Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves

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FOREWORD

Horizontal curves represent a significant safety problem on two-lane rural roads. For example, the accident rates on curves are one and a half to four times higher than similar tangent sections of roadway.

This report documents the results of a research study that developed relationships between various geometric features of horizontal curves and accidents. These features are: degree of curve, length of curve, roadway width, presence of a spiral, superelevation, roadside condition, and average daily traffic.

This report, "Cost-Effective Geometric Improvements for Safety Upgrading of Horizontal Curves," (Report No. FHWA-RD-90-021) will be of interest to persons performing research in the area of geometric design and to highway design engineers interested in the background material used to develop Report No. FHWA-RD-90-074, "Safety Improvements on Horizontal Curves for Two-Lane Rural Roads - Informational Guide." Report No. FHWA-RD-90-074 provides a step by step procedure for estimating the safety impacts of various geometric improvements at horizontal curves.

Sufficient copies of Report No. FHWA-RD-90-021 are being distributed to provide a minimum of one copy to each Region and Division Office and State highway agency. Direct distribution is being made to the Division Offices. Additional copies for the public are available from the National Technical Information Services (NTIS), Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. A small charge will be imposed by NTIS.

RJ Betsold

R. J. Betsold, Director
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NOTICE

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FHWA contract managers: George Pilkington, Justin True (HSR-20)
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16. Abstract

The purpose of this study was to determine the horizontal curve features which affect safety and traffic operations and to quantify the effects on accidents of various curve-related improvements. The primary data base developed and analyzed consisted of 10,900 horizontal curves in Washington State. Three existing Federal data bases on curves were also analyzed. These data bases included the cross-section data base of nearly 5,000 mi (8,050 m) of roadway from 7 States, a surrogate data base of vehicle operations on 78 curves in New York State, and 3,277 curve segments from 4 States.

Based on statistical analyses and model development, variables found to have a significant effect on accidents include degree of curve, roadway width, curve length, ADT, presence of a spiral, superelevation, and roadside condition. Curve flattening is expected to reduce accidents by up to 80 percent, depending on the amount of flattening. Widening lanes or shoulders on curves can reduce curve accidents by as much as 33 percent, while adding spiral transitions on curves was associated with a 5-percent accident reduction. Improving deficient superelevation can reduce accidents by 10 percent or more, while the effects of specific roadside improvements were also quantified. An economic analysis was conducted to determine when curve flattening and/or widening are cost effective.

An informational guide entitled "Safety Improvements on Horizontal Curves for Two-Lane Roads" (FHWA-RD-90-074) was developed in conjunction with this report to give specific guidance for the design of new curves and for upgrading existing curves.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

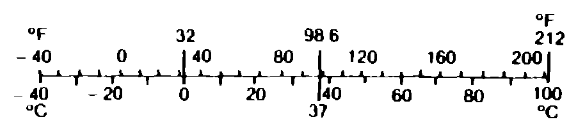
Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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CHAPTER 1 - INTRODUCTION

Background

Horizontal curves represent a considerable safety problem on rural two-lane highways. A 1980 study estimated that there are more than 10 million curves on the two-lane highway system in the U.S.[1] Accident studies further indicate that curves experience a higher accident rate than do tangents, with rates that range from one and a half to four times higher than similar tangents.[2]

While accidents on horizontal curves have been a problem for many years, the issue may perhaps be more important in light of improvements being made related to resurfacing, restoration, and rehabilitation projects, commonly known as the 3R program. These improvements generally consist of selective upgrading of roadways within the available right-of-way usually following the existing alignment. Because the surface of the road must be continually repaved to protect the underlying roadbed structure, the issue of what else should be done at horizontal curves to enhance (or at least hold constant) the level of safety is critical at this time.

A variety of questions remain unanswered, such as which curves (with which characteristics) should be improved to gain the maximum safety benefits per dollar spent, and which countermeasures could be expected to produce this benefit at a specific curve. Part of the reason for this current lack of knowledge is that many of the past research studies have concentrated on only one aspect of the horizontal curvature question (e.g., degree of curve, pavement widening, etc.). Another reason has been the research community's difficulties in consolidating all of the knowledge gained from past evaluations in a scientifically sound manner. While there is general knowledge of the types of countermeasures that can be implemented at horizontal curves, little is known of the true effectiveness of these countermeasures. Also, there currently is no easily usable and readily available guide for determining which of the potential countermeasures will provide the biggest benefit per dollar spent or which should be used for a curve with a combination of specific characteristics.

Thus, there has been a need to better quantify accident and operational effects of curve features and to quantify the effects on accidents of curve flattening, curve widening, addition of spiral transitions, improvement to deficient superelevation, and improvements to the roadside. Vehicle operations also need to be determined for various curve features, since traffic operational measures can be indicative of excessive driver delay, sudden vehicle braking, potential loss of vehicle control on curves, as well as the potential for accident problems. In addition, the costs of various curve improvements need to be determined and used along with accident benefits to determine which improvements are cost effective under various roadway conditions.

Study Objectives and Scope

The major objectives of this study were to:

1. Determine the horizontal curve features which affect safety and traffic operations on various highway sections influenced by traffic volume, vehicle speed, and other factors.

2. Determine those countermeasures for existing horizontal curves which will improve safety and operations.

3. Develop and use a procedure to assess the benefits and costs of these countermeasures and provide guidelines on curve conditions in which various countermeasures are cost-effective. A methodology should also be developed for use by local agencies in evaluating countermeasures at specific curve sites.

This study included a detailed review and critique of available safety research and traffic operational literature on horizontal curves and related countermeasure effectiveness. Significant issues and gaps in available knowledge were also identified, and relevant curve data bases were identified and critically reviewed for usefulness in addressing these key issues. This led to the study research design, as discussed in chapter 3. The study next involved an analysis of hard-copy reports of curve accidents in North Carolina to gain insights into the types of crashes which occur on rural, two-lane curve sections.

A data base was developed of 10,900 horizontal curves in Washington State with corresponding accident, geometric, traffic, and roadway data variables.

This data base was analyzed along with an existing FHWA data base of 3,277 curves from four States to quantify the accident effects of degree of curve, roadway width, superelevation, presence of spiral transition curves, and other curve features.[2] From these developed accident relationships, accident reductions were determined which are expected due to curve flattening, lane and shoulder widening on curves, adding transition spirals on curves, and improving deficient superelevation.

The expected accident effects of specific roadside improvements on curves (e.g., clearing trees, relocating utility poles, flattening sideslopes), were quantified based on a data base of approximately 5,000 mi (8,050 km) of rural, two-lane roads in seven States.[3] The roadway factors affecting vehicle operations on curves were analyzed using an existing data base of 78 curves from the State of New York.[4] Based on expected effects of various curve improvements on crashes and vehicle operations, an economic analysis was conducted. General guidelines are provided for safer curve designs and for improvements to existing curve for various traffic and geometric conditions. This study deals with horizontal curves on two-lane rural roads only.

CHAPTER 2 - CRITICAL REVIEW OF LITERATURE

A review and critique was conducted of articles and/or abstracts for more than 200 articles, reports, and publications related to safety and operations on horizontal curves. The criteria used in selecting literature for detailed critical reviews were as follows:

Criterion 1: Articles should be reasonably current. Studies no older than about 25 years are most appropriate in general, since current accident data bases (if taken from States with relatively good data sources) would more likely correspond to present accident relationships. Also, vehicle characteristics differ today compared to 25 to 40 years ago, in terms of size (minicars versus large cars), acceleration and braking ability, truck sizes (longer and wider trucks) and weights, use of occupant restraints (i.e., safety belts), and other factors. Another reason for using more recent studies is that pavement delineation (i.e., edgelining with paint beads), signing practices, and pavement surfaces differ today compared to 25 years ago.

Criterion 2: Studies should be of reasonable validity. Studies were omitted which (1) contain one or more "fatal" flaws (i.e. obvious major errors in their methodology, data base, or analyses as discussed later), or (2) include data for extremely low sample sizes (e.g., at the extreme, one excluded study had data from only one site).

Criterion 3: Studies should contain "real" data on accidents or vehicle operations. Studies were excluded which contained only the results of laboratory tests of driver responses at curves or merely the authors' opinions or discussion of horizontal curve designs. Studies were considered for detailed review and critique only if they contained information on one or more of the following issues:

- Accident effects of geometric features on curves.
- Operational effects of roadway features on curves.
- Countermeasure evaluation (accident-based or operations-based) on curves.

Criterion 4. Articles must contain information and results for two-lane rural horizontal curves. While hundreds of publications could have been reviewed involving accident relationships with some roadway features or effectiveness of countermeasures on various roadway types, the review was limited to studies containing information specifically on horizontal curves (or for which a horizontal curve was a variable in the analysis).

Eleven articles and publications were selected for further analysis, as summarized in table 1. (See references 2 and 4 through 13.) Of the 11 studies, 7 involved attempts to quantify relationships between accidents and various geometric and/or curve-related roadway features. Of these seven studies, those by the Federal Highway Administration (FHWA), and Deacon involved data collection and analyses on individual curve sections, while studies by Dart and Mann, and Jorgensen, involved accident modelling for roadway segments where horizontal curvature (e.g., percent of section 3 degrees or greater) was one of several variables in the model.[2,4,9,10,5,6] The Zador study used sites of fatal rollover crashes and comparison sites to determine effects of superelevation.[7] Only one study, Taylor and Foody, involved an accident evaluation of actual field countermeasures (i.e., delineation treatments).[8]

Operational measures (e.g., lateral vehicle placement, speed changes) were used to measure the effects of curve characteristics in several studies by the FHWA.[2,4,9] Curve-related countermeasures were evaluated using operational measures in studies by Jennings and Demetsky, Rockwell and Hungerford, and Rockwell.[11,12,13] The 1983 FHWA study was the only one which included results of vehicle simulations on curves using the Highway-Vehicle-Object Simulation Model (HVOSM).[2] In addition to the 11 publications mentioned above, more general information on relationships between accidents and numerous roadway features is contained in the literature summary by Jorgensen and the critical review of literature by the FHWA.[6,14]

Each of the 11 articles was reviewed for such basic information as its objective, data collection procedures, analysis method, and results. Then a critical analysis was conducted of each using the following seven criteria:

1. Did authors consider relevant variables?
2. Did errors exist in data collection?

Table 1. Summary of studies selected for critical reviews.

Author(s)	Date	States Included	TYPE OF STUDY					
			Evaluation of Countermeasures		Accident Relationships with Design Features		Vehicle Operations on Curves	HVOSM
			Accident Study	Operational Study	Curve Sections	General Two-Lane Roads		
Dart and Mann	1970	Louisiana				X		
Jorgensen and Assoc.	1978	Washington,* Maryland				X		
Glennon, Newman & Leisch	1983	Texas, Ohio, Florida, Ill.			X		X	X
Zador, Stein, Hall, and Wright	1985	New Mexico, Georgia				X		
Taylor and Foody	1966	Ohio	X					
Terhune and Parker	1986	New York** Alabama, Ohio			X		X	
Datta, Perkins, Taylor & Thompson	1983	Michigan			X		X	
Deacon	1986	Texas, Ohio Florida, Ill.			X			
Jennings & Demetsky	1985	Virginia		X				
Rockwell & Hungerford	1979	Ohio		X				
Rockwell, Malecki & Shinar	1975	Ohio		X				

*New York State was used for data collection initially, but excluded for development of accident relationships.
**Data from Alabama and Ohio were used for validating the predictive models developed from sites in New York State.

3. Was data detail sufficient?
4. Were sample sizes large enough?
5. Were statistical assumptions met?
6. Were proper statistical tests used?
7. Did authors correctly interpret the results?

In addition, for each article, the implications to the current HSRC study were determined. A discussion of the highlights of the literature review are given on the following pages.

Geometric Design Features and Accidents

Several studies were reviewed which provided information on relationships between roadway geometric features and accidents. In the early phases of three FHWA studies, variables were listed which were believed to be related to accidents on horizontal curves, based on their review of the literature and also on judgment.[2,4,9] Twenty roadway variables were mentioned, by one or more of the studies, as having strong potential relationships to accidents, or as having a promising or potential accident relationship, as shown in table 2. The FHWA four-State curve study mentions 17 of the 20 variables, while the New York and Michigan studies of accident surrogates mention 12 and 7 variables, respectively, as accident-related based on their reviews of the literature.[2,4,9] The authors of all three studies then used their lists of potential variables in selecting which variables to collect and analyze, in order to verify which variables are indeed related to accidents and/or vehicle operations on curves.

In terms of accident relationships with horizontal curvature, Dart and Mann, and Jorgensen and Associates both attempted to develop accident predictive models based on roadway and geometric features on sections of two-lane rural roads.[5,6] The model by Dart and Mann used "percent of section > 3 degrees" as a variable in its model.[5] However, this factor accounted for only a 7 percent difference in total accident rate between a nearly tangent section and a section with nearly continuous horizontal curves. Jorgensen found a 13 percent lower accident rate for short highway sections with less than 3 degree curves, compared to sections with horizontal curvature of 3 degrees or more.[6]

Table 2. Summary of roadway variables reported to be safety-related based on literature review and/or subjective judgments from three studies.

Roadway Variables	FHWA Curve Study (2)	New York Surrogate Study (4)	Michigan Surrogate Study (9)
Degree (Radius) of Curve	P	S	S
Length of Curve	P	P	
Superelevation (Rate or Maximum Value)	P		P
Superelevation Deficiency		P	
Superelevation Runoff Length	P		
Distribution of Superelevation (Between Tangent and Curve)	P		
Presence and Length of Transition	P		
Stopping Sight Distance on Curve (or Approach)	P		
Lane Width	P	P	P
Shoulder Width	P	P	
Shoulder Type	P	P	
Shoulder Slope	P		
Roadside Hazard (Sideslope and Clear Zone)	P	P	
Vertical Alignment Elements	P	S	S
Distance to Adjacent Curves	P		
Presence/Distance to Nearest Event (Intersection, Bridges)	P		
Number of Access Points on Curve		P	
Pavement Friction	P	P	P
Presence and Type of Traffic Control Devices (Signs and Delination)	P	S	P
Traffic Volume		S	P

S = cited as "strong" in terms of potential relationship to accidents at horizontal curves.

P = "promising" or potential relationship to accidents.

Several accident research studies involved analyzing accident and roadway data specifically on horizontal curve segments to determine accident-related variables, as summarized in table 3. The four-State curve study represents the most comprehensive study conducted to date on the safety of horizontal curve sections.(2) Using an analysis of variance on 3304 curve sections with only roadway variables, those found to have a significant association with total accident rate included:

- Length of curve.
- Degree of curve.
- Roadway width.
- Shoulder width.
- State.

A discriminant analysis (which included additional data items for 333 sites) revealed that the variables significant in predicting low and high-accident sites include:(2)

- Length of curve.
- Degree of curve.
- Shoulder width.
- Roadside hazard rating.
- Pavement skid resistance.
- Shoulder type.

While these results were useful for predicting high-accident curve sites, they did not provide adequate measures of expected accident reductions due to curve improvements (e.g., curve flattening, roadside improvements, pavement surfacing).

Deacon further analyzed the FHWA four-State curve data base to better quantify the expected change in accidents due to various types of geometric curve improvements.(10) Based on data tabulations, a model was derived for estimating the number of accidents on curved segments. Then expected accident reduction percentages were computed due to horizontal curve flattening projects. For various central angles and degrees of curve (before and after improvement), expected accident reductions from curve flattening range from 16 to 83 percent. These results may be the best available information on previous studies of the effects of curve flattening projects on horizontal curves.

Table 3. Summary of accident relationship found in previous research on horizontal curves.

