683	Henry	0	8.29
623	2	R	70	627	Patrick	0	5.83
670	2	R	SR	8	Patrick	0	8.5
674	2	R	SR	8	Floyd	35.65	45.6
677	2	R	SR	24	Bedford	9.29	19.2
684	2	R	SR	40	Franklin	44.44	50.21
689	2	R	SR	43	Bedford	9.32	16.94
711	2	R	SR	57	Henry	10.86	19.03
716	2	R	SR	103	Patrick	0	9.13
717	2	R	SR	116	Franklin	0	9.5
719	2	R	SR	122	Franklin	7.38	17.2
720	2	R	SR	122	Bedford	17.4	27.31
731	2	R	US	58	Carroll	204.32	213.44

737	2	R	US	221	Floyd	43.09	52.92
740	2	R	US	221	Floyd	68.71	77.9
742	2	R	US	501	Bedford	82.36	92.29
793	3	R	14	602	Buckingham	0	8.69
801	3	R	14	610	Buckingham	0	9.74
829	3	R	15	615	Campbell	0	9.77
830	3	R	15	615	Campbell	9.77	18.27
849	3	R	15	699	Campbell	0	9.15
877	3	R	19	727	Charlotte	0.28	9.7
962	3	R	71	622	Pittsylvania	0	9.61
970	3	R	71	640	Pittsylvania	9.94	19.32
1009	3	R	71	841	Pittsylvania	0	8.77
1015	3	R	71	863	Pittsylvania	8.17	14.8
1026	3	R	73	630	Prince Edward	10.37	18.97
1040	3	R	SR	20	Buckingham	8.83	18.74
1043	3	R	SR	24	Appomattox	71.06	80.86
1045	3	R	SR	26	Appomattox	0.5	8.49
1046	3	R	SR	40	Pittsylvania	50.21	59.34
1053	3	R	SR	41	Pittsylvania	4.73	14.5
1057	3	R	SR	45	Cumberland	20.28	29.87
1073	3	R	SR	57	Halifax	75.85	85.75
1075	3	R	SR	92	Charlotte	16.57	23.18
1077	3	R	SR	130	Amherst	12.67	22.43
1090	3	R	US	15	Prince Edward	53.99	59.06
1091	3	R	US	15	Buckingham	65.94	75.58
1096	3	R	US	60	Amherst	78.34	87.38
1097	3	R	US	60	Amherst	92.38	99.72
1101	3	R	US	60	Cumberland	142.26	150.7
1103	3	R	US	501	Halifax	28.29	38.25
1170	4	U	20	604	Chesterfield	4.86	14.41
1171	4	U	20	625	Chesterfield	0	7.44
1175	4	U	20	653	Chesterfield	4.39	10.31
1176	4	U	20	654	Chesterfield	3.78	11.92
1177	4	U	20	655	Chesterfield	0	9.58
1178	4	U	20	655	Chesterfield	9.58	15.17
1179	4	U	20	667	Chesterfield	0	9.97
1220	4	R	37	606	Goochland	0	9.77
1371	4	U	SR	5	Henrico	1.18	8.23
1395	4	R	SR	47	Mecklenburg	22.89	28.43
1407	4	U	SR	144	Chesterfield	6.51	11.95
1413	4	U	SR	156	Henrico	31.95	41.78
1414	4	U	SR	156	Hanover	51.15	60.58
1481	5	U	46	665	Isle of Wight	0	6.76
1491	5	U	61	628	Suffolk	0	5.26
1493	5	U	61	634	Suffolk	1.35	6.88
1607	5	U	99	620	York	0	6.87
1609	5	U	SR	5	James City	43.94	49.86
1610	5	R	SR	10	Sussex	41.89	51.66
1613	5	U	SR	10	Suffolk	82.43	88.13
1624	5	U	SR	125	Suffolk	0	6.24
1762	6	R	88	601	Spotsylvania	0	8.78
1787	6	U	89	610	Stafford	0	7.31
1801	6	R	SR	2	Caroline	34.25	43.85

1830	6	R	SR	208	Spotsylvania	33.64	42.52
1843	7	R	2	614	Albemarle	6.24	11.55
1857	7	R	2	664	Albemarle	0	5.93
1870	7	U	2	743	Albemarle	1.73	8.19
1874	7	R	2	810	Albemarle	0	8.42
1894	7	R	23	685	Culpeper	0	8.98
1922	7	R	60	709	Montgomery	0	9.64
1933	7	R	32	600	Fluvanna	0	8.6
1934	7	R	32	601	Fluvanna	0	9.36
1967	7	R	54	613	Louisa	16.85	23.89
1969	7	R	54	618	Louisa	0	9.29
2036	7	U	SR	20	Albemarle	31.01	36.73
2041	7	R	SR	22	Albemarle	0	9.06
2046	7	R	SR	53	Albemarle	0	9.51
2048	7	R	SR	55	Fauquier	35.59	44.5
2049	7	R	SR	208	Louisa	0	8.9
2053	7	R	SR	230	Madison	11.39	20.58
2059	7	R	US	15	Fluvanna	98.5	107.87
2073	7	R	US	522	Louisa	26.72	32.89
2100	8	R	7	612	Augusta	11.32	21.17
2103	8	R	7	616	Augusta	0	9.42
2110	8	R	7	657	Augusta	0	6.22
2111	8	R	7	664	Augusta	0	6.7
2132	8	R	7	865	Augusta	0	9.71
2172	8	R	34	628	Frederick	0	8.05
2245	8	R	82	613	Rockingham	5.32	14.91
2252	8	R	82	644	Rockingham	0	6.6
2260	8	U	82	724	Rockingham	0.00	5.30
2285	8	R	85	675	Rockbridge	12.33	17.94
2303	8	R	93	603	Warren	0	5.2
2313	8	R	93	638	Warren	6.67	15.37
2326	8	R	SR	42	Augusta	204.17	212.95
2336	8	R	SR	55	Shenandoah	5.53	15.25
2337	8	R	SR	55	Warren	18.29	25.5
2344	8	R	SR	252	Augusta	10.25	20.15
2350	8	R	SR	259	Rockingham	5.38	14.41
2356	8	R	US	11	Rockbridge	188.23	194.19
2358	8	R	US	11	Rockingham	267.85	277.82
2363	8	R	US	220	Bath	135.84	145.59
2373	8	R	US	250	Augusta	49.03	54.26
2375	8	R	US	340	Augusta	19.62	29.51
2397	9	U	29	674	Fairfax	0.21	7.24
2406	9	R	53	621	Loudoun	6.29	16.14
2411	9	U	53	659	Loudoun	7.81	17.11
2433	9	R	76	619	Prince William	15.47	24.58
2441	9	U	SR	234	Prince William	2.72	9.35
2445	9	R	US	15	Loudoun	222.05	230.74