Roadway Variables	FHWA Curve Study (2) High/Low Subset (333 sites)	FHWA Curve Study (2) Total Curve (3304 sites)	New York Surrogate Study (4) (78 sites)	Michigan Surrogate Data Base(9) (25 sites)
Length of Curve	S	S	N	
Degree of Curve	S	S	S	S (ROR)
Roadway Width	N	S		
Shoulder Width	S	S	N	N
Superelevation	N			
Superelevation Deficiency (Error)	N		N	S (ROR)
Superelevation Transition Length	N			
Superelevation Distribution	N			
Sight Distance to Curve	N			
Horizontal Alignment on Curve App.	N			
Vertical Alignment on Curve Approach	N		N	N
Roadside Hazard Rating	S		N	
Pavement Condition	N			
Pavement Skid Resistance	S			
Curve Signing	N		N	
Pavement Markings	N			
Presence of Driveways, Structures		N		
Shoulder Type	S			
ADT	N	N	S	S (RE)
State	N	S		
Sideslope Angle				S (RE)
Distance to Last Event			N	S (OL)
Fixed Object Rating				N
Type of Accident Measure	High & Low Acc Sites	Total Acc. Rate	Total Acc. Rate	Acc. Rates by Type

N = Collected but not found to be significant.

S = Significantly related to accidents.

Accident Types given in parentheses = ROR = Run-off-road
OL = Outside lane
RE = Rear-end

Accident reductions for other curve-related improvements (e.g., roadside improvements, pavement surfacing, adding proper superelevation, pavement widening) also need to be quantified for comparing with curve flattening projects.

Studies of accident surrogates on curves in New York and Michigan attempted to quantify accident relationships for both geometric and operational types of measures based on a more limited number of curve sites (78 and 25 sites, respectively).[4,9] Of nine basic variables tested, the New York surrogate study found that only degree of curve and average daily traffic (ADT) have significant effects on total accident rate.[4] The Michigan surrogate study concluded that degree of curve and superelevation deficiency have significant relationships to run-off-road (ROR) accident rates; ADT and sideslope angle were related to rear-end accident rates; and the distance to last event was related to outer-lane accident rates.(9)

A study by Zador found that the superelevation rates at fatal crash sites after adjusting for curvature and grade were deficient compared to those at comparison sites.[7] The authors conclude that "inadequate superelevation presents a risk that should be eliminated from the roadway system." Although one of the basic study assumptions (i.e., that the occurrence of a fatal accident is the result solely of superelevation deficiency at the crash sites and not partly due to other site problems), the laws of physics do suggest the need for adequate superelevation on sharp horizontal curves.

Vehicle Operations on Curves

One phase of the FHWA four-State curve study involved monitoring vehicle speeds and lateral placement through five horizontal curves in Illinois and Ohio. For data collection purposes, a stationary, high-speed motion picture camera was placed in a parked vehicle on the roadside opposite the traffic lane to be studied.[2] Markers were placed on the roadway and served as references to measure speed and lateral placement. Some of the key findings relative to curves of that analysis were:[2]

(1) Drivers tend to overshoot the curve radius, producing minimum vehicle path radii sharper than the highway curve. Furthermore, the tendency to overshoot is independent of speed.

(2) Drivers position themselves in advance of the curve to effect a spiral transition. Drivers who spiral gradually tend to produce less severe path radii.

(3) The tangent alignment immediately in advance of the curve is a critical region of operations. At about 200 ft (60 m) before the beginning points of the curve, which is about 3 seconds of driving time, drivers begin simultaneously adjusting both their speed and path. Such adjustments are particularly large on sharper curves.

(4) Points (2) and (3) demonstrate the significant operational benefits of spiral transitions to highway curves. Spirals of sufficient length enable the driver to adjust both speed and path in a manner that reduces or eliminates severe overshoot of the curve radius, thereby preventing the build-up of excessive levels of lateral acceleration.

(5) Both the speed studies and vehicle traversal studies point out the criticality of sharp, underdesigned curves on high-speed highways. The combination of high speeds and overshoot path behavior produces highly critical dynamics for much of the vehicle population on underdesigned curves.

(6) Present highway curve design policy presumably equalizes the dynamic effects of curve radius and superelevation. However, drivers tend to overshoot the curve radius. This behavior effectively increases the importance of curvature relative to superelevation. Therefore, under present design policies for curves, milder curves with lesser superelevation produce lower friction demands than presumably equivalent sharper curves with greater superelevation.

Vehicle speed data were also observed by the authors on 25 to 30 free-moving vehicles as they traversed 60 curve approaches.[2] A total of 1,400 radar-gun speeds were recorded at 4 points entering each curve. The sharpness of the impending curve was the factor which most explained speed changes by the driver. Drivers tend to begin adjusting their speeds only as the curve becomes imminent. For milder curves (less than 4 degrees), speed changing is slight, whereas on curves of 6 degrees or sharper, speed reduction increases linearly with increasing degree of curve. Further, only a slight difference in speed was found for narrow vs wide roadways.[2]

Jennings and Demetsky collected traffic volume, vehicle speed, and lateral placement data at five curve sites in Virginia using a traffic recorder with tapeswitch installations.(11) Although the primary focus of the study was to evaluate the effects of post-mounted delineator systems, the authors also analyzed driver responses in general at eight other sites. Similar average speeds, vehicle placements, and centerline encroachments were observed at various sites which had similar delineators (i.e., chevrons). Vehicles were found to travel further from the roadway edge when delineation was present.(11)

The New York surrogate study collected such operational measures as traffic volume, vehicle centerline and edgeline encroachments, and speed reduction by lane in addition to geometric and accident data at 78 horizontal curve sites. Those operational measures found to be related to accident rate included traffic volume (outer lane and total), average speed reduction (outer lane), rate of centerline encroachments (outer lane), and edgeline encroachments (inner lane and total vehicles). However, none of the operational measures were included in the best fitting accident predictive models.(4)

In an FHWA study on accident surrogates, several operational measures were collected at 25 curve sites, including (1) encroachment rate (number of edgeline plus centerline touches per 100 vehicles entering the curve), (2) speed differential of vehicles in the outside travel lane (between points on the curve approach and the curve midpoint), (3) speed differential for inner lane travel, and (4) average speed reduction efficiency (ratio of observed speed reduction to desirable speed due to curvature and superelevation averaged for both directions of travel).(9) Speed differential and traffic volume were the only operational measures included in any of the best fitting accident predictive models along with several non-operational (sideslope, degree of curve, superelevation error, etc.) variables.

Several studies also used operational measures to evaluate the effectiveness of various curve delineation treatments. Examples include two studies by Rockwell in Ohio; and a study by Jennings and Demetsky in Virginia.(12,13,11) These are discussed in the next section.

Countermeasure Evaluation on Curves

Of the 11 articles and publications which were critically reviewed, four contained results of evaluations of low-cost treatments (e.g., signs and markings) on curves. These included studies by Taylor and Foody, Jennings and Demetsky, and two studies by Rockwell.(8,11,12,13)

In the 1975 study by Rockwell, five curve modifications at five rural Ohio sites were evaluated:(13)

- Transverse striping beginning 1,100 ft (335 m) prior to the curve with gradual decreasing spacing to the beginning of the curve.
- Widening the inside edge marking to accent the inside perspective angle.
- Using the Wendt illusion, herring bone lines 500 ft (152 m) prior to the curve with decreased line spacing into the curve, to cause an illusion of road narrowing prior to the curve.
- Use of a "deceptive curve" sign.
- Use of a deceptive curve sign along with a diamond painted on the pavement prior to the signs.

Numerous operational measures (such as eye-movements, control movements, and speed and acceleration) were collected for test drivers for periods before modification, immediately after modification, and 30 days after modification. Likewise, speed profiles, severe lateral displacement, and following curve speed were collected for regular road users. The most effective treatment was the inside perspective angle modification. The signing treatments were largely ineffective. Also, subsequent curve speed measures indicated that little carryover effect was present. On the positive side, the modifications tended to reduce speed variance, primarily through a reduction at the high end of the speed distribution. Overall, the authors concluded that the use of pavement markings on rural curves could be beneficial, particularly for transient drivers since deceptive curve problems tend to be quickly noted by local drivers.

In a later study, Rockwell tested six delineation treatments at six rural sites near Columbus, Ohio. These included:(12)

- Six standard post delineators.
- One large chevron followed by carsonite delineators.
- Three large chevron delineators.
- Six standard delineators arranged in increasing height and distance from the roadway, known as the ascending in/out (AIO) pattern.
- Transverse (reflective) striping with decreasing spacing.
- Raised pavement markers (life lites) mounted on the centerline.

Speed and lateral placement measures were collected at six points into the curve using tape switches and radar devices, driving periods before treatment, the same day after treatment, and 2 to 4 weeks after treatment. Eye movements were also recorded for test subjects. The three large chevron signs and carsonite delineators were not very effective, whereas the AIO delineators, life lite delineators, and transverse stripes all showed some positive results. Long-term effects were much less than "the night after" period, probably due to adjustments by local drivers. The authors recommend the selective use of novel delineation systems at such locations as two-lane rural curves with high nighttime accident rates and a high proportion of transient drivers (since such delineation systems are considered to be more effective on transient drivers than on local drivers).(12)

Jennings and Demetsky conducted an operational evaluation of three types of post-mounted delineation systems in use in Virginia. These systems included:(11)

- 3 by 8-in (7.6 by 20.3-cm) reflectors on wooden posts.
- 6 by 48-in (15.2 by 121.9-cm) special-striped delineators.
- Chevron alignment signs.

An illustration of these three delineators are given in figure 1.

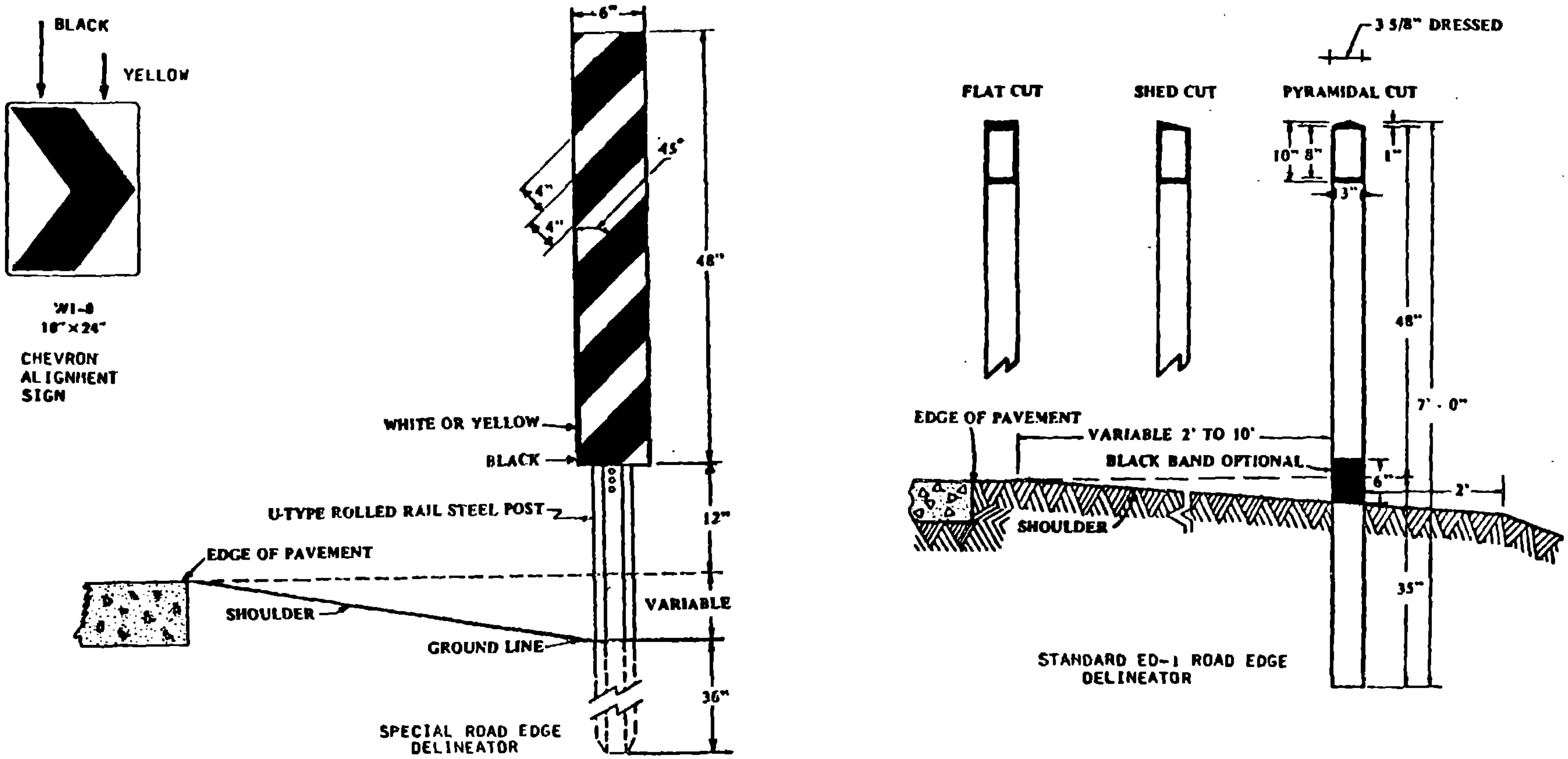

Figure 1. Delineator alignment signs tested in Virginia.(11)

1 ft = 0.3048 m
1 in = 2.54 mm

Changes in vehicle speed and lateral placement were measured at each of the five test sites (where the three delineator systems were alternately installed) using a Lerrpold and Stevens traffic data recorder. For the two curve sites with the greatest degree of curvature (greater than 7 degrees), the chevron signs produced the best results in terms of lowest centerline encroachments and better vehicle placement. At the three sites with more gentle curvature (i.e., 4 or 5 degrees), the standard and special delineators (particularly the standard delineators) were more effective than the chevron signs.(11)

The evaluation of post delineators on curves was evaluated by Taylor and Foody in Ohio at 557 curve sites using accident data.(8) Comparable accident data were also collected at 357 similar control sections where delineators were not installed. For the total delineation program in Ohio, significant reductions were found in total accidents (.05 level). The greatest reduction (29.7 percent) in total accidents was found for curves with a degree of curvature of 5 to 10 degrees combined with central angles of between 20 and 40 degrees. Treated curve sites with degree of curve and central angle outside of this range experienced an 11 percent accident reduction.(11)

Vehicle Simulation on Curves

HVOSM (Highway-Vehicle-Object Simulation Model) is a computerized mathematical model, originally developed and refined by Calspan Corporation (formerly Cornell Aeronautical Laboratories), which is capable of simulating the dynamic responses of a vehicle traversing a three-dimensional terrain configuration. Of the various research studies conducted on vehicle simulation using HVOSM, the FHWA four-State curve study was the only one found which was oriented toward vehicle simulations on horizontal curves. In fact, the authors attempted to use HVOSM to address the following four objectives:(2)

- Demonstrate the applicability of HVOSM as a tool for studying the dynamic responses of vehicles traversing highway curves.
- Study the sensitivity of tire friction demand, vehicle placement, and vehicle path for critical vehicle traversals to various highway design parameters.

- Study the sensitivity of tire friction demand and driver discomfort for moderate encroachments onto the shoulder of highway curves with various cross-slope breaks.
- Study the rollover potential of moderate vehicular encroachments onto various roadside slopes on highway curves.

A 1971 Dodge Coronet was used by the authors as the test vehicle. A fixed wagon-tongue or probe length (of 0.25 seconds) was assumed for simulating driver response to the vehicle path tracking the curve. Runs were made using unspiraled highway curves with superelevation runoff lengths similar to those specified by the American Association of State Highway and Transportation Officials (AASHTO). The superelevation runoff was distributed 70 percent on the tangent and 30 percent on the curve.

Simulation runs revealed findings relative to several geometric and curve design features. The results suggest that an existing highway curve that is underdesigned for the prevailing operating speed can present a severe roadway hazard. Also, the addition of spiral transitions to highway curves dramatically reduces the friction demands of the critical vehicle traversals. Examination of roadside slope characteristics showed that skidding is very likely for even mild roadside slopes (6:1) and that on unstabilized roadside surfaces, there is a high expectation of vehicle rollover.

In terms of the usefulness of the HVOSM techniques for horizontal curve simulations, the authors note success in replicating maximum dynamic response of extreme vehicle behavior on curves. They also note, however, that the simulated rate of vehicle spiraling was more severe than those observed in the field. Further, the authors suggest a more complex model for driver preview of the curve (i.e., since drivers' preview is longer on the curve approach than while the vehicle is actually negotiating the curve).