[a]Districts

1 - Bristol 2 - Salem 3 - Lynchburg
4 - Richmond 5 - Hampton Roads 6 - Fredericksburg
7 - Culpeper 8 - Staunton 9 - Northern Virginia

APPENDIX B

CRASH DOCUMENT VARIABLES

The following variables are recorded in the crash document database and were extracted for this study:

- Route Number
- Node Number
- Crash Date
- Crash Hour
- Surface Type
- Lane Width
- Shoulder Width
- Weather
- Surface Condition
- Road Defects
- Lighting
- Collision Type
- Major Factor
- Severity
- Persons Injured
- Persons Killed
- Number of Vehicles
- Day of Week
- Vehicle Type
- Vehicle Maneuver
- Driver Age
- Driver Sex
- Driver Action

Tables B.1. through B.13. provide the various codes for each variable.

Table B.1. Surface Type

Code	Field
3	Asphalt
4	Gravel
5	Bituminous
6	Bituminous
7	Asphalt

Table B.2. Weather

Code	Field
0	Not stated
1	Clear
2	Cloudy
3	Fog
4	Mist
5	Raining
6	Snowing
7	Sleeting
8	Smoke or dust
9	Other

Table B.3. Surface Condition

Code	Field
1	Dry
2	Wet
3	Snowy
4	Icy
5	Muddy
6	Oily
7	Other
8	Not stated

Table B.4. Road Defect

Code	Field
0	Not stated
1	No defects
2	Holes, ruts, or bumps
3	Soft or low shoulders
4	Under repair
5	Loose material
6	Restricted width
7	Slick pavement
8	Roadway obstructed
9	Other defects

Table B.5. Lighting

Code	Field
1	Dawn
2	Daylight
3	Dusk
4	Darkness (highway lighted)
5	Darkness (highway not lighted)
6	Not stated

Table B.6. Collision Type

Code	Field
1	Rear-end
2	Angle
3	Head-on
4	Sideswipe (same direction)
5	Sideswipe (opposite direction)
6	Fixed object in road
7	Train
8	Non-collision
9	Fixed object off road
10	Deer
11	Other animal
12	Pedestrian
13	Bicyclist
14	Motorcyclist
15	Backed into
16	Other
17	Not stated

Table B.7. Major Factor

Code	Field
0	Miscellaneous
1	Driver or pedestrian handicap
2	Driver under the influence
3	Driver speeding
4	Driver inattention or error
5	Vehicle defective
6	Weather or visibility conditions
7	Road defective
8	Road slick
9	Not stated

Table B.8. Severity

Code	Field
0	Fatal pedestrian
1	Fatal vehicular
2	Injury pedestrian
3	Injury vehicular
4	Property damage only
5	No injury but pedestrian

Table B.9. Day of Week

Code	Field
1	Monday
2	Tuesday
3	Wednesday
4	Thursday
5	Friday
6	Saturday
7	Sunday

Table B.10. Vehicle Type

Code	Field
0	Not stated
1	Passenger car
2	Passenger truck, pick-up, or jeep
3	Van
4	Straight truck, flatbed
5	Tractor-trailer
6	Tractor-double trailer
7	Motor home, RV
8	Oversized vehicle, road equipment
9	Bicycle
10	Moped
11	Motorcycle
12	Emergency vehicle
13	School bus
14	City or privately owned bus
15	Commercial passenger bus
16	Other

Table B.11. Vehicle Maneuver

Code	Field
1	Going straight ahead
2	Making right turn
3	Making left turn
4	Making U-turn
5	Slowing or stopping
6	Starting in traffic lane
7	Starting from parked position
8	Stopped in traffic lane
9	Ran off road (right)
10	Ran off road (left)
11	Parked
12	Backing
13	Passing
14	Changing lanes
15	Other
16	Not stated

Table B.12. Driver Sex

Code	Field
1	Male
2	Female
3	Unknown

Table B.13. Driver Action

Code	Field
1	None
2	Exceeded speed limit
3	Exceeded safe speed but not speed limit
4	Overtaking on hill
5	Overtaking on curve
6	Overtaking at intersection
7	Improper passing of school bus
8	Cutting in
9	Other improper passing
10	Wrong side of road, not overtaking
11	Did not have right-of-way
12	Following too close
13	Fail to signal or improper signal
14	Improper turn—wide right turn
15	Improper turn—cut corner on left turn
16	Improper turn from wrong lane
17	Other improper turning
18	Improper backing
19	Improper start from parked position
20	Disregarded officer or watchman
21	Disregarded stop-go light
22	Disregarded stop or yield sign
23	Driver inattention
24	Fail to stop at through highway—no sign
25	Drive through safety zone
26	Fail to set out flares or flags
27	Fail to dim headlights
28	Driving without lights
29	Improper parking location
30	Avoiding pedestrian
31	Avoiding other vehicle
32	Avoiding animal
33	Crowded off roadway
34	Hit and run
35	Car ran away—no driver
36	Blinded by lights
37	Other violations
38	Avoiding object in roadway
39	Eluding police
40	Fail to maintain proper control
41	Improper passing
42	Improper or unsafe lane change
43	Over correction

APPENDIX C

FAULT TREE RESULTS

Table C.1. Results of Fault Tree Analysis, Rural Primary Highways

Collision Type	Injury Crashes	Property Damage Only Crashes
Rear-end	Lane width < 10 ft; shoulder width 3-5 ft	Lane width < 10 ft; shoulder width 3-5 ft
	ADT > 5,000; turning lanes	Steep grade; operational speed 55-60 mph
	Crash hour 9 A.M.-1 P.M.	ADT > 5,000; turning lanes
	Steep grade; operational speed 55-60 mph	Crash hour 9 A.M.-1 P.M.
	High cross-street density; presence of stoplights	Presence of stoplights
	Surface condition not dry; raining, snowing, or sleeting	Crash day Tuesday-Thursday
	Driver action: following too close	Driver action: following too close
Angle	Lane width < 10 ft; shoulder width 3-5 ft	Lane width < 10 ft
	ADT > 5,000; turning lanes	ADT > 5,000; turning lanes
	Presence of stoplights	Steep grade; operational speed 55-60 mph
	Steep grade; operational speed 55-60 mph	Presence of stoplights
	Crash hour 9 A.M.-1 P.M.	Presence of doglegs
	Driver action: did not have right of way	Crash hour 9 A.M.-1 P.M.
	Low curve density	Driver action: did not have right of way
Head-on	Crash hour 1 A.M.-5 A.M.; highway not lighted	Steep grade; operational speed 55-60 mph
	ADT > 5,000; passing allowed	ADT > 5,000; passing allowed
	Steep grade; operational speed 55-60 mph	Crash hour 1 A.M.-5 A.M.; highway not lighted
	No curvature	No curvature
	Presence of doglegs	Surface condition not dry; raining, snowing or sleeting
	Driver action: improper passing or turning	Driver action: improper passing or turning
	Lane width 10-12 ft	Lane width 10-12 ft
Sideswipe	Crash hour 9 A.M.-1 P.M.	Lane width < 10 ft
	ADT > 5,000; passing allowed	Passing allowed
	Steep grade; operational speed 55-60 mph	Steep grade; operational speed 55-60 mph
	Moderate to sharp curvature	Crash hour 9 A.M.-1 P.M.
	Few to no chevrons	Moderate to sharp curvature
	Lane width 10-12 ft	Crash day Friday-Sunday
	Crash day Tuesday-Thursday	Driver action: improper passing or turning
Run-off-the-road	Lane width < 10 ft	Lane width < 10 ft
	Steep grade; operational speed 55-60 mph	ADT 2,000-5,000; passing allowed
	ADT 5,000-10,000; passing allowed	Steep grade; operational speed 55-60 mph
	Crash hour 9 A.M.-1 P.M.	Crash hour 1 A.M.-5 A.M.; highway not lighted
	Sharp curvature	Driver age < 25
	Driver age < 25	Sharp curvature; raining, snowing, or sleeting
		Some chevrons
Deer	ADT > 5,000; passing allowed	Lane width < 10 ft
	Crash hour 9 A.M.-1 P.M.	ADT > 5,000; passing allowed
	High cross-street density	Steep grade; operational speed 55-60 mph
	Steep grade; operational speed 55-60 mph	Low cross-street density
	Lane width < 10 ft	Crash hour 1 A.M.-5 A.M.; highway not lighted
	No curvature; darkness	Raining, snowing, or sleeting
	Low curve density	Low curve density
	Speed differential < 0 (speeding)	Driver age < 25

Other	Lane width < 10 ft	Lane width < 10 ft
	Crash hour 9 A.M.-1 P.M.	ADT < 5,000; passing allowed; turning lanes
	ADT 2,000-10,000	Steep grade; operational speed 55-60 mph
	Steep grade; operational speed 55-60 mph	Crash hour 1 A.M.-5 A.M.; highway not lighted
	High cross-street density	Sharp curvature
	Sharp curvature; raining, snowing, or sleeting	Few chevrons
	Few chevrons	Crash day Friday-Sunday
	Driver age < 25	