Effective Horizontal Curve Designs and Countermeasures

Several sources of information were used in compiling a list of potential design improvements and other countermeasures (e.g., delineation, guardrail, signing, etc.) at horizontal curve sites, including:

- Review and critique of literature on countermeasures.
- Discussions and other information from State and local highway agencies.

Design Improvements on Curves

A summary is given in table 4 of eight potential design improvements, along with conditions where they would most likely be effective and other pertinent information. Of these eight curve-related design improvements, one of them (i.e., constructing curves of near-constant degree of curvature and/or adding spiral transitions) usually pertains to new road construction. Curve flattening is usually quite costly and is most likely to be cost effective at accident curve locations. Improvements to superelevation, however, can often be implemented as a part of routine pavement overlays. Roadside improvements, such as sideslope flattening and roadside obstacle removal are treatments to minimize the adverse effects for vehicles after they have run off the curves and/or to better enable the vehicles to recover back onto the roadway.

Other Curve Treatments

In addition to improvements to the roadway design at horizontal curves, numerous other treatments have been used, including:

- Signs (chevron alignment signs, advisory speed signs, arrow board signs, deceptive curve sign, curve warning signs, etc.).
- Delineators (striped delineator panels, post-mounted reflectors, raised pavement markers, reflectors on guardrail, trees, utility poles.
- Pavement markings (wide edgelines, reflectorized edgeline and/or centerline, transverse striping with decreasing spacing, widening of inside of curve, Wundt illusion, reflectorized paint on trees, etc.).
- Signals (flashing beacons with warning signs).
- Guardrail.
- Others (e.g., rumble strips on pavements, crash cushions, etc.).

Not all of these treatments are known to be effective based on previous studies, and in fact, the actual effect of most of them is largely unknown.

Table 4. Summary of potential design improvements for horizontal curves.

Design-Related Improvement	Limitations of Effective Use	Comments
1. Curve Flattening	1. Particularly appropriate for sharp curves (particularly 10 degrees or greater) with central angels of 10 degrees or more. 2. Also useful for sharp curves at the end of a long tangent (where driver expectancy problem exists). 3. Should be considered for sharp curves with a high experience of run-off-road accidents, since curve flattening is expensive, and such expensive treatments of relatively low accident curves would not likely be cost effective and may be correctable through improved delineation or signing.	1. TRB study includes a table of expected accident reductions (16 to 83 percent) 83 percent) which are expected due to curve flattening improvements. (10)
2. Provide adequate superelevation	1. AASHTO Standards should be used. 2. This treatment can be most practically applied to a series of curves during routine pavement resurfacing.	1. Superelevation on a curve may change over time based on pavement wearing and settling, and through uneven pavement overlays.
3. Providing spiral transitions	1. This is most practically applied to curves on new roads, or through widening existing curves and curve approaches and providing painted edgelines and centerlines to approximate a spiral transition. 2. Most appropriate for sharp curves.	1. On rural areas near Phoenix, AZ, spirals are installed on existing curves after widening and restriping.
4. Curve Widening (Lane and Shoulder Improvements, Including Surfacing)	1. Pavement widening on curves are most feasible during 3R resurfacing and/or at high accident curves. 2. Lane widening should be more feasible for lane widths of 10 ft (3 m) or less, and/or with narrow shoulders.	1. Effectiveness of lane and shoulder widening and shoulder surfacing improvements have been quantified for 2-lane rural roads in a recent FHWA/TRB research study.(3) 2. 3R and AASHTO Guidelines should be followed for widening projects.(15)
5. Sideslope Flattening on Curves	1. Most effective on curves with a high incidence of rollover and other run-off-road accidents, and where other improvements are impractical (e.g., curve flattening is too expensive) or ineffective (e.g., delineation and signing have not reduced accidents). 2. Sideslopes flattening is beneficial, particularly for sideslopes of 3:1 or steeper which are flattening to 4:1 or flatter (based on recent FHWA study on cross-section design (3)), but additional flattening (e.g., to 5:1 to 7:1) may be justified on horizontal curves due to increased friction demand (and transition problems from positive superelevation to negative sideslope).	1. FHWA four-State study cities the need for flatter sideslopes on curves than on tangents due to increased friction demands from cornering.(2)
6. Resurfacing	1. Most practical for curve sites during routine (e.g., 3R) resurfacing projects.	1. Improvements to highway drainage and/or superelevation may be needed in conjunction with routine overlays.

Table 4. Summary of potential design improvements for horizontal curves (continued).

Design-Related Improvement	Limitations of Effective Use	Comments
6. Resurfacing (Con't)	2. Of most benefit for curve sites which exhibit a high rate of wet-weather accidents (e.g., run-off-road and/or head-on accidents), and/or where pavement skid numbers are low (e.g., 20 or less) and/or where pavement is unusually rough or patched.	2. Special anti-skid surfaces may be justified on roads with high wet-weather accident experience.
7. Roadside Obstacle Improvements	1. These are most effective at curve sites with a high incidence of fixed-object accidents, and/or sharp curves with rigid roadside obstacles (e.g., trees, utility poles) close to the roadway edge.	1. Guidance for effectiveness of various counter-measures for utility pole accidents are given in a 1983 FHWA study. (16) 2. Example of roadside obstacle improvements include tree removal, providing culverts flush with the ground, installing breakaway sign supports and relocating utility poles further from roadway edge.
8. Construct Curves of Near-Constant Degree of Curve (New Road Construction Projects Only)	1. In constructing new roads in mountainous areas where numerous curves must be provided and driver expectancy may be a problem (e.g., high percent of non-local drivers).	1. Used in Utah on Canyon roads with curves of 4 degrees. 2. This practice is an attempt to minimize driver expectancy problems which may result when the driver is faced with some sharp and some mild curves in succession.

A summary of some of the so-called other (i.e., non-design treatments) used and/or tested at highway curves is given in table 5. These include chevron alignment signs, post-mounted reflectors, striped delineators, raised pavement markers, curve warning signs, painted edgelines and centerlines, transverse pavement striping (with decreasing spacing), guardrail and flashing beacons (with curve warning signs). The list does not include experimental devices (e.g., the Wundt illusion pavement markings, deceptive curve signs, diamond painted on pavement next to curve signs). While the effect of each of these treatments on curve accidents and operations is largely unknown, all of them (except transverse pavement stripes) are used routinely by some State and local agencies in an attempt to improve horizontal curves.

Table 5. Summary of potential low-cost treatments for horizontal curves.

Countermeasure	Limitations of Effective Use	Comments
1. Chevron Alignment Signs	1. May be most effective at curves with degree of curve of 7 degrees or more. 2. Most effective when tested with numerous signs visible to driver at all times throughout the curve. 3. Most effective at sites with a high nighttime accident rate.	1. Rockwell found that using only 3 chevron signs was ineffective.(13) 2. Jennings and Demetsky found Chevron to be more effective than delineators on curves of 7 degrees or more.(11) 3. Chevrons were found to reduce nighttime run-off road accidents by 49 percent (62 locations) in West Virginia and 32 percent (5 locations) in Montana at high accident sites.(18,19)
2. Post-Mounted Reflectors (e.g., 3 in by 8 in) (7.6 cm by 20.3 cm)	1. Most effective at sites with a high nighttime accident rate. 2. May be more effective than chevrons on curves of less than 5 degrees.	1. These were tested by Jennings and Demetsky in Virginia and found to be effective for curves less than 5 degrees.(11) 2. Taylor tested nine delineation configurations at one horizontal curve and recommended amber delineators for right-turning curves and crystal delineators on far left-turning curves.(20) 3. Taylor and Foody found post-mounted delineators to significantly reduce accidents in Ohio.(8)
3. Special Striped (6 by 48 in) (15.2 by 121.9 cm) Delineators	1. Most effective at sites with a high nighttime accident rate. 2. May be more effective than Chevrons on curves of 4 or 5 degrees.	1. These were tested in Virginia by Jennings and Demetsky and found to be more effective than chevrons for curves of 4 or 5 degrees, although not quite as effective as post-mounted reflectors.(11)
4. Raised Pavement Markers	1. Most effective at sites with a high rate of nighttime wet-weather accidents (compared to paint striping alone). 2. Most practical in warmer climates, where snow plows are not a problem in destroying RPM's. 3. RPM's along the centerline combined with painted edgelines may be an effective treatment on hazardous horizontal curves.	1. Because of the greatly improved vision of the roadway by drivers after RPM's are installed, there may be a potential for drivers to increase their speed at certain sites. 2. Numerous types and brands of RPM's are currently on the market. 3. RPM's placed on centerline and across 4 ft (1.2 m) wide shoulder (at 45 degree angle) can cause a decrease in fixed-object and injury accidents.
5. Standard Curve Warning Signs	1. Advisory speed signs and/or other curve warning signs may be effective on sharp curves, particularly at the end of a long tangent and/or, if a high single-vehicle accident rate exists. As with other traffic control measures, curve warning signs are most effective if used selectively and sparingly (i.e., overuse will decrease motorist respect for signs).	1. Most states surveyed use curve warning and advisory speed signs, although less than half of the states consider such signs as highly effective.(17) 2. Lyles' study results suggest that advisory speed plates and regulatory signs will generally be ineffective at hazardous curves.(21) 3. A California study found that advisory speed limit signing in combination with curve warning signs

Table 5. Summary of potential low-cost treatments for horizontal curves (continued).

Countermeasure	Limitations of Effective Use	Comments
5. Standard Curve (Con't)		appeared to reduce single-vehicle crashes significantly.(22) 4. Arrow board signs are used in Michigan at selected sharp curves.
6. Painted Edgelines and Centerlines	1. Retroreflective pavement markers are more visible than non-reflective paint. 2. The use of supplemental RPM's on the centerline improve driver visibility under rainy nighttime conditions, and have been found to result in lower accident rates compared to roads with only painted centerlines.(25) 3. The use of wider (8 in) (20.3 cm) edgelines may be considered (although not found to reduce accidents). (26)	1. Three-quarters of the states surveyed by Wright use standard markings as a countermeasure for Run-off-road accidents, but only 24 percent considered them among most effective treatments.(17) 2. Taylor found that newly painted centerlines resulted in improved driver behavior, and the addition of edgelines on horizontal curves improved lateral placement.(20) 3. More than half of the states use retroreflective pavement markers on edgelines and centerlines.(17) 4. One study on delineation for FHWA found that pavement markers are more effective than post-mounted delineators.(23)
7. Transverse (reflective) Striping with Decreasing Spacing	1. May be most effective at sites with high volumes of non-local drivers. 2. This is still an experimental treatment, and widespread use is not recommended.	1. Rockwell found some positive benefits from transverse striping at 5 sites in Ohio. (13) 2. Agent found transverse markings to be effective at high-accident curve sites in Kentucky.(24)
7. Transverse Striping (Con't)		3. Michigan found a long-term speed reduction of 4.3 mi/h (6.9 km/h) due to transverse stripes.
8. Guardrail	1. Most effective at hazardous curve sites with steep sideslope (i.e., particularly 2:1 or steeper) and/or with numerous severe roadside obstacles. 2. Guardrail should be installed only if design improvements (curve reconstruction, roadside improvements, etc.) are too expensive and other treatments (delineation, resurfacing, etc.) have been found to be ineffective.	1. The new AASHTO Roadside Guide provides guidance on determining where guardrail should be installed.(27)
9. Flashing Beacons (with Curve Warning Signs)	1. Flashing beacons may be useful to emphasize an unusually hazardous curve as an interim measure until design improvements can be made.	1. Hanscom found speed reductions at critical curve locations when flashing beacons were used with curve warning signs.(28)

CHAPTER 3 - RESEARCH DESIGN

The research design for this study first involved identifying key analysis issues of concern and gaps in current knowledge relative to horizontal curves. Then, available data bases were critically assessed to determine which ones could help provide answers to those issues. Finally, a specific research analysis plan was developed. These three steps are discussed below in detail.

Key Analysis Issues and Gaps

The review and critique of literature was useful in identifying key issues and gaps in current knowledge. The primary focus of this study was on accident research, based on the philosophy that accident research is the best way to quantify the safety effects of various roadway and geometric features on curves. Developing such relationships will ultimately allow for estimating the expected accident reductions which will result from various roadway improvements on curves. Also of concern is the effect of curve features on vehicle operations, which also should be better understood to ensure proper curve design.

While much can be learned from past literature on horizontal curves, the following issues were identified where gaps exist in available knowledge.

- Issue No. 1: Characteristics and severity of curve accidents. While some statistics are available from the literature on curve crashes, more detailed information would be useful to better quantify:

  - Crash severity on various curve geometrics (e.g., curves with hazardous roadsides, various pavement widths, varying degrees and lengths of curve, ADT levels, central angles).
  - The severity of occupant injuries, and contributing factors (e.g., pavement condition, light condition, alcohol related, vehicle type) associated with curve accidents compared to accidents on tangents.
  - Percentage of rollover, head-on, fixed-object, and other types of accidents on various curve designs and ADT levels.

In addition to looking at such accident statistics for a large sample of curve sites, it would also be used to better define the types of crashes that occur on rural two-lane curves, and their related circumstances. Such information would help us to better understand curve crashes and appropriate treatments.

- Issue No. 2: Curvature effects on accidents. There is clearly a significant relationship between accident experience and such variables as degree of curve and length of curve, where accident rates are generally higher for greater degree of curve and accident frequencies are higher on longer curves. However, there are also interactive effects of curvature and other variables which have not been quantified. For example, in the FHWA cross-section study, the authors found that roadsides are typically more hazardous and curvature is sharper on lower class roads, whereas roadsides are generally safer on flatter curves on higher class roads. Thus, there is thought to be an interaction between curvature and roadside condition (and perhaps many other roadway variables). Previous studies either did not attempt or were not able to quantify the interaction of such variables relative to accident experience. The two FHWA surrogate studies provided useful information on traffic operations and geometrics as they affect accidents on curves.[4,9] However, the relatively small curve samples in those studies (78 New York sites and 25 Michigan sites, respectively) did not allow for determining such complex data interactions. The large (3,304 sites) four-State data base analyzed in the FHWA study did not yield an accident predictive model for estimating accident effects of degree of curvature.[2] The data base of 333 curve sites contained roadside data, superelevation data and other variables in addition to curvature ADT, accident and other information. While that data was used successfully in a discriminant analysis (and yielded a model for predicting high accident curve sites), it did not allow for determining interactive effects of variables, since the data base contained only the high and low accident extremes. Thus, there is still a great need to better quantify such interaction effects of roadway variables on accidents.

- Issue No. 3: Curve lane and shoulder width effects on accidents. The effect of lane width, shoulder width, and shoulder type on curve accidents is unclear. Mixed results were found from analysis of the high/low data base and the total curve four-State data base relative to lane width having a significant effect. In two studies (i.e., the two FHWA surrogate studies, shoulder width was found to have no significant effect on accidents, but did have a significant effect according to the FHWA four-State curve study.[4,9,2] Shoulder type was only investigated in one of the studies (high/low data base). In the FHWA cross-section study, all three of these variables were found to significantly affect accidents on two-lane rural roadway sections (included sections with both curves and tangents).[3] There continues to be a need to better quantify the specific effects of lanes and shoulders on curve accidents.

- Issue No. 4: Effect of roadside conditions on accidents. Roadside conditions were found to have an important effect on accidents based on the FHWA cross-section study for rural two-lane sections using such roadside measures as sideslope, average roadside recovery distance, and roadside hazard scale.[3] An analysis of the FHWA four-State data base found roadside hazard to be important in predicting high-accident sites.[2] However, this high/low accident data subset does not allow for determining accident reduction factors for various roadside improvements. The roadside hazard scales in the cross-section study did provide accident reduction factors for roadside improvements, but they were for rural sections of from 1 to 8 mi (1.6 to 12.9 km) in length and not for individual curve sites. Thus, there is a need to better quantify the effects of roadside conditions (including sideslope) on accidents at curve locations.