Table C.2. Results of Fault Tree Analysis, Rural Secondary Highways

Collision Type	Injury Crashes	Property Damage Only Crashes
Rear-end	Crash hour 9 A.M.-1 P.M.	Crash hour 9 A.M.-1 P.M.
	Sharp curvature; raining, snowing, or sleeting	Steep grade; operational speed 45-50 mph
	Steep grade; some advisory signs; operational speed 55-60 mph	ADT 5,000-10,000; no centerline
	ADT 5,000-10,000; turning lanes	Sharp curvature
	Lane width < 10 ft	Few or no chevrons
	Crash day Tuesday -Thursday	Speed differential < 0 (speeding)
	Driver action: following too close	Lane width 10-12 ft
		Crash day Tuesday -Thursday
Angle	Raining, snowing, or sleeting	Crash hour 1 A.M.-8 A.M.; highway not lighted
	ADT 5,000-10,000	Steep grade; operational speed 45-50 mph
	Crash hour 6 A.M.-8 A.M.	ADT 5,000-10,000
	Steep grade; operational speed 45-50 mph	High cross-street density; presence of stoplights
	Few or no chevrons; sharp curvature	Lane width 10-12 ft
	Lane width 10-12 ft; shoulder width 3 ft	Driver action: improper turning
	Driver action: improper turning	Crash day Friday -Sunday
Head-on	Crash hour 6 A.M.-1 P.M.	ADT < 2,000; no passing allowed
	Slight curvature; raining, snowing, or sleeting	Low cross-street density
	Moderate to steep grade; operational speed 45-50 mph	Sharp curvature; raining, snowing, or sleeting
	Low cross-street density	Moderate to steep grade; operational seed 45-50 mph
	ADT < 5,000; no passing allowed	Lane width < 10 ft
	Lane width 10-12 ft	Truck 2-6%
	Driver action: improper passing or lane change	
	Crash day Friday -Sunday	
Sideswipe	ADT 5,000-10,000; no passing allowed	Crash hour 9 A.M.-1 P.M.
	Moderate to steep grade; operational speed 45-50 mph	Sharp curvature; raining, snowing, or sleeting
	Crash hour 7 P.M.-5 A.M.; highway not lighted	ADT < 5,000; no passing allowed
	Sharp curvature	Moderate to steep grade; operational speed 45-50 mph
	Few or no chevrons	Lane width 10-12 ft
	Lane width 10-12 ft	
	Speed differential < 0 (speeding)	
	Crash day Friday -Sunday	
Run-off-the-road	Steep grade; operational speed 45-50 mph	Crash hour 9 A.M. -1 P.M.
	ADT < 5,000; no passing allowed; no turning lanes	Steep grade; operational speed 45-50 mph
	Low cross-street density	ADT 2000-5,000; no passing allowed; no turning lanes

	Crash hour 9 A.M.-1 P.M.	Sharp curvature; raining, snowing, or sleeting
	Lane width 10-12 ft; shoulder width 3-5 ft	Lane width 10-12 ft
	Driver age < 25	Driver age < 25
	Sharp curvature; raining, snowing, or sleeting	Crash day Friday -Sunday
Deer	Crash hour 1 A.M.-5 A.M.; highway not lighted	Low cross-street density
	Sharp curvature; raining, snowing, or sleeting	Steep grade; operational speed 55-60 mph
	Low cross-street density	ADT 5,000-10,000
	Steep grade; operational speed 55-60 mph	Lane width < 10 ft
	Lane width 10-12 ft	
	Driver age < 25	
	Crash day Friday -Sunday	
Other	Steep grade; operational speed 45-50 mph	Crash hour 9 A.M.-1 P.M.
	ADT 5,000-10,000; no passing allowed	High cross-street density
	Crash hour 9 A.M.-1 P.M.	ADT 5,000-10,000; no passing allowed
	Sharp curvature	Steep grade; operational speed 45-50 mph
	Lane width < 10 ft	Lane width 10-12 ft
	Driver age < 25	Driver age < 25
	Crash day Friday-Sunday	Crash day Friday-Sunday

Table C.3. Results of Fault Tree Analysis, Urban Primary Highways

Collision Type	Injury Crashes	Property Damage Only Crashes
Rear-end	ADT > 5,000; passing allowed; turning lanes	Lane width < 10 ft; shoulder width 0-2 ft
	Crash hour 9 A.M.-1 P.M.	No grade; operational speed 55-60 mph
	No grade; operational speed 55-60 mph	Crash hour 1 A.M.-5 A.M.
	Presence of stoplights and stop signs	ADT > 5,000
	Presence of school zone	Presence of stoplights and stop signs
	Truck 2-6%	Presence of school zone
	Lane width 10-12 ft	Truck 2-6%
	Crash day Tuesday -Thursday	Crash day Tuesday -Thursday
	Driver action: following too close	
Angle	Crash hour 1 A.M.-5 A.M.; highway lighted	Crash hour 9 A.M.-1 P.M.
	ADT > 5,000; turning lanes	ADT > 5,000; turning lanes
	No grade; operational speed 55-60 mph	No grade; operational speed 55-60 mph
	Presence of stoplights and stop signs	Presence of school zone
	Presence of school zone	Lane width 10-12 ft
	Lane width 10-12 ft	Driver action: improper turning
	Low curve density	Low curve density
	Driver action: improper turning	Crash day Tuesday -Thursday
	Truck 6-10%	
Head-on	Crash hour 9 A.M.-1 P.M.	Crash hour 9 A.M.-1 P.M.
	Few advisory signs; operational speed 55-60 mph	Moderate grade; operational speed 50-55 mph
	ADT > 5,000	ADT 5,000-10,000; passing allowed
	Low curve density	Sharp curvature
	Lane width 10-12 ft	Low curve density
	Driver action: driver inattention/ failure to maintain control	Crash day Tuesday -Thursday
		Surface condition not dry; raining, snowing, or sleeting