- Issue No. 5: Safety effects of spiral transitions. While the literature suggests the advantages of spiral transitions, particularly on sharp curves, more quantitative evidence is needed on the magnitude of the effects of spirals on accidents. Thus, it would be useful to better determine the safety effects of spirals.

- Issue No. 6: Effects of lack of proper superelevation on curve accidents. There is also little quantitative information concerning the effects of superelevation (superelevation deficiency, superelevation transition length, etc.) on accidents. While the laws of physics suggest the importance of proper superelevation on curves, the previous literature gives inconsistent results. Of the studies which analyzed superelevation deficiency, the FHWA four-State curve study, and the New York State surrogate study found no significant effects, while the FHWA surrogate study in Michigan and the Zador study found it to be important.[2,4,9,7] The Zador study concluded that superelevation was an important factor at fatal crash sites.[7]

- Issue No. 7: Combined effects of grades and curves. While some previous studies indicate some particular problems associated with horizontal curves which are located on a downgrade, more needs to be known about the effects of such situations on accidents.

- Issue No. 8: Effects of distance since last curve on crashes. The literature has mixed results as to the importance of "distance from last curve" (or distance to nearest roadway event) on accident rate. Of the two FHWA surrogate studies, their conclusions differ on whether this has a significant effect on accidents.[4,9] Logically, one may assume that many drivers would be less prepared to safely negotiate a horizontal curve after a long tangent (i.e., low driver expectancy) than if a similar curve were in the middle of a winding section. Thus, there would be some value in better determining the effects of "distance since last curve" on accidents. If there is truly an increased safety problem for curves at the end of a long tangent, then perhaps some types of traffic control improvements (e.g., delineators, chevrons, flashing lights) may be proposed for use at such sites.

- Issue No. 9: Effects of low-cost curve treatments on crashes. Mixed results have been found on the effects of low-cost treatments (chevrons, delineators, pavement edgelines, curve warning signs, etc.) on traffic operations with little information on their effect on accidents. More information on the benefits of such measures would be useful, particularly regarding curve conditions where these treatments are most effective in reducing accidents.

- Issue No. 10: Accident benefits of various curve improvements. Perhaps the biggest gap in available literature and knowledge on horizontal curve design is the lack of a comprehensive accident predictive model for horizontal curves. Such a model would ideally contain the primary traffic, geometric, and roadway variables of importance in terms of their interrelated effects on curve accidents. Such a model would provide useful information on expected accident reductions due to one or more types of curve improvement projects.

• Issue No. 11: Operations of vehicles on curves. Traffic operational measures on curves can indicate the adequacy of the curve design in handling the traffic mix on the curve and possible accident problems on the curve which may result. Thus, more information would be useful on vehicle speed change, lateral vehicle placement, and vehicle path as affected by various curve designs. Such information could supplement the data collected at five sites in the FHWA four-State curve study, and other operational studies.(2)

• Issue No. 12: Need for additional information on vehicle dynamics. The FHWA four-State curve study conducted HVOSM runs examining vehicle dynamics on curves.(2) However, HVOSM is not well suited for modeling driver behavior, which is an important component of how vehicles respond on curves. The authors assumed a fixed "probe length" which simulated the driver preview of the alignment ahead. The authors point out that drivers are more likely to reduce their probe length as they enter the curve. The study reveals the potential usefulness of HVOSM for further analysis on curves, particularly for various vehicle types, vehicle characteristics, curve geometrics, vehicle speeds, and various inputs on driver probe length. Thus, further HVOSM runs could be potentially useful.

To address these key analysis issues and gaps, numerous data bases and sources were considered. A critical assessment of available State data bases and existing research data bases was made in terms of possible uses in this study. The following is a discussion of the outcome of that analysis of data bases.

Critical Assessment of Data Bases

A review of the available data bases was conducted to determine their relevance for use in assessing the safety and/or traffic operations effectiveness of various designs and/or countermeasures at horizontal curves. This review involved initially making contacts with highway officials in several States and within FHWA and NHTSA, in addition to reviewing published and unpublished documents for potentially useful data bases.

Data bases of most interest were those which contained accident, roadway, and geometric information on large samples of horizontal curve sections on two-lane rural roads (e.g., FHWA four-State curves data base). Also, data samples for longer sections of rural two-lane roads in general were of interest if they contained details on horizontal curves within those sections (e.g., FHWA cross-section data base). Accident data bases containing detailed crash severity and vehicle data for curve accidents were also of interest, such as the National Accident Sampling System (NASS) data base.

Another criterion for selecting potential data bases was the availability of geometric curve variables which would allow for addressing the previously-discussed key questions about horizontal curves. For example, the availability of data on spirals transitions, superelevation, and roadside conditions (along with accident, traffic, and other roadway data) for a sample of horizontal curves would hopefully allow for better quantifying the effects of improvements to these features (e.g., roadside improvements, correction of superelevation, and/or adding spiral transitions to compound curves).

Data bases from numerous State highway agencies were excluded for a variety of reasons, including:

- Several States had computerized files with curve data (e.g., degree of curve, length of curve, and location of each curve) and vertical alignment data. However, other needed variables of interest such as superelevation, presence of spirals, and roadside data were not available.
- Several States were not considered desirable for accident research studies due to their high accident reporting thresholds (e.g., tow away, injury and fatal accidents only). At least one of these States has greatly inconsistent reporting of accidents within the State itself. Use of sites in such States would ignore a large percentage of property damage and minor injury accidents. Thus, true accident relationships with geometric features would be difficult to quantify using data from such States.

- One State had begun computerizing horizontal and vertical alignment data for computer plotting purposes. However, this process was still in the early stages.

- While several States reportedly collected detailed horizontal and alignment data using an instrumented vehicle, such data were not computerized and/or were not examined for reliability and accuracy.

- Many States contacted either had no horizontal or vertical alignment data or the data they did have did not provide sufficient details for analysis purposes.

Based on all available information, the data bases selected to be critically reviewed for possible use in this study included:

1. FHWA Four-State Curve Data Base. This file was developed as part of the 1983 FHWA study entitled, "Safety and Operational Considerations for Design of Rural Highway Curves."(2) This data base consists of accident, traffic, and geometric data for 3,304 curve sections and 244 tangent sections in four States (Ohio, Florida, Illinois, and Texas) plus supplemental data for the subset of 333 high- and low-accident curve sites.

2. Cross-Section Data Base. This data base was developed for FHWA as part of the study entitled "Cost-Effective Cross-Section Design for Two-Lane Rural Roads."(3) The data base consists of detailed accident, traffic, roadway, and roadside data (325 data elements per section) for 1,944 highway sections (nearly 5,000 miles) from 7 U.S. States. For each section, summary data is given for percent of section with horizontal curvature within various degrees of curvature categories.

3. New York Surrogate Data Base. A sample of accident, geometric, vehicle operation (vehicle encroachments on edgelines and centerline, vehicle speed changes, etc.), and roadway feature data was collected for 78 curve sites in New York State. This data base was developed during a 1986 FHWA study entitled "Evaluation of Accident Surrogates for Safety Analysis of Rural Highways."(4)

4. Washington State Data Bases. These include four separate computer files, including the horizontal curve file, vertical curve file, roadway and intersection inventory, and accident file. The horizontal curve file contains alignment information on 21,315 curves including spiral transition curves on the State rural primary system.

5. National Accident Sampling System (NASS) Data Base. This is a national accident data base operated by NHTSA. Each NASS investigation includes examining the police report along with any newspaper reports, photos, etc., and on-scene examination

for reconstruction of the crash, interviews with witnesses, and other data sources forming a detailed accident file.

A critical review of each of these five data bases was conducted and basic information was compiled for:

- Summary and use of the data bases (source of data base, general description, etc.).
- Reference identification of the data base (States included, type, format, number of records, basis of the record (such as accident, curve section), total sampled roadway mileage, data elements).
- Critical Analysis:
  - Did the author(s) consider all relevant variables?
  - Did the author(s) sufficiently control for errors in data collection?
  - Was sufficient detail maintained in the data collection to describe the particular design elements of interest?
  - Did the author(s) collect a large enough sample for establishing statistically reliable results?
  - What were the assumptions made, and were the assumptions required by the statistical model met?
  - Were appropriate tests of significance applied?
  - Did the author(s) properly interpret the results?

A summary is given in table 6 of the important roadway and accident variables, in terms of which ones are contained in the five data bases. All five of these data files were considered to be potentially useful for this study, although each had definite limitations. The four-State curve data base (3,304 curve sections) was considered a strong candidate for additional analysis because of the large sample, the availability of accident data and some useful details on degree of curve, length of curve, roadway width, ADT, and other variables. One of the limitations of this data base is the lack of such information as superelevation, presence of transition spirals, roadside data, etc. Although some of these additional variables were collected for the 333 high/low accident sites, such data must be available for the full range of sites (e.g., sites with accident experience in the middle range) to allow for

Table 6. Summary of important roadway variables contained in the five data bases.

Roadway Variables	FHWA Curves Data Base: High/Low Subset	FHWA Curves Data Base: Total Curve Sites	FHWA Cross-Section Data Base [*a]	Wash. State Curve/ Acc./ Roadway Data	New York State Surrogate Data Base	NASS Data Base [*b]
Length of Curve	X	X	X	X[d]	X	
Degree of Curve (or Curve Radius)	X	X	X	X	X	X
Roadway Width	X	X	X	X		X
Shoulder Width	X	X	X	X	X	X
Superelevation	X					X
Superelevation Deficiency (Error)	X				X	
Superelevation Transition Length	X					
Superelevation Distribution	X					
Sight Distance to Curve	X					
Horizontal Alignment on Curve Approach	X			X		
Vertical Alignment on Curve or Approach	X			X	X	X
Roadside Hazard Rating	X		X		X	
Pavement Condition	X					X
Pavement Skid Resistance	X					
Curve Signing	X				X	X
Pavement Markings	X		X			X
Presence of Driveways, Structures	X		X			
Shoulder Type	X		X	X		X
ADT	X	X	X	X	X	
State	X	X	X	X	X	X
Sideslope Angle			X			X[c]
Distance to Last Event					X	
Presence of Spirals				X		
Accident Variables						
Accident Type (Run-off-road, head-on, etc.)			X	X		X
Accident Severity			X	X		X
Day/Night			X	X		X
Wet/Dry			X	X		X
Rollover Accidents vs Non-rollover			X	X		X
Vehicle Types Involved in Accident				X		X

*[a]For the Cross-Section data base, all variables are summarized for each roadway section (generally 1 to 8 miles (1.6 to 12.9 km) each).
*[b]The NASS data base contains summary data for each <u>accident</u>, not each curve.
X[c]Sideslope data available for more recent NASS data.
X[d]Length of curve can be derived based on curve radius and central angle in the Washington state curve file.

estimating accident reductions due to improvements to these geometric features. Thus, supplementing the full FHWA four-State curve data base with other needed variables was considered as a possible alternative.

The cross-section data base also contains much useful data for a large sample of sections not found with any other data sources. For example, field sideslope measurements and detailed roadside inventory data can be extracted from paper files by location and fit to individual horizontal curves for sample sections in the seven States. However, this computerized data base corresponds to roadway sections (generally 1 mile (1.6 km) or more) and would thus only allow for a more general analysis of curvature (i.e., percent of sections with curves of < 2 degrees, 2 to 5 degrees, etc.) Any other use of this data base would require using the "raw" files of geometric and roadside data (recorded for each 0.1 mile (0.16 km) along each section) supplemented by data on each curve from another source (e.g., Washington State curve file).

The Washington State data files (i.e., horizontal curve, traffic volume, vertical curve, roadway and accident files) must be linked before analysis would be possible for analysis of individual horizontal curves. While useful information is available on more than 20,000 horizontal curves (including data on spirals), information is not available on superelevation, roadside features, or sideslope. Supplementing a sample of horizontal curves with these needed data elements (e.g., roadside data from the cross-section file or field measurements of superelevation) would be useful, if data merging were feasible.

The NASS data base represents detailed crash data variables for a sample of accidents in selected areas in the U.S. One possible use of this data base for the current curve study may be to analyze the roadway characteristics and nature of driver injury for rollover and other run-off-road accidents on horizontal curves. Although the data base is not random in some respects (i.e., fatal and injury accidents are oversampled) useful insights may be obtained for the NASS accident subset related to horizontal curves.

A summary of data and information sources which may be appropriate for addressing each issue is summarized in table 7.

Table 7. Data bases which can be used to answer analysis issues.

Gaps in Available Information (Issues of Concern)	DATA BASES AND INFORMATION SOURCES										
	Literature	Wash. State Curve Acc. Roadway Data	FHWA Cross Section Data Base	FHWA Curves Data Base: High/Low Subset	FHWA Curves Data Base: Total Curve Sites	New York State Surrogate Data Base	NASS Data Base	State Accident and Countermeasure Data Base	Field Data Collection	HVOSM Runs	Selected for Study
1. Characteristics and Severity of Curve Accidents	X	X					X	X			Yes
2. Effects of Curvature on Accidents	X	X			X						Yes
3. Effects of Lane and Shoulders on Accidents	X	X	X		X						Yes
4. Effects of Roadsides Features on Accidents	X		X	X							Yes
5. Effects of Spiral Transitions on Accidents	X	X									Yes
6. Effects of Superelevation on Accidents	X					X			X		Yes
7. Combined Accident Effects of Grades and Curves	X	X									Yes
8. Effects of Curve Approach on Accidents	X	X				X					Yes
9. Accident Effects of Low-Cost Treatments	X							X			No
10. Accident Benefits of Various Curve Improvements	X	X	X	X	X						Yes
11. Vehicle Operational Effects on Curves	X					X			X		Yes
12. Dynamic Effect of Vehicles on Curves	X									X	No

Research Issues Selected for Study

Because of the large number of important gaps in current knowledge on horizontal curves and budget limitations in this study, all of the indicated issues could not be fully resolved in this study alone. Therefore, efforts were made to establish priorities for issues to be addressed based on the following criteria:

- The importance of the issue in horizontal curve design and improvements.
- Issues for which countermeasures are practical and reasonable.
- The availability of adequate data bases where there is a high probability of obtaining meaningful results.
- Non-prohibitive costs for performing the analysis (i.e., all of the project funds will not be spent trying to resolve only one issue).

To assist in making a final selection of issues and related activities for this study, a one and a half day safety research panel meeting was held, which included project team members, project consultants, and selected highway designers and researchers experienced in curve design and/or safety. The participants reviewed the 12 proposed issues and suggested others for consideration. Detailed discussions were held on each suggested curve issue, and the following issues were selected for this study:

- Quantifying the characteristics and severity of curve accidents (Issue 1).
- Determining the accident effects of curvature, lane and shoulder width, roadside features, spiral transitions, superelevation, grade-curve combinations and distance since last curve (Issues 2 through 8).
- Determining the combined effects of various roadway features on accidents (Issue 10).
- Investigating the effects of curve features on vehicle operations (Issue 11).

If successful, the resolution of these issues should facilitate determining the safety effects of geometric treatments on curves, such as curve widening, curve flattening, roadside correction, superelevation, enhancement and combinations of curve improvements. Also, the effects of such geometric improvements on traffic operations could be better understood.

Those issues <u>not</u> selected for analysis include:

- Effects of low-cost delineation treatments on accidents (Issue 9) - While it was felt that more information would be useful on the effects of chevron signs, post delineators, and other delineation measures, numerous previous studies have already been made in this regard. Also, a major commitment of time and resources would be needed to conduct before/after (with controls) field testing of devices to have any chance of meaningful results due to the confounding influence of so many roadway factors. Also, since operational measures (e.g., speed changes, lateral placement) would likely be used as outcome variables, it is difficult to relate such operational effects with accidents (e.g., does a decrease in edgeline encroachments imply a reduction in run-off-road accidents or an increase in head-on accidents, or both?).

- Dynamic effects of vehicles on curves (Issue 12) - HVOSM computer simulation runs would be needed to determine the dynamic effects of such features as transition spirals, combined curvature and grades, superelevation, and perhaps specific shoulder and roadside design improvements on vehicles.