Sideswipe	Crash hour 9 A.M.-1 P.M. and 7 P.M.-1 A.M.; highway not lighted	Crash hour 9 A.M.-1 P.M. and 7 P.M.-1 A.M.; highway not lighted
	ADT > 5,000; passing allowed	No grade; operational speed 55-60 mph
	Sharp curvature; raining, snowing, or sleeting	Sharp curvature; raining, snowing, or sleeting
	Surface condition not dry	ADT > 5,000; passing allowed
	Few advisory signs	Presence of school zone
	Low curve density	Lane width 10-12 ft
	Lane width 10-12 ft	
	Truck 2-6%	
Run-off-the-road	Lane width < 10 ft; shoulder width 0-2 ft	Crash hour 9 A.M.-1 P.M.
	Crash hour 9 A.M.-1 P.M. and 7 P.M.-1 A.M.; highway not lighted	Lane width < 10 ft; shoulder width 0-2 ft
	ADT > 5,000; passing allowed; turning lanes	Low cross-street density
	No grade; operational speed 55-60 mph	Sharp curvature; highway not lighted
	Sharp curvature; not lighted; raining, snowing, or sleeting	ADT > 5,000; passing allowed; turning lanes
	Driver age < 25	No grade; operational speed 55-60 mph
		Driver age < 25
		Low curve density
		Crash day Friday-Sunday
Deer	Crash hour 9 A.M.-1 P.M.	No curvature; raining, snowing, or sleeting
	Moderate curvature; raining, snowing, or sleeting	ADT > 5,000; passing allowed
	ADT > 5,000; passing allowed	No grade; operational speed 55-60 mph
	No grade; operational speed 55-60 mph	Crash hour 1 A.M.-5 A.M.; highway not lighted
	Driver age < 25	Lane width 10-12 ft
	Crash day Friday-Sunday	Driver age < 25
	Truck 2-6%	
	Lane width 10-12 ft	
Other	Crash hour 9 A.M.-1 P.M.	Moderate curvature; raining, snowing, or sleeting
	Moderate curvature; raining, snowing, or sleeting	No grade; operational speed 55-60 mph
	ADT 5,000-10,000; passing allowed; turning lanes	ADT > 5,000; passing allowed; turning lanes
	No grade; operational speed 55-60 mph	Crash hour 9 A.M.-1 P.M.
	Low curve density	Some chevrons
	Presence of school zone	Presence of school zone
	Driver age < 25	Low curve density
	Crash day Tuesday-Thursday	Lane width 10-12 ft
		Driver age < 25

Table C.4. Results of Fault Tree Analysis, Urban Secondary Highways

Collision Type	Injury Crashes	Property Damage Only Crashes
Rear-end	Steep grade; few advisory signs; operational speed > 60 mph	Steep grade; operational speed 50-55 mph
	ADT > 5,000; turning lanes	Crash hour 9 A.M.-1 P.M.
	Crash hour 9 A.M.-1 P.M.	Low cross-street density
	Low cross-street density	ADT 2000-5,000; turning lanes
	Truck 2-6%	No curvature; raining, snowing, or sleeting
	Lane width 10-12 ft; shoulder width 0-2 ft	Truck 2-6%
	Driver action: following too close	Lane width 10-12 ft; shoulder width 0-2 ft
	Crash day Tuesday -Thursday	Crash day Tuesday -Thursday
		Driver action: following too close
Angle	Very steep grade; operational speed 50-55 mph	ADT < 5,000; turning lanes
	ADT < 5,000; turning lanes	Seep grade; operational speed 50-55 mph
	Crash hour 9 A.M. -1 P.M.	Crash hour 9 A.M.-1 P.M.
	Low cross-street density; presence of stoplights and stop signs	Low cross-street density; presence of stoplights and stop signs
	Presence of doglegs	Truck 2-6%
	Lane width 10-12 ft; shoulder width 0-2 ft	Moderate curvature; some chevrons
	Truck 2-6%	Lane width 10-12 ft; shoulder width 0-2 ft
	Presence of school zone	Driver action: did not have right of way
Head-on	Crash hour 1 A.M.-5 A.M.; highway not lighted	Crash hour 9 A.M.-1 P.M.
	No curvature; raining, snowing, or sleeting	ADT < 5,000; passing allowed
	Truck 2-6%	Moderate to steep grade; operational speed 50-55 mph
	ADT < 5,000; no passing allowed	Low cross-street density
	Lane width 10-12 ft; shoulder width 0-2 ft	Sharp curvature; raining, snowing, or sleeting
	Driver action: improper passing or turning	Truck 2-6%
	Crash day Tuesday -Thursday	Few to no chevrons
	Speed differential -5 to -10 (speeding)	Lane width < 10 ft; shoulder width 0-2 ft
		Crash day Friday-Sunday
Sideswipe	Steep grade; operational speed 50-55 mph	Steep grade; operational speed 50-55 mph
	ADT < 5,000; passing allowed	ADT < 5,000; passing allowed
	Low cross-street density	Crash hour 9 A.M. -1 P.M.
	Crash hour 9 A.M. -1 P.M.	No curvature
	No curvature; raining, snowing, or sleeting	Lane width < 10 ft; shoulder width 0-2 ft
	Truck 2-6%	Crash day Tuesday -Thursday
	Lane width 10-12 ft; shoulder width 0-2 ft	
Run-off-the-road	Steep grade; operational speed 50-55 mph	ADT < 5,000; passing allowed
	Low cross-street density	Steep grade; operational speed 50-55 mph
	ADT < 5,000; no passing allowed	Low cross-street density
	Crash hour 9 A.M.-1 P.M.	Crash hour 1 A.M.-5 A.M.; highway not lighted
	Driver age < 25	Driver age < 25
	Lane width 10-12 ft; shoulder width 0-2 ft	Truck 2-6%
	Truck 2-6%	Lane width 10-12 ft; shoulder width 0-2 ft
	Crash day Friday-Sunday	Crash day Friday-Sunday
Deer	Steep grade; some advisory signs; operational speed 50-55 mph	Low cross-street density
	ADT < 5,000; passing allowed	Steep grade; few advisory signs; operational speed 50-55 mph
	Low cross-street density	ADT 2,000-5,000; passing allowed
	Crash hour 9 A.M. -1 P.M.	Crash hour 9 A.M. -1 P.M.

	No curvature; raining, snowing, or sleeting	Moderate curvature; raining, snowing, or sleeting
	Truck 2-6%	Few chevrons
	Lane width 10-12 ft	Lane width < 10 ft
	Driver age < 25	Driver age < 25
Other	ADT < 5,000; passing allowed; turning lanes	Crash hour 9 A.M.-1 P.M.
	Low cross-street density	Steep grade; some advisory signs; operational speed 50-55 mph
	Crash hour 9 A.M.-1 P.M.	ADT > 5,000; passing allowed; turning lanes
	Steep grade; some advisory signs; operational speed 50-55 mph	Low cross-street density
	Lane width 10-12 ft	Crash hour 1 A.M.-5 A.M.; highway not lighted
	Truck 2-6%	Truck 2-6%
	Driver age < 25	Sharp curvature; raining, snowing, or sleeting
		Lane width 10-12 ft
		Driver age < 25

APPENDIX D

GLM RESULTS

The crash estimation equations, based on the negative binomial distribution, for each highway classification and collision type are as follows.

Rural Primary

$$\text{Rear End Crashes} = \exp(0.1392 + 0.0004 * \text{AADT} - 0.6168 * \text{Turn Lanes} - 4.6359 * \text{Grade} + 0.5551 * \text{Cross Street Density} + 3.7705 * \text{Stoplights})$$

$$\text{Angle Crashes} = \exp(1.3272 + 0.0002 * \text{AADT})$$

$$\text{Head-on Crashes} = \exp(-1.1305 + 0.0003 * AADT)$$

$$\text{Sideswipe Crashes} = \exp(0.6332 + 0.0003 * \text{AADT} + 0.8267 * \text{Passing Allowed} - 0.0012 * \text{Curvature})$$

$$\text{Run-off-the-road Crashes} = \exp(2.5757 + 0.0002 * AADT + 0.7659 * \text{Passing Allowed} - 0.0014 * \text{Curvature})$$

$$\text{Deer Crashes} = \exp(-0.3416 + 0.0003 * \text{AADT} + 1.446 * \text{Passing Allowed})$$

$$\text{Other Crashes} = \exp(1.5422 + 0.0002 * \text{AADT} - 0.0008 * \text{Curvature} + 0.0722 * \text{Chevrons})$$

Rural Secondary

$$\text{Rear End Crashes} = \exp(-0.3539 + 0.0006 * \text{AADT} + 0.0251 * \text{Speed Differential})$$

$$\text{Angle Crashes} = \exp(0.689 + 0.0005 * \text{AADT} - 0.2936 * \text{Chevrons})$$

$$\text{Head-on Crashes} = \exp(2.4805 + 0.0003 * AADT + 1.2605 * \text{Passing Allowed} - 0.5071 * \text{Lane Width})$$

$$\text{Sideswipe Crashes} = \exp(-0.1091 + 0.0003 * \text{AADT} + 0.485 * \text{Passing Allowed})$$

$$\text{Run-off-the-road Crashes} = \exp(2.6854 + 0.0003 * \text{AADT} - 0.0005 * \text{Curvature})$$

$$\text{Deer Crashes} = \exp(0.5103 + 0.0006 * \text{AADT})$$

$$\text{Other Crashes} = \exp(1.0185 - 7.2102 * \text{Grade} + 0.0003 * \text{AADT})$$

Urban Primary

$$\text{Total Crashes} = \exp(4.4527 + 0.0006 * \text{AADT} + 1.784 * \textit{Length} - 1.2843 * \text{Passing Allowed} - 349.989 * \text{Grade})$$

Urban Primary

$$\text{Total Crashes} = \exp(4.4527 + 0.0006 * \text{AADT} + 1.784 * \textit{Length} - 1.2843 * \text{Passing Allowed} - 349.989 * \text{Grade})$$

Urban Secondary

$$\text{Total Crashes} = \exp(-0.0441 + 0.0409 * \textit{OperationalSpeed} + 0.0002 * \textit{AADT} + 0.3888 * \textit{Length} + 0.2517 * \textit{CrossStreetDensity} + 0.0409 * \textit{Truck} - 0.0029 * \textit{Curvature})$$

APPENDIX E

SITES NEEDING CURVATURE IMPROVEMENT

Table E.1. Sites Needing Curvature Improvement

Site	Route Number	Begin Milepost	End Milepost	Posted Speed Limit (mph)	Minimum Radius (ft)[1]	Weighted Radius (ft)	Rehabilitation Required
303	16	26.21	31.9	45	540	646	No
312	42	38.05	47.52	55	877	1093	No
323	67	15.45	22.36	45	540	367	Yes
332	72	41.51	49.19	45	540	450	Yes
337	80	23.88	33.32	55	877	612	Yes
338	80	35.12	45.04	45	540	453	Yes
345	91	3.31	12.92	55	877	839	Yes
346	91	17.35	22.78	35	292	657	No
352	94	19.34	28.39	55	877	729	Yes
356	11	46.98	56.47	55	877	961	No
357	11	56.47	66.38	45	540	1100	No
358	21	5.5	11.41	55	877	791	Yes
364	52	58.13	67.96	55	877	424	Yes
368	58	88.91	94.03	55	877	800	Yes
377	460	0	9.65	40	410	1100	No
379	23	5.74	13.7	55	877	643	Yes
674	8	35.65	45.6	55	877	520	Yes
670	8	0	8.5	45	540	788	No
677	24	9.29	19.2	50	694	1055	No
684	40	44.44	50.21	55	877	986	No
689	43	9.32	16.94	55	877	499	Yes
711	57	10.86	19.03	45	540	1015	No
716	103	0	9.13	55	877	1043	No
717	116	0	9.5	55	877	850	Yes
719	122	7.38	17.2	45	540	988	No
720	122	17.4	27.31	55	877	919	No
731	58	204.32	213.44	55	877	971	No
737	221	43.09	52.92	55	877	861	Yes
740	221	68.71	77.9	55	877	923	No

[1]AASHTO, 2004.