  This item generated much discussion from panel members. In particular, concern was expressed regarding the current lack of a comprehensive driver model on horizontal curves, which is needed input for HVOSM. Further, the reliability of the HVOSM results for curves depends on the accuracy of the driver model, and the development and validation of a comprehensive driver model would exceed the scope of this study.

  Another point which was mentioned is that drivers do not all react the same when driving around a horizontal curve. Thus, it is unclear whether an appropriate driver model for HVOSM on curves should assume the "average" driver response, or a "very poor" driver reaction (e.g., driver response to curve conditions either too fast or too slow). While HVOSM has been shown to work well for approximating crash dynamics for conditions where driver influence is minimal (e.g., the vehicle has already left the road and encounters a steep sideslope), it may be less helpful for horizontal curve situations until a more comprehensive driver model is developed.

Study Methodology

Based on the selected study issues, a series of analysis activities was formulated which included the following:

- Activity 1 - Examine characteristics of curve-related accidents. This involved a detailed review of 200 hard copy accident reports of randomly selected curve accidents in North Carolina over the past 3 years. Summaries were generated of characteristics of importance, such as severity, time, contributing cause, accident type (e.g., fixed object, head-on, rollover), and other factors. One of the purposes of this activity was to gain a better understanding of contributing factors of curve accidents and to verify or modify forms of crash models and relationships to be tested. This activity was useful in addressing Issue 1 (i.e., determining characteristics and severity of curve-related accidents).

- Activity 2 - Supplement, merge and analyze Washington State data bases. The Washington State curve file was considered to be highly desirable for analysis purposes along with the roadway, traffic volume, vertical curve, and accident files. This activity involved creating a merged file of such traffic, geometric and accident variables for each horizontal curve on rural two-lane roadways on the State highway system. Of 10,900 curves selected, roadside obstacle data were extracted from paper files for approximately 1,000 curves from roadway sections used in the previous FHWA cross-section study in which detailed roadside data were collected. Field measurements of superelevation of approximately 700 of those 1,000 curves were made as a part of this study. This was the primary data base used to develop accident relationships with degree of curve, ADT, roadway width, presence of spiral, superelevation, vertical curvature, distance since last curve, and roadside hazard (Issues 2 through 8).

- Activity 3 - Create and analyze matched pair data base. The 10,900 curve sample was used to create a file of matched pairs of curves with adjacent tangents where the tangent lengths were equal to those of the corresponding curve. This resulted in 3,427 matched pairs which, among other things, were used to determine accident problems associated with curves as compared to tangents (Issue 1). This data set was also used to verify the accident effects of degree of curve and presence of spiral on accidents (Issues 2 and 5).

- Activity 4 - Analyze the FHWA four-State curves data subset. An analysis of the 333 accident sites was used to gain further insights on the effect of superelevation on safety (to supplement the knowledge gained on superelevation from the 700 Washington State curves in Activity 1).

- Activity 5 - Validate accident relationships. The four-State curve data set was used to validate the results of the modeling of the Washington State data base. After data verification and deletion of questionable data, 3,277 of the 3,304 original curve sections were used in the final analysis.

- Activity 6 - Analyze FHWA cross-section data base to quantify roadside effects on accidents. The cross-section data base contains roadside data for rural two-lane roads in seven States (Alabama, Michigan, Montana, North Carolina, Utah, Washington, and West Virginia). Although Activity 2 will analyze roadside data for a limited number of curve sites in Washington, the full cross-section file provides a much larger sample of curves. This analysis will investigate the effects of sideslope flattening, replacing culvert headwalls, clearing trees, relocating utility poles, guardrails, etc., and other roadside improvements.

- Activity 7 - Analyze New York surrogate curves file. This activity made use of the existing FHWA curves file to further analyze the operational and geometric data collected at 78 curve sites in New York State. This analysis was intended to focus on the influence of varying curve designs on such operational measures as speed reduction and encroachment characteristics (Issue 10). Curve features included in this analysis were degree of curve, curve length, superelevation deficiency, shoulder width, grade, and roadside hazard.

- Activity 8 - Incorporate available information on safety effects of various roadway improvements - This process involved making use of the various analysis results conducted in this study as well as previous literature to summarize the best information currently known on the interrelated effects of various roadway variables on horizontal curve accidents. Then, accident reduction factors were developed for various curve treatments.

- Activity 9 - Conduct economic analysis. Construction costs were obtained for various curve improvements, along with construction delay and travel time benefits due to curve flattening. Accident costs, interest rates, and other economic values were also used along with accident costs and benefits to determine the economic impact of geometric improvements under various roadway conditions. This should assist designers and safety analysts in selecting the optimal curve improvements.

An overview of the study methodology is given in figure 2, which shows the interaction of the nine project activities and the key analysis issues which are being addressed. The results of the first seven activities with some input from the literature led to the development of the best available knowledge on accident relationships with geometric curve features (Activity 8). These

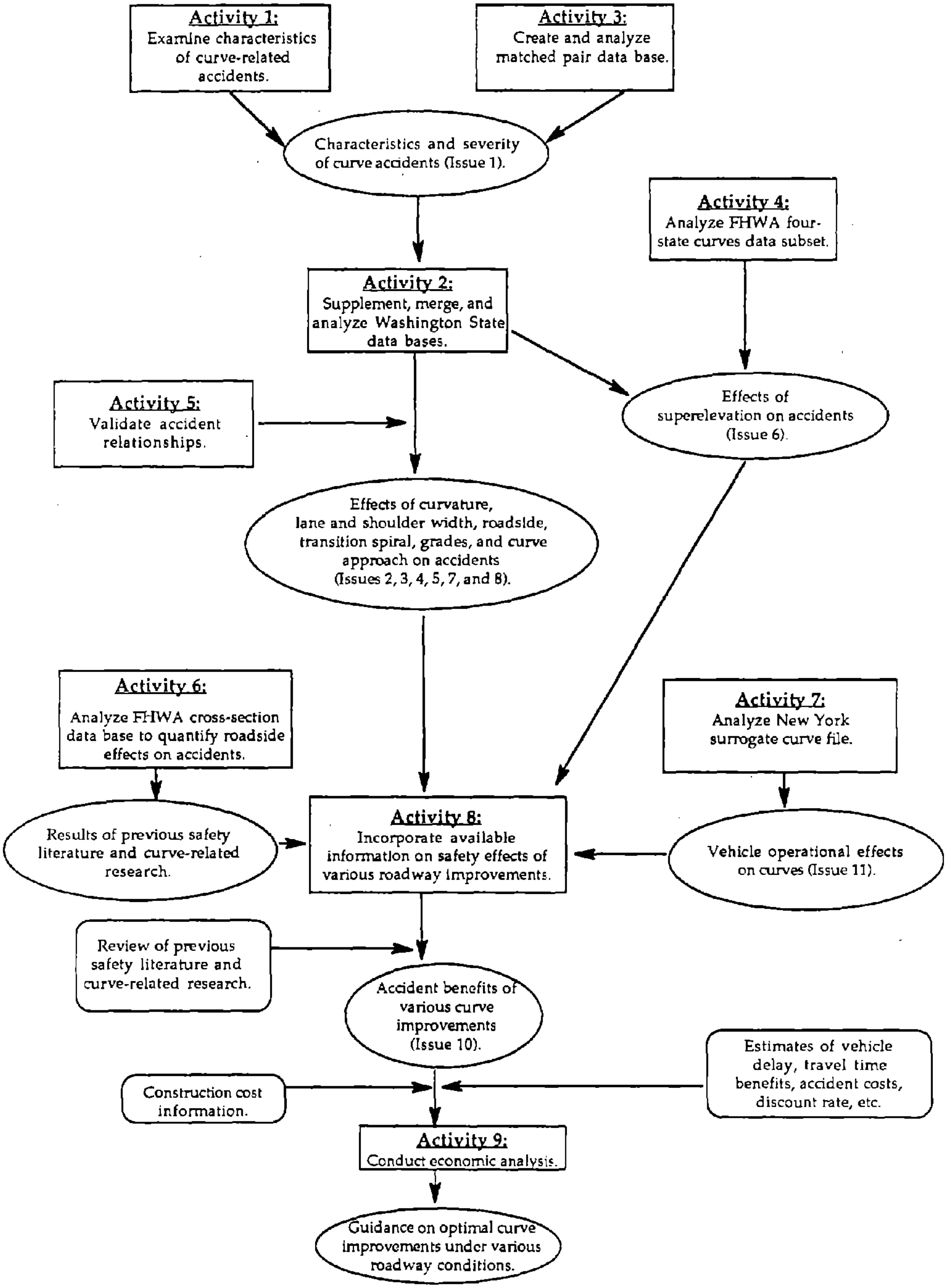

Figure 2. Overview of study methodology.

relationships were then translated into accident reduction factors for various countermeasures (e.g., curve flattening, curve widening). Construction cost data were used along with vehicle delay, travel time savings, accident costs, and other economic values to compute benefits and project costs in the economic analysis (Activity 9). The results of the economic analysis should provide guidance on curve improvements which are optimal under various roadway conditions.

CHAPTER 4 - ANALYSIS OF HARD COPIES OF ACCIDENTS OCCURRING ON CURVES

In an attempt to better define the types of crashes that occur on rural, two-lane curves, a sample of fatal and a second sample of non-fatal North Carolina accidents were studied in more detail. For each of these samples, hard copies of the crash reports were obtained from the Department of Motor Vehicles to look closely at the types of maneuvers that were occurring during the accident as well as the types of circumstances that might differentiate the fatal from the non-fatal crashes. One hundred four fatals were pulled from the first nine months of 1987 (which represented the total numbers of fatal crashes that occurred on rural curves in North Carolina during that time period) and a subset consisting of 104 non-fatal crashes occurring during the same time period were pulled.

For each of the hard copies, the narrative was read and the sketch was studied. Additional variables which are not normally coded for computer use but which were extracted included (1) which vehicle was the striking vehicle and which was the struck vehicle, (2) speed of the striking vehicle, (3) the series of individual maneuvers that occurred in the accident sequence for the striking vehicle, (4) whether the first maneuver was toward the inside or outside of the curve, (5) the position of the first maneuver relative to the beginning, the center, the end, or the tangent section after the curve, and (6) the location of the actual crash (again beginning, center, end or tangent after the curve). With respect to maneuvers of the striking vehicle, a code was assigned regarding each of the maneuvers that the vehicle underwent during the accident sequence. For example, a given striking vehicle might run off the road to the right toward the outside of the curve, then run back across the road and off to the left, then strike a fixed object (i.e., "RORR-O-RORL-FO"). As another example, the vehicle may cross left of center toward the inside of the curve and then strike another vehicle head-on (i.e., "LOC-I-HO").

The analyses then consisted of comparing the vehicles involved in the fatal crashes with those involved in the non-fatal crashes. The findings relative to these comparisons can be grouped to some extent into two categories. First there is a category related to the actual occurrence of the accident, that is to say, which maneuvers or factors led to the ultimate crash.

The second set of factors is related to the resulting severity of the accident. We will first look at the factors related to the occurrence of the accident, and then at those related to severity.

It was initially noted that the fatal and non-fatal crashes were very similar in terms of whether they were single or multivehicle crashes. Both sets were approximately 68 percent single-vehicle crashes. Motorcycles were slightly overrepresented in the fatal crashes, but there was not much difference for other vehicle types (e.g., neither heavy trucks nor light trucks were found to be overrepresented in either sample). Fatal accidents were less likely to occur on icy roadways and more likely to occur on dry roadways. Fatal accidents were more likely to occur at night (58 percent versus 47 percent for the non-fatals) and were more likely to involve a driver who had been drinking (56 percent versus 23 percent for non-fatals).

There were only minor differences in the type of the first maneuver that instituted the crash sequence (see table 8). For example, the first maneuver was "left of center" for 23.1 percent of the non-fatal striking vehicles and 24 percent of the fatal striking vehicles. (NOTE: Many of the following results concern the "striking vehicle." This term is defined as including both the vehicle judged to be the striking vehicle in multivehicle crashes <u>and</u> the single vehicle involved in a single-vehicle crash. Thus, "striking vehicle" is not limited to multivehicle crashes.) "Ran-off-road left" occurred in 21.2 percent of the non-fatal cases versus 20 percent of the fatals. The first maneuver was ran-off-road right in 46 percent of the non-fatals and 47 percent of the fatals. The only minor differences involved a larger proportion of pedestrian accidents in the fatal group and a larger proportion of in-lane rear-end crashes in the non-fatal group.

Table 8. First manuevers for striking vehicles.

	Fatal	Non-fatal
Left of center	24.0%	23.1%
RORL	20.0%	21.2%
RORR	47.0%	46.1%
Pedestrians	4.0%	0.0%
Angle crashes	3.0%	1.9%
Rear-end	2.0%	7.7%
Total	100.0%	100.0%

The finding from this analysis was that in more of the fatal accidents, the first maneuver was toward the outside of the curve (77 percent versus 64 percent). (As will be noted later, the higher proportion of fatals toward the outside of the curve could well be a function of the speed at which these vehicles were traveling.) However, contrary to what might be expected, the most interesting finding here is that a significant proportion of the first maneuvers were toward the inside of the curve (in the direction opposite the centrifugal forces on the vehicle). Here, 22 percent of the fatal accidents and 35 percent of the non-fatal accidents were toward the inside of the curve.

To further examine these crashes, a study was made of the inside versus outside of fatal and non-fatal curve crashes categorized by the type of first maneuver that occurred. Here, the trend continues with the fatal vehicles continuing to run off the outside of the curve more often than the non-fatal vehicles within each maneuver type. For example, in the accidents in which "left of center" was the first maneuver, 52 percent of the fatals versus 42 percent of the non-fatals ran off the outside of the road. In the ran-off-road right crashes, 97 percent of the fatals versus 77 percent of the non-fatals were to the outside. However, it is again emphasized that there remains a significant problem with vehicles running off to the inside of the curve (22 percent of the fatals and 35 percent of the non-fatals). This may be partly the result of driver overshoot which was found to occur in previous observational studies of vehicles on curves. Problems with excessive pavement edge dropoffs could also contribute to part of this problem at some curve locations.

With respect to speed (see table 9), which affects both occurrence and subsequent injury, the estimated speed prior to the fatal crashes was much higher than to the non-fatals. This could not be attributed to travel on greatly different roadways, since the speed limits for the striking vehicles in both groups were very similar. For example, 76 percent of the non-fatal striking vehicles were in crashes which occurred on roads with speed limits equal to or greater than 55 mi/h (89 km/h) versus 77 percent of the fatal striking vehicles. However, even with these similar speed limits, the fatal crashes occurred with the striking vehicle traveling at a much higher estimated speed. While the officers estimated that speeds for 73 percent of the non-fatal striking vehicles were equal to or less than 55 mi/h (89 km/h), only 41 percent of the fatal vehicles were traveling at 55 mi/h (89 km/h) or less. Whereas only 8.7 percent of the non-fatal vehicles were traveling at more than 74 mi/h (119 km/h), 23 percent of the fatal vehicles were traveling at more than 74 mi/h (119 km/h). These higher speeds were also probably related to the finding that the fatal vehicles were much more likely to have more maneuvers in their sequences than did non-fatal vehicles. Thus, while only 7 percent of the non-fatal striking vehicles were involved in four or more distinct types of maneuvers, 18 percent of the fatal vehicles were involved in four or more maneuvers.

Table 9. Estimated speed prior to crash for fatal and non-fatal striking vehicles.

	Fatal	Non-fatal
55 mi/h or less	41.0%	72.8%
56 to 74 mi/h	36.0%	18.5%
75+ mi/h	23.0%	8.7%
Total	100.0%	100.0%

1 mi/h = 1.6 km/h

The location on the curve where the first maneuver occurred was also studied. It was found that the fatal striking vehicles were getting into trouble more often at the two ends of the curve and less often in the center of the curve than the non-fatal sample. This was consistent at both the beginning of the curve (12.1 percent versus 8.7 percent) and at the end (49.5 percent versus 40.4 percent). However, what is also of interest here is the fact that over 40 percent of the first maneuver by the fatal and non-fatal striking vehicles was found to occur at the end of the curve. It might have been hypothesized, for example, that the most critical point on a curve would be the beginning or center of the curve where the driver simply does not make the turn (perhaps from the "overshoot phenomenon" described in reference 2) or simply can't hold the vehicle in the curve.(2) However, it also appears that a significant proportion of the vehicles arrive at the end of the curve before making the first maneuver. There is no easy explanation for this. (Note that the judgement concerning location on the curve had to be made from the officer's sketch.) At times, this was a difficult judgement, and, in reality, the proportions may not be as large as those cited above or perhaps may be larger. However, the size of the end-of-curve proportion leads support to further consideration of this issue in curve-traversing theory.)