continues

Table E.1. Sites Needing Curvature Improvement *(continued)*

Site	Route Number	Begin Milepost	End Milepost	Posted Speed Limit (mph)	Minimum Radius (ft)[1]	Weighted Radius (ft)	Rehabilitation Required
1053	41	4.73	14.5	55	877	1053	No
1057	45	20.28	29.87	55	877	1058	No
1073	57	75.85	85.75	55	877	1038	No
1075	92	16.57	23.18	55	877	935	No
1077	130	12.67	22.43	55	877	1039	No
1090	15	53.99	59.06	55	877	1100	No
1091	15	65.94	75.58	55	877	1100	No
1096	60	78.34	87.38	55	877	1050	No
1097	60	92.38	99.72	55	877	988	No
1101	60	142.26	150.7	55	877	1100	No
1103	501	28.29	38.25	55	877	880	No
1395	47	22.89	28.43	45	540	1091	No
1610	10	41.89	51.66	45	540	977	No
1801	2	34.25	43.85	45	540	1100	No
1830	208	33.64	42.52	50	694	797	No
2041	22	0	9.06	45	540	867	No
2046	53	0	9.51	45	540	548	No
2048	55	35.59	44.5	55	877	350	Yes
2049	208	0	8.9	55	877	972	No
2053	230	11.39	20.58	55	877	906	No
2059	15	98.5	107.87	55	877	897	No
2073	522	26.72	32.89	55	877	684	Yes
2326	42	204.17	212.95	55	877	993	No
2336	55	5.53	15.25	55	877	850	Yes
2337	55	18.29	25.5	45	540	990	No
2344	252	10.25	20.15	55	877	607	Yes
2350	259	5.38	14.41	55	877	1093	No
2356	11	188.23	194.19	55	877	915	No
2358	11	267.85	277.82	45	540	1063	No
2363	220	135.84	145.59	35	292	813	No
2373	250	49.03	54.26	35	292	1100	No
2375	340	19.62	29.51	55	877	964	No
2445	15	222.05	230.74	45	540	1000	No

[1]AASHTO, 2004.

APPENDIX F

NUMBER OF REAR-END CRASHES AT STUDY SITES FOR THE PERIOD 2001-2004

Table F.1. Number of Rear-End Crashes at Study Sites for the Period 2001-2004

Site Number	District[a]	Rural/ Urban	Route Number	Jurisdiction (County)	Begin Milepost	End Milepost	No. of Rear-end Crashes (2001-2004)
2441	9	U	234	Prince William	2.72	9.35	227
2397	9	U	674	Fairfax	0.21	7.24	153
2445	9	R	15	Loudoun	222.05	230.74	145
1170	4	U	604	Chesterfield	4.86	14.41	107
1407	4	U	144	Chesterfield	6.51	11.95	106
711	2	R	57	Henry	10.86	19.03	85
1176	4	U	654	Chesterfield	3.78	11.92	64
2036	7	U	20	Albemarle	31.01	36.73	59
1414	4	U	156	Hanover	51.15	60.58	57
1870	7	U	743	Albemarle	1.73	8.19	53
2046	7	R	53	Albemarle	0	9.51	53
337	1	R	80	Russell	23.88	33.32	51
720	2	R	122	Bedford	17.4	27.31	49
1371	4	U	5	Henrico	1.18	8.23	45
1609	5	U	5	James City	43.94	49.86	41
677	2	R	24	Bedford	9.29	19.2	39
719	2	R	122	Franklin	7.38	17.2	37
2373	8	R	250	Augusta	49.03	54.26	37
2411	9	U	659	Loudoun	7.81	17.11	37
1613	5	U	10	Suffolk	82.43	88.13	36
1830	6	R	208	Spotsylvania	33.64	42.52	31
2350	8	R	259	Rockingham	5.38	14.41	27
2375	8	R	340	Augusta	19.62	29.51	27
2041	7	R	22	Albemarle	0	9.06	26
1090	3	R	15	Prince Edward	53.99	59.06	22
1178	4	U	655	Chesterfield	9.58	15.17	22
2049	7	R	208	Louisa	0	8.9	22
2406	9	R	621	Loudoun	6.29	16.14	22
1101	3	R	60	Cumberland	142.26	150.7	21
1787	6	U	610	Stafford	0	7.31	20
2337	8	R	55	Warren	18.29	25.5	20
356	1	R	11	Smyth	46.98	56.47	17
1175	4	U	653	Chesterfield	4.39	10.31	17
2053	7	R	230	Madison	11.39	20.58	17
2059	7	R	15	Fluvanna	98.5	107.87	17
670	2	R	8	Patrick	0	8.5	15
2336	8	R	55	Shenandoah	5.53	15.25	15
2363	8	R	220	Bath	135.84	145.59	14
332	1	R	72	Dickenson	41.51	49.19	13

continues

Table F.1. Number of Rear-End Crashes at Study Sites for the Period 2001-2004 *(continued)*