Turning back now briefly to the question of factors that might lead to the difference between the severity of fatal and non-fatal crashes, the most significant factor is probably the earlier-noted large difference in the estimated speed prior to the crash. The final maneuver of the vehicle was reviewed to see, for example, if there was a chance that the final maneuver might have been more "dangerous" for the fatal vehicles (e.g., more rollovers for the fatal group). However, the percentage of last maneuvers which were overturns was approximately 30 percent for both fatals and non-fatals. Fixed object hits were slightly lower for the fatal crashes (28 percent versus 36 percent for the non-fatal crashes). The most significant difference here was the fact that only 14 percent of the non-fatal crashes involved a head-on collision with another vehicle, whereas 29 percent of the fatal crashes involved such a collision. This, coupled with the fact that fatal and non-fatal crashes were in approximately the same proportion of multivehicle crashes, leads to the conclusion that fatal multivehicle crashes are much more likely to be head-on, whereas non-fatal ones are more often sideswipe, rear-end, or other types of crashes which are less life-threatening.

The final analysis dealing with crash severity differences categorized the type of first maneuver as single-vehicle or multivehicle crashes. The results again emphasized the contributions of speed and head-on crashes in the occurrence of fatalities. For example, for approximately 28 percent of the fatal accidents versus only 8.8 percent of the non-fatal ones, the vehicle ran off the road to the right and then returned to be involved in a crash. In the single vehicle crashes, 9.5 percent of the fatals versus 5.7 percent of the non-fatals were left of center as a first maneuver, a position that would increase the probability of striking an oncoming vehicle. No differences were found in the single-vehicle, ran-off-road categories between the two samples.

In summary, the significant findings appear to be that, as might be expected, speed is a definite factor, perhaps in both the occurrence of and also the severity of crashes on curves. Fatalities were much more likely to occur in the higher speed crashes. It is also interesting to note that there is a significant problem with the first maneuver in the crash sequence being toward the <u>inside</u> of the curve for both the fatal and non-fatal accidents. This could be hypothesized to result from a number of different factors, perhaps including the fact that overcorrection from an "overshoot phenomenon" might lead to a first maneuver toward the inside of the curve. (It might also mean that speeds are too low for the superelevation, but this is not thought to be a reasonable explanation.) Finally, many of the crashes were characterized by the first maneuver occurring at the end of the curve rather than at the beginning or the center, meaning that a theoretical model for curve crashes should probably take into account vehicles which have almost successfully navigated the curve before the crash occurs.

CHAPTER 5 - ACCIDENT TRENDS BETWEEN CURVES AND ADJACENT TANGENTS

The selection of appropriate countermeasures for curve accidents requires an understanding of the characteristics of those accidents and the roadway and environmental factors which are involved. An analysis was conducted to determine accident trends which differ between accidents on curves, as compared to accidents on adjacent tangents. Such an analysis was believed to be helpful in determining abnormal accident patterns associated with curves and then selecting corresponding roadway improvement. For example, if an abnormally high percentage of nighttime accidents occurs on curves of 5 degrees or greater, this may suggest a need for improved curve delineation (e.g., post delineators, raised pavement markers, chevron markers) and perhaps curve flattening for some curves of that type. An abnormally high percentage of fixed object and rollover accidents involving curves with a small roadside recovery area (e.g, less than 10 ft (3.0 m)) might suggest sideslope flattening and/or obstacle removal (e.g., clearing trees within 20 ft (6.1 m) of the road at curves) as candidate safety improvements.

To perform this analysis, a data base of 3,427 curve and tangent pairs from Washington State was used. (A more complete description of that full data base is given in chapter 6.) The data base was produced based on selecting all curve samples from the 10,900 curves in Washington State which had a tangent of equal or greater length directly after the curve, in addition to a buffer area of 0.05 mi (.08 km) after the preceding curve and before the next curve. The 0.05-mi (0.8 km) buffer was considered important to minimize the effect of accident location reporting error (e.g., crashes actually occurring on the curve and reported incorrectly on the tangent beyond the curve). This buffer area was also intended to eliminate accidents which involved vehicles losing control on the curve and striking a vehicle or object just past the curve (i.e., within 0.05 mi (.08 km), or about 260 ft (79 m) beyond the curve). Crashes in this .05-mi (.08 km) buffer were not used in this analysis.

When building this data base, the assumption was that accidents on curves could be compared with an equal length of tangent just beyond the curve which would be assumed to have approximately the same traffic volume, vehicle mix, roadway geometrics (e.g., lane width, shoulder width, shoulder type), roadside condition, road surface conditions (e.g., approximately the same amount of rain, snow, and ice), environmental conditions (e.g., climate, temperature, fog). Thus, it may be assumed that the primary difference in accident patterns and frequencies between a curve and its matched tangent "partner" would be essentially the result of the difference between the tangent and the curve features (e.g., degree of curve, central angle, presence of spiral or not).

While many deviations from this assumption are certain to occur (e.g., the roadside of a given curve may be different than the roadside on the approach tangent), the analyses assumes no major systematic deviations. For example, for all curve/tangent pairs, the differences in roadside hazard may roughly cancel out so that roadsides on curves are not greatly different than roadsides on tangents. Thus, if curves are usually widened in Washington State by an additional 6 ft (1.8 m) on the curve compared to the approaching tangents, then any change in accidents between curves and tangents could be the result of the differences in road width as well as due to the effect of curvature.

The analysis of paired data involved classification of accidents for curves and tangents by the following groupings:

- Accident type (head-on, opposite direction sideswipe, fixed object, rollover, same direction sideswipe, rear-end both moving, or other accident types).
- Accident severity (worst injury in the crash: property damage only, C-type injury, B-type injury, A-type injury, or fatal).
- Light conditions (daylight or dark, where dark also includes dawn or dusk).
- Pavement conditions (dry, wet, or snow/ice).
- Driver sobriety (drinking, sober, or unknown).
- Vehicle type (passenger car, pickup truck, truck with semi-trailer, motorcycle, or other vehicle types). Note that because many accidents involve two or more vehicles, the number of vehicle accident involvements exceeds the total number of accidents.

As shown in table 10 for the 3,427 curve/tangent pairs, there were 7,775 accidents, which included 4,211 (54.2 percent) on curves, and 3,564 (45.8

Table 10. Summary of curve and tangent accidents by accident characteristics.

Accident Characteristics	Totals	Curve Accidents No. (%)	Tangent Accidents No. (%)	Ratio of Curve Accs/ Tangent Accs
All Accidents	7,775	4,211	3,564	1.18
1. Accident Type				
Head-on Accidents	311	177 (56.9)	134 (43.1)	1.32
Opposite Direction Sideswipe	281	160 (56.9)	121 (43.1)	1.32
Fixed Object	2,800	1,556 (55.6)	1,244 (44.4)	1.25
Rollover	1,215	685 (56.4)	530 (43.6)	1.29
Same Direction Sideswipe	96	49 (51.0)	47 (49.0)	1.04
Rear-End Both Moving	253	128 (50.6)	125 (49.4)	1.02
Other Types	2,819	1,456 (51.6)	1,363 (48.4)	1.07
2. Accident Severity				
Property Damage Only	4,188	2,216 (52.9)	1,972 (47.1)	1.12
C-Type Injury	1,004	559 (55.7)	445 (44.3)	1.26
B-Type Injury	1,572	864 (55.0)	708 (45.0)	1.22
A-Type Injury	837	464 (55.4)	373 (44.6)	1.24
Fatal	171	107 (62.6)	64 (37.4)	1.67
3. Light Condition				
Daylight	4,384	2,334 (53.2)	2,050 (46.8)	1.14
Dark, Dawn, Dusk	3,391	1,877 (55.4)	1,514 (44.6)	1.24
4. Pavement Condition				
Dry Pavement	4,599	2,524 (54.9)	2,075 (45.1)	1.22
Wet Pavement	1,590	872 (54.8)	718 (45.2)	1.21
Snowy/Icy Pavement	1,586	815 (51.4)	771 (48.6)	1.05
5. Driver Sobriety				
Drinking Driver	1,655	952 (57.5)	703 (42.5)	1.35
Sober Driver	4,836	2,575 (53.2)	2,261 (46.8)	1.14
Unknown Sobriety	1,284	684 (53.3)	600 (46.7)	1.14
6. Vehicle Type				
Passenger Car	6,515	3,535 (54.3)	2,980 (45.7)	1.19
Pickup Truck	3,080	1,618 (52.5)	1,462 (47.5)	1.11
Truck and Semi Trailer	474	264 (55.7)	210 (44.3)	1.26
Motorcycle	234	130 (55.6)	104 (44.4)	1.25
Other Vehicles	462	234 (50.6)	228 (49.4)	1.03

percent) on tangents. The ratio of total curve accidents to total tangent accidents was therefore 1.18. The numbers of curve and tangent accidents by each accident type is also given in table 10, along with the ratio of curve accidents to tangent accidents. Ratios of specific accident types considerably above 1.18 may, therefore, be an indication of an accident type which is overrepresented on curves compared to tangents. A review of the preliminary accident summaries in table 10 reveals that accident types with curve-to-tangent accident ratios above 1.18 include head-on, opposite direction sideswipe, fixed-object, and rollover. These accident types would all logically be related to curves. In terms of accident severity, all injury levels have ratios above 1.18. In fact, fatal accidents are 1.67 times higher on curves than on their paired tangent sections.

Other accident groupings with curve to tangent accident ratios above 1.18 include non-daylight accidents, drinking drivers, motorcycle and truck with semitrailers. In terms of pavement type, ratios above 1.18 exist for dry accidents and wet accidents, which may be the result of a higher than expected incidence of snowy/icy accidents on tangents.

Chi-square tests were carried out to compare the distributions between curves and tangents for each accident group. For example, consider accidents on curve and tangent pairs by light conditions in table 11 as follows:

Table 11. Accident summary on tangent and curve pairs by light condition.

Light Condition	Number of Accidents (Percent)					
	Curves		Tangents		Totals	
	No.	Percent	No.	Percent	No.	Percent
Daylight	2,334	55.4	2,050	57.5	4,384	56.4
Dark (includes dusk and dawn)	1,877	44.6	1,514	42.5	3,391	43.6
Totals	4,211	100.0	3,564	100.0	7,775	100.0

The Chi-square value for 1 degree of freedom is 3.4, which corresponds to a p-value of 0.052. Thus, we have approximately 95 percent confidence that there is a significant difference in the distribution of daylight and dark accidents on curves compared to tangents for the full curve/tangent data set. A higher percentage of accidents occur at night on curves compared to tangents (44.6 percent vs. 42.5 percent). Significant differences were found in accident type (e.g., head-on, fixed object, etc.) between curves and tangents at the .05 level (i.e., probability of .018) (table 12). Accident groups where curves and tangents had significantly different accident distributions (at the .05 level) include pavement condition (P = 0.046) and drinking driver accidents (P = 0.008). Significant differences at the 0.10 level were found between curve and tangent accident distributions for light condition (P = 0.064) and accident severity (P = 0.052). No significant differences were found for curve vs. tangent crashes by vehicle type.

Table 12. Chi-square summaries for comparison of curves and tangents by accident groupings.

Accident Characteristics	Chi-Square Value	P-Value
Accident Type	15.3	0.018
Accident Severity	9.4	0.052
Light Condition	3.4	0.064
Pavement Conditions	6.2	0.046
Driver Sobriety	9.6	0.008
Vehicle Type	5.3	0.256

While the previous discussion involves comparing distributions of various accident groups between curve and tangent accidents for all geometric conditions, it is also useful to make similar comparisons by degree of curve, roadway width, ADT, and other roadway conditions. Such an analysis could, for example, find a large difference in increased dark accidents on sharp curves (e.g., above 5 degrees) with narrow road widths, although little or no differences may occur on mild curves with wide road widths. Thus, this analysis will allow for identifying the curve geometric and roadway conditions where certain crash types (e.g., fixed-object, nighttime accidents, fatal accidents) are most critical. A series of Chi-square tests was carried out to compare distributions of various accident classes between curves and tangents for the following geometric conditions:

- All curve/tangent pairs.
- Maximum grade on the curve (0 to 2 percent, above 2 percent).
- Central angle of the curve ($\leq$ 30 degrees, > 30 degrees).
- Degree of curve ($\leq$ 2 degrees, > 2 to 5 degrees, $\geq$ 5 degrees).
- Length of curve (0.01 to 0.05 mile (0.016 to 0.081 km), > 0.05 to 0.10 mi (0.016 to 0.16 km), > 0.10 to 0.20 mi (0.16 to 0.32 km), > 0.20 mi (0.32 km)).
- Functional class (Principal Arterial, Minor Arterial, Major Collector).
- Total road width including lane widths plus shoulder width of lanes plus shoulders ($\leq$ 30 ft (9.1 m), > 30 ft (9.1 m)).
- ADT ($\leq$ 2,000, > 2,000 to 5,000, > 5,000).
- Recovery area distance ($\leq$ 10 ft (3.0 m), > 10 ft (3.0 m)).

The following is a summary of results for each of the six accident groupings listed in table 10.

Accident Type

Chi-square statistics were generated to compare the differences in accident type distributions for curves vs. tangents. For example, the percentages of curve accidents and tangent accidents are given in table 13 for head-on, opposite direction sideswipe, fixed object, rollover, opposite direction, sideswipe, rear end (both moving), and other accident types for curve/tangent pairs having curve central angle of greater than 30 degrees. Note that of the 1,740 total curve accidents, 41.3 percent (718 of 1,740) are fixed object, compared with 35.2 percent of tangent accidents (502 of 1,425). Also, rollover accidents represent 18.3 percent of all curve accidents (319 of 1,740 accidents) compared to 13.7 percent (195 of 1,425) tangent accidents. The Chi-square value is 46.9, or a probability level of 0.000. Thus, the null hypothesis is rejected, that is, there is a significant difference between accident type distributions between curves and tangents for curve/tangent pairs of greater than 30 degree central angles. Further, the differences appear to be primarily due to higher percentages of fixed object and rollover crashes on curves and a higher percentage of "other accident types" on tangents than curves (39.0 percent, compared to 28.6 percent).

A similar table was also produced for curve/tangent pairs for central angles of 30 degrees or less. However, the Chi-square value for that distribution was 0.717, or no significant difference in the distribution of accident types between curves and tangents for curves with < 30 degree central angle. Thus, the accident patterns by accident type between curves and tangents differs for greater central angles (i.e., above 30 degrees) but not for lower central angles. This may seem reasonable, since drivers' potentials for running off the road (and thus hitting fixed objects or rolling over) may be greater on curves with greater central angles than on curves with lower central angles.

The results of numerous chi-square tables similar to those described above in table 13 were produced for various curve conditions, as summarized in table 14. Notice that various roadway groups are listed in the left column, such as all curves, groups of maximum grade, central angle, degree of curve, length of curve, functional class, total road width (lanes plus shoulders), ADT, and recovery area distance. Each roadway group (row of information in table 14) represents the results of a separate contingency table, as illustrated previously. For example, on curves with central angles of greater than 30 degrees, 3,165 accidents occurred on the curve/tangent pairs with a p-value of 0.000, as discussed earlier. Likewise, accident samples and probability levels are given for other roadway groups. Columns are given of each accident type or group, and +'s and -'s are given for roadway groups with p-values of .05 or less. A "+" indicates that curves have a higher accident percentage than tangents for a given accident type by a difference of 1 percent or greater and a "-" indicates that tangents have a higher percent of that accident type than curves. Comments are provided in the last column to provide details on where accident differences occur for roadway groups where probability levels of .05 or less exist.

Table 13. Chi-square table of accidents by type for curves and tangents: curves with central angles of 30 or greater.

Accident Type	Curve	Tangent	Total
Head-On	67 2.12* 55.37** 3.85***	54 1.71 44.63 3.79	121 3.82
Opposite Direction Sideswipe	76 2.40 58.46 4.37	54 1.71 41.54 3.79	130 4.11
Fixed Object	718 22.69 58.85 41.26	502 15.86 41.15 35.23	1220 38.55
Rollover	319 10.08 62.06 18.33	195 6.16 37.94 13.68	514 16.24
Same Direction Sideswipe	17 0.54 58.62 0.98	12 0.38 41.38 0.84	29 0.92
Rear End (Both moving)	46 1.46 46.94 2.64	52 1.64 53.06 3.65	98 3.10
Other Types	497 15.70 47.20 28.56	556 17.57 52.80 39.02	1053 33.27
Total	1740 54.98	1425 45.02	3165 100.00

*Overall percentage
**Row percentage
***Column percentage

Sample Size = 3,165 Accidents
Degrees of Freedom = 6
Chi-Square Value = 46.9
P-value = 0.000

Table 14 reveals that roadway groups having significant differences (at the .05 level) in the distribution of accident types between curves and tangents include:

- All curve groups combined.
- Maximum grade above 2 percent.
- Central angle above 30 degrees.
- Degree of curve > 2 to 5 degrees.
- Curve lengths ≤ 0.05 mi (< 0.08 km) or > 0.2 mi (> 0.32 km).
- Minor Arterials.
- Roadside recovery distance ≤ 10 ft (3.0 m).

In nearly all of these roadway groups, curves had a higher percentage of fixed object and rollover accidents than tangents (indicated by "+" values). In many of these groups, curves also had a higher percentage of head-on and opposite direction sideswipe accidents than tangents. Such findings seem logical, since the most restrictive geometric conditions (e.g., narrow roads, large central angle, short roadside recovery distance) would be expected to have more fixed object and rollover accidents as well as more accidents with opposing vehicles (i.e., head-on and opposite direction sideswipe) than less restrictive geometrics. Detailed tables similar to table 14 for other accident groups (i.e., accident severity, light condition, pavement condition, driver sobriety, and vehicle type) were also produced, and the results are summarized below.

Accident Severity

The distribution of accidents was also compared between curves and tangents by accident severity (i.e., property damage only, C-type injury, B-type injury, A-type injury, and fatal) for each roadway group. Significant differences were found in these distributions for several roadway groups including:

- Minor Arterials.

- Roadway widths 30 ft (9.1 m) or less.

- ADT's less than 2,000.

- Recovery area distance 10 ft (3.0 m) or less.

Table 14. Chi-square tests by accident types.

Roadway Group	Accident Sample Size	p-value	Accident Type: Head-On	OD Side-swipe	Fixed Object	Rollover	SD Side-swipe	Rear-End	Others	Comments
All Curves	7,775	0.018			+	+			-	Curves have a higher percentage of head-on acc. (4.2% compared to 3.8%), opposite direction sideswipe accidents (3.8% compared to 3.4%), fixed object (37.0% compared to 34.9%) and rollover acc. (16.3% compared to 14.9%) than tangents.
Overall: Max. Grade	7,436	0.029*								For max. grades of greater than 2%, curves have a higher percentage of head-on, opposite direction sideswipe, fixed object, and rollover accidents than tangents.
0-2%	4,347	0.932								
> 2%	3,089	0.000*			+	+			-	
Overall: Central Angle	7,775	0.022*								For central angles of greater than 30 degrees, curves have a higher percentage of fixed object accidents (41.3% compared to 35.2%) and rollover accidents (18.3% compared to 13.7%) than tangents.
≤ 30 Degrees	4,610	0.717								
> 30 Degrees	3,165	0.000*			+	+		-	-	
Overall: Degree of Curve	7,775	0.140								For curves with degree of curve between 2 and 5, curves have a higher percentage of fixed object accidents (37.1% compared to 33.6%) and rollover accidents (16.6% compared to 13.2%) than tangents.
≤ 2 Degrees	3,411	0.909								
> 2-5 Degrees	2,876	0.002*			+	+			-	
> 5 Degrees	1,488	0.647								

Table 14. Chi square tests by accident types (Continued).

Roadway Group	Accident Sample Size	p-value	Accident Type: Head-On	OD Side-swipe	Fixed Object	Rollover	SD Side-swipe	Rear-End	Others	Comments
Overall: Length of Curve	7,775	0.078								For curves of greater than 0.2 miles, curves have a higher percentage of fixed object and rollover accidents than tangents. For short curves of 0.01 to 0.05, tangents have a higher percentage of fixed object and rollover accidents than curves.
0.01 - 0.05 Mi	546	0.001*		+	-	-	-	+	+	
> 0.05 - 0.10 Mi	1,350	0.875								
> 0.10 - 0.20 Mi	2,374	0.192								
> 0.20 Mi	3,505	0.001*			+	+			-	
Overall: Funct. Rd. Class	7,775	0.025*								On Minor Arterials, curves have a higher percentage of fixed object accs. (37.0% compared to 34.8%) and rollover accidents (18.0% compared to 15.1%) than tangents.
Principal Arterial	3,687	0.401								
Minor Arterial	3,135	0.039*			+	+		-	-	
Major Collector	953	0.583								
Overall: Roadway Width	7,775	0.046*								
≤ 30 ft	2,656	0.091								
> 30 ft	5,119	0.143								
Overall: ADT	7,775	0.023*								
≤ 2,000	1,422	0.168								
> 2,000-5,000	3,747	0.600								
> 5,000	2,606	0.324								
Overall: Recov. Area Dist.	1,114	0.000*								For recovery area distances of 10 feet or less, curves have a higher percentage of head-on, opposite direction sideswipe, fixed object, and rollover accidents than tangents. Fixed object accidents are 39.2% on curves and 28.6% on tangents. Rollover accidents are 15.8% on curves, compared to 9.6% on tangents for this same roadway group.
≤ 10 ft	788	0.000*	+	+	+	+			-	
> 10 ft	326	0.523								

1 mi = 1.61 km
1 ft = 0.3048 m

For all of the above roadway groups, fatal accidents have a higher percentage on curves than tangents. A-type injury accidents also have higher accident percentages on curves than tangents in all but one of those situations, while B-type and/or C-type injury accidents also have greater percentages on curves for each roadway group, with lower property damage accident percentages on curves than tangents. For the overall sample of curve/tangent pairs, the percent of fatal, A-type, B-type, and C-type accidents was higher on curves than tangents. These trends indicate a generally higher severity of accidents on curves than tangents. Recall that some of these restrictive geometrics were also associated with high percentages of fixed-object, rollover, and head-on accidents, which tend to be quite severe. Thus, one might expect to find a greater percentage of injury and fatal accidents on roadway groups with high fixed-object, rollovers, and head-on accidents.

Light Condition

Accidents occurring in daylight versus dark (i.e., night, dawn, or dusk) conditions were also investigated using a series of Chi-square tests for various roadway groups. For all of the curve/tangent pairs combined, curves had a slightly higher percentage of dark accidents (44.6 percent) than tangents (42.5 percent). This difference of only 2.1 percent was significant at a $p = 0.064$. The difference, however, was more apparent for the following roadway groups, in terms of curves having a higher percentage of dark accidents than tangents:

- Maximum grade above 2 percent ($p = .005$).
- Central angle > 30 degrees ($p = .000$).
- Degree of curve > 5 degrees ($p = .009$).
- Curve lengths > 0.20 mi (0.32 km) ($p = .048$).
- Recovery area distance $\leq$ 10 ft (3.0 m) ($p = .023$).

For central angles above 30 degrees, a fairly large difference was found between the percentage of dark accidents on curves (46.8 percent) versus tangents (39.9 percent), a difference of 6.9 percent. Likewise, for degree of curve > 5, dark accidents represented 50.4 percent on curves versus 43.5 percent on tangents, a difference of 6.9 percent. Such values indicate where countermeasures may be particularly justified for nighttime curve accidents.

Pavement Condition

The presence of water or ice and snow on the roadway surface can have definite effects on the ability of vehicles to decelerate and maneuver properly. The question of whether such pavement conditions affect accidents differently on curves versus tangents was investigated using a series of Chi-square tests for various roadway groups.

Using the overall sample of 3,427 curve/tangent pairs, there was a significant difference in the distributions of accidents by pavement conditions ($p = 0.046$). The primary difference was that the percentage of snow and ice accidents was higher on tangents (59.9 percent) than on curves (58.2 percent). It may be speculated that this difference could be partly the result of some motorists traveling on snowy and icy roads who attempt to brake on the tangent approaching a curve and slide off the road or strike another vehicle or a fixed object prior to reaching the curve. For the overall sample, curves have a slightly higher percentage of wet accidents (20.7 percent compared to 20.2 percent) and dry accidents (59.9 percent compared to 58.2 percent) than tangents.

A review of differences in accident differences for specific roadway groups reveals that tangents have a higher percentage of icy/snowy accidents related to curve/tangent pairs with the following characteristics:

- Maximum grade of 2 percent or less ($p = .014$).
- Degree of curve of > 5 ($p = 0.060$).
- Curve of 0.10 mi (0.16 km) or less ($p = 0.018$ and .036 for curves of 0.01 to 0.05 mi (0.016 to 0.08 km) and > 0.05 to 0.10 mi (0.08 to 0.16 km), respectively).
- Roadway widths of greater than 30 ft (9.1 m) ($p = 0.045$).
- ADT's of > 5,000 ($p = 0.000$).

From the information above, it appears likely that the higher percentage of ice/snow accidents on tangents may be largely the result of roads with ADT's above 5,000 on generally wide roads (greater than 30 ft (9.1 m)). In many cases, motorists are probably striking other vehicles or sliding off the road on icy tangent sections while braking prior to curves. The presence of sharp curves (5 degrees or greater) as a factor may be associated to the driver's need to slow down considerably (i.e., brake harder) on the approach tangent, which could increase the likelihood of driver loss of control on snowy and icy roads.

One might have expected that wet pavement accidents would have been overrepresented on curves as compared to tangents. This is because side friction demands are greater on curves than tangents, and wet roads would reasonably create more critical side friction conditions on curves than tangents. However, the percentage of wet pavement accidents was only slightly higher on curves (20.7 percent) than tangents (20.2 percent), which does not really support the idea that insufficient friction in wet weather is a major problem on accidents on the available sample of Washington State curves.

Driver Sobriety

Chi-square analyses were conducted on the percentage of curve and tangent accidents involving accidents where at least one driver had been drinking. For the overall curve/tangent paired data set, there was a significant difference ($p = .008$) in the percent of drinking driver accidents between curves (22.6 percent) and tangents (19.7 percent). A review of the various roadway groups revealed that drinking driver accidents were more of a problem on curves than tangents for the following conditions:

- Central angle greater than 30 degrees ($p = .000$), where drinking drivers account for 25.5 percent of curve accidents and 17.2 percent of tangent accidents.
- Degree of curve greater than 2 degrees ($p = .001$ for > 2 to 5 degree curves, and $p = .044$ for curves greater than 5 degrees). For curves greater than 5 degrees, the percent of drinking driver accidents is 31.3 percent on curves and 25.3 percent on tangents.
- Curve length of > 0.10 to 0.20 ($p = .017$).
- Roadways greater than 30 ft (9.1 m) ($p = .035$).
- ADT's above 5,000 ($p = .003$).

- Recovery area distance of 10 ft (3.0 m) or less (.006). The percent of drinking driver accidents in this roadway group was 27.6 percent on curves and 18.1 percent on tangents.

In summary, drinking drivers seem to be having a particular accident problem on sharp curves, large central angles (30 degrees or more), high volume routes, and curves with recovery distances of less than 10 ft (3.0 m). These factors may all be expected, due to possible impaired driving abilities of drinking drivers which could be compounded under these roadway situations. The greater percentage of drinking driver accidents on curves for wide roadways may simply be a reflection of greater accident potential for drinking drivers on high volume roads.

Vehicle Type

The analysis of accidents by vehicle type produced no significant differences in distributions between curves and tangents for the overall data set (p = .256). There was one isolated roadway situation, however, where significant effects occurred. For curves longer than 0.2 mi (0.3 km), curves have a slightly higher percentage of passenger car accidents than tangents (62.8 percent compared to 59.8 percent), a higher percentage of tractor semitrailer accidents (5.4 percent compared to 4.6 percent), and a lower percentage of pickup truck accidents (26.5 percent compared to 29.0 percent). Although accident differences were significant (p = .047), these differences are quite small. One may speculate, however, that a truck tractor/semitrailer may be expected to have more accident problems on curves than tangents due to the offtracking of the rear of the trailer (i.e., greater swept path of the truck) when travelling around curves compared to tangents.

Summary of Chi-Square Results

The discussions of accident distributions between curves and tangents provided a variety of results which may be useful in formulating specific problems caused by curve conditions and candidate corrective treatments. As shown in table 15, five groups of accidents were generally found to have higher percentages on curves than tangents. These include:

Table 15. Summary of accident types which are higher for curves than tangents by roadway condition.

Roadway Conditions		Accident Type: Head-on or Opp. Dirc. Sideswipe	Fixed Obj. & Rollover	A-type Inj. & Fatal	Dark	Drunk Driver
Maximum grade:	0-2%					
	> 2%	•	•		•	
Central angle:	≤ 30°					
	> 30°		•		•	•
Degree of curve:	≤ 2°					
	> 2°-5°	•	•			•
	> 5°				•	•
Length of curve:	0.01 to 0.05					
	> .05 to 0.10					
	> .10 to 0.20					•
	> 0.20		•		•	
Roadway Functional Class:	Principal arterial					
	Minor arterial		•	•		
	Major collector					
Total width:	≤ 30 ft			•		
	> 30 ft					•
ADT:	≤ 2,000			•		
	> 2,000 to 5,000					
	> 5,000					•
Roadside recovery distance:	≤ 10 ft	•	•	•	•	•
	> 10 ft					

• = Accident types which have significantly greater percentages on curves than tangents for specific roadway conditions.

1 ft = 0.3048 m

- Head-on and opposite direction sideswipe accidents.
- Fixed-object and rollover accidents.
- Fatal and A-type injury accidents.
- Dark light condition accidents.
- Drinking driver accidents.

The analyses also revealed that several types of roadway conditions were associated with these higher accident occurrences on curves. Roadside recovery distances of 10 ft (3.0 m) or less were associated with higher accident occurrence of each of the five accident types above. Sharper curves (greater than 2 degrees) and central angles above 30 degrees were also associated with most of these accident types. Maximum grades above 2 percent were associated with higher accident percentages for curves than tangents for three of the five accident groups, while relatively long curves (> .10 mi (.16 km)) were a problem on curves for three accident types. Narrow roads were associated with higher accident severities.

The fact that Minor Arterial routes and certain ADT groups were associated with higher accident percentages for curves than tangents may be partly an indication of their correlation with some other deficient roadway features. For example, low ADT roads may typically have sharper curves, narrower roadways, and worse roadside conditions than higher volume roads which may lead to more severe accidents (e.g., vehicles hitting trees or head-on accidents). On the other hand, the high-volume roads may increase the probability of a drunk driver striking another vehicle compared to lower volume roads.

Some of the candidate countermeasures for reducing these problems include:

- Flatten curves.
- Provide adequate superelevation.
- Use spiral transitions.
- Widen lanes and shoulders and pave shoulders.
- Flatten sideslopes.
- Pavement resurfacing.
- Roadside obstacle improvements.
- Construct curves of near constant curvature.
- Add pavement delineation (edgelines, raised pavement markers, past delineation, etc.).
- Provide advance warning signs and/or chevrons.
- Provide guardrail.

- Correct shoulder dropoffs.
- Install nighttime lighting.
- Others.

The selection of the optimal curve improvement depends on the specific deficiencies of the curve, the traffic volume, accident patterns, project costs, and other factors. More information on these factors is provided in the following chapters.