Site Number	District[a]	Rural/ Urban	Route Number	Jurisdiction (County)	Begin Milepost	End Milepost	No. of Rear-end Crashes (2001-2004)
1607	5	U	620	York	0	6.87	13
2358	8	R	11	Rockingham	267.85	277.82	12
717	2	R	116	Franklin	0	9.5	11
1171	4	U	625	Chesterfield	0	7.44	11
1801	6	R	2	Caroline	34.25	43.85	11
2433	9	R	619	Prince William	15.47	24.58	11
674	2	R	8	Floyd	35.65	45.6	10
1040	3	R	20	Buckingham	8.83	18.74	10
1103	3	R	501	Halifax	28.29	38.25	10
1177	4	U	655	Chesterfield	0	9.58	10
345	1	R	91	Washington	3.31	12.92	9
1053	3	R	41	Pittsylvania	4.73	14.5	9
1624	5	U	125	Suffolk	0	6.24	9
1922	7	R	709	Montgomery	0	9.64	9
2100	8	R	612	Augusta	11.32	21.17	9
303	1	R	16	Smyth	26.21	31.9	8
684	2	R	40	Franklin	44.44	50.21	8
731	2	R	58	Carroll	204.32	213.44	8
740	2	R	221	Floyd	68.71	77.9	8
1091	3	R	15	Buckingham	65.94	75.58	8
2252	8	R	644	Rockingham	0	6.6	8
1843	7	R	614	Albemarle	6.24	11.55	7
1933	7	R	600	Fluvanna	0	8.6	7
2326	8	R	42	Augusta	204.17	212.95	7
338	1	R	80	Buchanan	35.12	45.04	6
364	1	R	52	Bland	58.13	67.96	6
588	2	R	683	Henry	0	8.29	6
1395	4	R	47	Mecklenburg	22.89	28.43	6
2356	8	R	11	Rockbridge	188.23	194.19	6
377	1	R	460	Buchanan	0	9.65	5
379	1	R	23	Wise	5.74	13.7	5
716	2	R	103	Patrick	0	9.13	5
829	3	R	615	Campbell	0	9.77	5
1481	5	U	665	Isle of Wight	0	6.76	5
1874	7	R	810	Albemarle	0	8.42	5
352	1	R	94	Wythe	19.34	28.39	4
539	2	R	674	Franklin	0	6.24	4
742	2	R	501	Bedford	82.36	92.29	4
962	3	R	622	Pittsylvania	0	9.61	4
1057	3	R	45	Cumberland	20.28	29.87	4
1096	3	R	60	Amherst	78.34	87.38	4
1097	3	R	60	Amherst	92.38	99.72	4
1491	5	U	628	Suffolk	0	5.26	4
312	1	R	42	Bland	38.05	47.52	3

continues

Table F.1. Number of Rear-End Crashes at Study Sites for the Period 2001-2004 *(continued)*

Site Number	District[a]	Rural/ Urban	Route Number	Jurisdiction (County)	Begin Milepost	End Milepost	No. of Rear-end Crashes (2001-2004)
368	1	R	58	Washington	88.91	94.03	3
526	2	R	634	Franklin	0	9.03	3
737	2	R	221	Floyd	43.09	52.92	3
1026	3	R	630	Prince Edward	10.37	18.97	3
1045	3	R	26	Appomattox	0.5	8.49	3
1077	3	R	130	Amherst	12.67	22.43	3
1179	4	U	667	Chesterfield	0	9.97	3
2103	8	R	616	Augusta	0	9.42	3
54	1	R	607	Dickenson	1.69	7.86	2
264	1	R	640	Wise	0	8.96	2
323	1	R	67	Tazewell	15.45	22.36	2
346	1	R	91	Washington	17.35	22.78	2
357	1	R	11	Wythe	56.47	66.38	2
358	1	R	21	Grayson	5.5	11.41	2
577	2	R	610	Henry	0	9.46	2
849	3	R	699	Campbell	0	9.15	2
1046	3	R	40	Pittsylvania	50.21	59.34	2
1075	3	R	92	Charlotte	16.57	23.18	2
1762	6	R	601	Spotsylvania	0	8.78	2
1967	7	R	613	Louisa	16.85	23.89	2
2111	8	R	664	Augusta	0	6.7	2
2132	8	R	865	Augusta	0	9.71	2
2313	8	R	638	Warren	6.67	15.37	2
2344	8	R	252	Augusta	10.25	20.15	2
2	1	R	606	Bland	0	9.85	1
123	1	R	615	Russell	2.18	11.69	1
185	1	R	600	Smyth	7.86	15.67	1
459	2	R	670	Carroll	1.5	10.75	1
689	2	R	43	Bedford	9.32	16.94	1
793	3	R	602	Buckingham	0	8.69	1
801	3	R	610	Buckingham	0	9.74	1
877	3	R	727	Charlotte	0.28	9.7	1
1015	3	R	863	Pittsylvania	8.17	14.8	1
1043	3	R	24	Appomattox	71.06	80.86	1
1073	3	R	57	Halifax	75.85	85.75	1
1413	4	U	156	Henrico	31.95	41.78	1
1493	5	U	634	Suffolk	1.35	6.88	1
1857	7	R	664	Albemarle	0	5.93	1
1969	7	R	618	Louisa	0	9.29	1
2048	7	R	55	Fauquier	35.59	44.5	1
2073	7	R	522	Louisa	26.72	32.89	1
2110	8	R	657	Augusta	0	6.22	1
2172	8	R	628	Frederick	0	8.05	1
2285	8	R	675	Rockbridge	12.33	17.94	1

continues

Table F.1. Number of Rear-End Crashes at Study Sites for the Period 2001-2004 *(continued)*

Site Number	District[a]	Rural/ Urban	Route Number	Jurisdiction (County)	Begin Milepost	End Milepost	No. of Rear-end Crashes (2001-2004)
60	1	R	637	Dickenson	0	9.37	0
77	1	R	607	Grayson	0	7.72	0
225	1	R	650	Tazewell	0	7.51	0
461	2	R	683	Carroll	0	9.94	0
486	2	R	610	Floyd	0	9.6	0
540	2	R	678	Franklin	0	6.61	0
623	2	R	627	Patrick	0	5.83	0
830	3	R	615	Campbell	9.77	18.27	0
970	3	R	640	Pittsylvania	9.94	19.32	0
1009	3	R	841	Pittsylvania	0	8.77	0
1220	4	R	606	Goochland	0	9.77	0
1610	5	R	10	Sussex	41.89	51.66	0
1894	7	R	685	Culpeper	0	8.98	0
1934	7	R	601	Fluvanna	0	9.36	0
2245	8	R	613	Rockingham	5.32	14.91	0
2260	8	U	724	Rockingham	0.00	5.30	0
2303	8	R	603	Warren	0	5.2	0

[a]Districts

1 - Bristol 2 - Salem 3 - Lynchburg
4 - Richmond 5 - Hampton Roads 6 - Fredericksburg
7 - Culpeper 8 - Staunton 9 - Northern Virginia