CHAPTER 6 - ANALYSIS OF WASHINGTON STATE CURVE DATA

As discussed in chapter 3, a total of nine basic activities were conducted in the development of guidelines on curve improvements. The Washington State data base of curves was the primary data source analyzed for determining the relationships between accidents and various traffic and roadway features. This chapter provides the details of the development of the Washington curves data base and the results of the resulting statistical analysis, including the accident prediction models.

Creating the Washington Curves Data Base

Washington State curves were selected as the primary data base for analysis because:

- There was an existing computerized data base of horizontal curve records for the State-maintained highway system (about 7,000 mi) (11,270 km) in Washington State.
- The curve files contained such information as degree of curve (i.e., curve radius), length of curve, curve direction, central angle, and presence of spiral transition on each curve.
- Corresponding computer files were available which could be merged with the curve file, including the roadway features file, vertical curve file, traffic volume file, and accident file. The accident file covered the period from January 1, 1982, through December 31, 1986. Being able to merge these files resulted in a study file with a large number of relevant traffic and roadway variables on curves, as shown in figure 3.
- Roadside data (i.e., roadside recovery distance, roadside hazard rating) on 1,039 curves in Washington State was available from paper files from the FHWA cross-section study by matching mileposts. Data on superelevation were collected in the field at 732 of those 1,039 curves.

The data files and the process involved in developing the final data base of 10,900 curves are illustrated in figure 4. From that data base, a subset of 3,427 curves was selected which had matching tangent sections. This subset was used for the analysis discussed in chapter 5. In short, the Washington State merged data base was considered to contain a large sample of curves with many important variables needed to quantify the effects of roadway features on crashes.

1. ADT - Annual average daily traffic on the curve section.

2. Degree of curve - The sharpness of the curve in degrees per 100 ft of arc.

3. Curve radius - The radius of the curve in ft.

4. Length of curve - The total distance around the curve in mi or tenth of a mi.

5. Direction - The direction of the curve (left or right) as one increases in milepost.

6. Angle (central angle) - The number of degrees taken up by a curve in terms of its direction before the curve and direction at the end of the curve, the angle equals the degree of curve (per hundred ft of arc) times the curve length in ft, or $I = \frac{D \times L}{100}$. When L is expressed in mi, I = (D) X (L) (52.8). Thus, an 8 degree curve which is 200 ft long would have an angle of

$$I = \frac{D \times L}{100} = \frac{8 \times 200}{100} = 16 \text{ degrees.}$$

7. Spiral (or spiral transition) - A curve with a gradually increasing curvature which is constructed to connect a tangent with a circular curve. It more closely corresponds to a driver's steering sequence when entering a curve as compared to entering a circular directly from the tangent.

8. Superelevation - The banking of a curve to counteract the centrifugal force created by a vehicle traveling around a curve. The superelevation, e, measures the rise over the run of a cross-section of the highway. For example, a one ft elevation from the inside to the outside edgelines of a 20 ft wide road would correspond to a superelevation of 1/20 = .05.

9. Superelevation deficiency - The amount of additional superelevation needed on a curve to correspond to AASHTO recommendations. For an actual superelevation of .06, with a .08 optimal superelevation, the superelevation deficiency would be .02.

10. Total Roadway width - The width (in ft) of the lanes plus shoulders of the curve.

1 ft = 0.3048 m

11. Roadway width - the width (in ft) of the two travel lanes of the curve.

12. Roadway type - The roadway surface material, coded as asphalt or concrete.

13. Inside shoulder width - The width of the shoulder on the inside of the curve. For a curve to the right, the inside shoulder would be the shoulder on the right side.

14. Outside shoulder width - The width of the shoulder on the outside of the curve.

15. Shoulder type - The shoulder surface, recorded as bituminous, concrete, gravel, or grass.

16. Tangent distance before and after curve - For each curve, a tangent distance is measured to the curve before and the curve after. Of those two tangents (although one or both tangents may be 0 length in the case of compound curves or reverse curves), the maximum and minimum distances were recorded.

17. Roadside recovery distance (or recovery area distance) - A measure of the average distance from the edgeline to rigid objects (e.g., trees, utility poles) or steep slopes (i.e., 3:1 or steeper) on both sides of the road on a curve).

18. Roadside hazard scale - A measure of the degree of hazard of the roadside for a run-off-road vehicle on a 7-point scale, where a 1 is the safest (i.e., clear level roadside relatively clear of rigid obstacles) and 7 is the worst (i.e., steep slope and/or rigid obstacles near the roadway edge).

19. Terrain - The general classification of the area, in terms of flat, rolling, or mountainous.

20. Maximum grade - The percent of vertical grade on the curve at the steepest point.

21. Functional class - The federal classification of the roadway, which may include major arterial, minor arterial, or major collector.

22. Total accidents - Total number of accidents on the curve in a 5-year period.

23. Accidents by severity - Number of fatal, injury, and property damage only accidents on the curve.

Figure 3. List of curve variables in the Washington State data base with definitions.

24. People injured and killed - Number of people hurt and killed on the curve.

25. Accidents by type - Number of head-on, opposite-direction sideswipe, fixed-object, rollover, same-direction sideswipe, rear-end (both moving), and other accident types on the curve.

26. Accidents by road condition - Number of accidents on the curve during dry, wet, and snowy/icy road surfaces.

27. Accidents by daylight conditions - Number of accidents on the curve during light and dark conditions (where dark includes dawn or dusk accidents).

28. Accident involvements by vehicle type - Number of accident involvements on the curve by passenger cars, pickup trucks, truck tractors with semi-trailers, motorcycles, and all other vehicles.

29. Accidents by driver sobriety - Number of accidents on the curve involving one or more drinking drivers, non-drinking drivers, and unknown driver sobriety.

30. Serious accidents by type - Number of injury or fatal accidents on the curve which were head-on, opposite-direction sideswipe, fixed-object, rollover, same-direction sideswipe, and rear-end (both moving).

31. Accidents by severity on curve + .05 mi buffer* - The number of PDO, injury, and fatal accidents on the curve plus .05 mile on either side of the curve.

32. Accidents by type on curve + .05 mile buffer* - The number of accidents involving head-on, opposite-direction sideswipe, fixed object, rollover, same direction sideswipe, rear-end (both moving) and total accidents on the curve plus .05 mile on either side of the curve.

33. Accidents by severity on curve + .10 mile buffer* - Same as item 28 above, except for .10 mile buffer on either side of the curve.

34. Accidents by type on curve + .10 mile buffer* - Same as item 29 above, except with .10 mile buffer on either side of the curve.

35. Accidents by severity on tangent sections - Same as item 20, except these are accidents on the tangent segment of the 3,427 matched curve/tangent pairs.

36. Accidents by type on tangent sections - Same as item 22, except these are accidents on the tangent segment of the 3,427 matched curve/tangent pairs.

*Accidents were coded for the curve plus the .05 (.08 km) or .10 mi (.16 km) buffer only if a tangent of at least 2 times that buffer existed for a given curve.

Figure 3. List of curve variables in the Washington State data base with definitions (Continued).

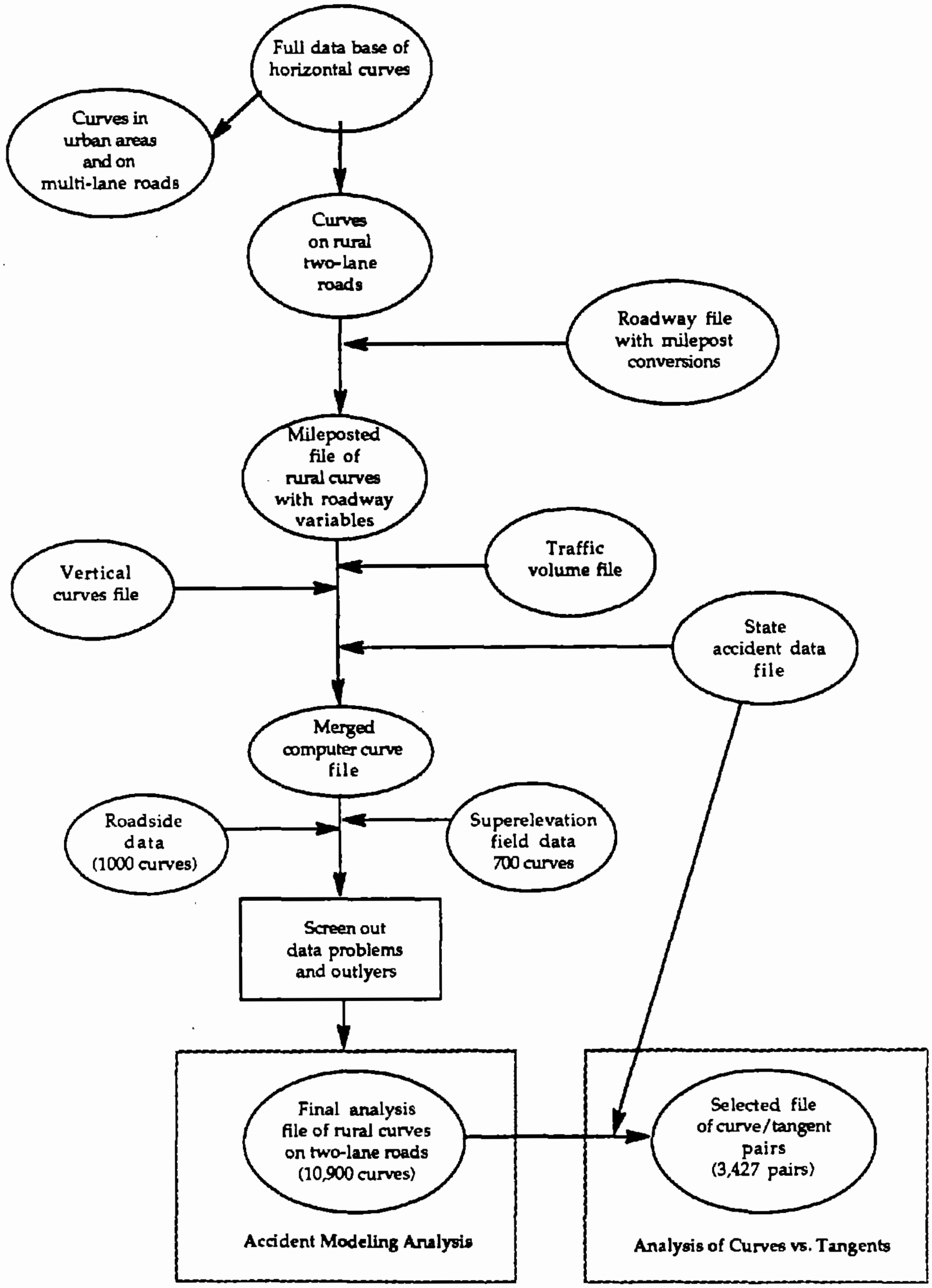

Figure 4. Sketch of the Washington data merging process and related data files.

In developing the curves data base, several key issues needed to be addressed. These included:

1. What should be the curve segment used as the unit for analysis? In the previous FHWA four-State curve study), the chosen segments included a curve with a tangent segment on both ends, such that each curve segment was approximately .61 mi (1.0 km) in length (or greater in a few cases).[10] This long segment of curve plus adjacent tangents was believed to include accidents related to the curve occurring just past the curve and/or accidents occurring on the curve where the milepost may have been incorrectly coded by the police officer as on the tangent. That type of data segment has some advantages for analysis purposes, but basically required omission of curves with short tangents between curves, which are quite common in mountainous areas. Thus, that data base consisted largely of "isolated" curves. For purposes of the current study, it was decided to select all horizontal curves regardless of the length between curves and to record the "tangent distance before curve" and "tangent distance after curve" as roadway variables for each curve. This would allow for determining the effect of adjacent tangent lengths on curve accidents and then control for that effect, if necessary. For the Washington State data base, a curve was considered to include the full length from the beginning to the end of the arc. If a spiral transition existed, the spiral length on both ends of the curve was included as part of the curve.

2. What was the area of influence of the curve for purposes of recording accidents related to the curve? It was believed that some accidents occur when a motorist loses control on a curve and strikes another vehicle or a fixed object on the tangent past the curve. Also, it was assumed that some curve accidents are coded incorrectly as occurring on the tangent just past the curve. Accident frequencies were plotted versus distance from the curve for nine categories of curve (i.e., combinations of various degree of curve and length of curve) to determine whether there appeared to be a "spillover" of accidents just beyond the curve. The results did show some spillover effect, but this was primarily for short curves. This seems logical since there is a greater chance for an officer to miscode a curve accident on a very short curve where the range of mileposts is small. As a result of this analysis, it was decided to omit curves in the data base which were extremely short (i.e., < 100 ft (30.5 m), or .019 mi (.03 km)), to minimize problems due to inaccurate accident location by the investigating officer. This accounted for only a relatively small number of curves being omitted. In addition, accident variables for each curve were coded to include three types of accident fields:

(1) accidents on the curve itself, (2) accidents on the curve + .05 mi (.08 km) of tangent on both ends, and (3) accidents on the curve + .10 mi (.16 km) of tangent on each end. Of course, such accident fields were possible only for curves with sufficient tangents on each end of the curve. Preliminary analysis of these accident fields revealed results basically similar to those using accidents on the curve alone. Thus, all further analyses discussed for the Washington State curves data base uses accidents only within the limits of the curve.

3. <u>Should curves be omitted based on traffic volume or location with respect to physical consistency</u>? The four-State curve study generally omitted curves with ADT's less than 1,500, curves which were within 330 ft (101 m) of a roadway width change, curves within 650 ft (198 m) of a bridge end, and/or curves within .61 mi (1.0 km) of an intersection.(2) It was decided not to delete curves for low ADT's, since a full range of curve conditions was desired for analysis purposes. Since individual curve segments were selected (instead of .61 mi (1.0 km) sections), intersection and bridge effects were believed to be less of a problem. However, to verify this, the analysis included not only total accidents but also "curve-related" accidents (i.e., fixed-object, head-on, rollover, and opposite direction sideswipe). The influence of intersection accidents (i.e., largely rear-end, angle and turning accidents) was not found to adversely affect the results. Specifically, the relationships between curve features and "related" accidents was found to be basically similar as their relationship to "total" accidents. In short, curves were not deleted based on those factors. However, curves were eliminated which were in urban areas, or on Interstates and other multilane roads. The curve sample, therefore, was only for two-lane rural roads.

4. <u>Should field superelevation data be collected</u>? Researchers of a recent FHWA curve study collected and analyzed superelevation data from a four-State curve sample.(2) This subsample consisted of data on 333 curves, approximately equally split among those having the highest accident rates from the original data set, and those having the lowest accident rates. The authors used linear discriminant analyses to analyze these data, and no significant effects were initially found for any measures of superelevation. However, these same data were reanalyzed in the current study with the objective of investigating various interactions of superelevation with other variables. Contingency table analyses and categorical data models were used to identify subsets of curves having a higher-than-expected proportion of high accident sites.

   Two significant interactions involving maximum superelevation were identified. One of these involved curves of moderate to high degree of curvature (> 1 degree) and low maximum superelevation (< .035). It should be noted that all but three of these curves had degrees < 3, so this was, for the most part, a problem of curves of moderate degree (1 to 3 degrees) and very little superelevation (< .035).

The other measure of superelevation which was analyzed with the four-State data base was the superelevation ratio, i.e., the ratio of the superelevation at the beginning of the curve (i.e., called the point of curve, or PC) divided by the maximum superelevation on the curve. A superelevation ratio of about .7 would correspond to a situation which is considered desirable according to current design policy, that is, 70 percent of the superelevation is provided on the tangent approach to the curve and the rest is added within the curve itself. For example, assume a curve has a maximum superelevation of .08 (at the center of the curve). If the superelevation is increased on the approach tangent to a value of .056 at the point of curve (PC) and increased proportionally to the .08 maximum, then the superelevation ratio would be .056/.08 = .70. A superelevation ratio of 0 would suggest no superelevation at the PC and thus, the driver faces a curve where all of the superelevation is added after entering the curve. Such low ratios would indicate less smooth transitions of superelevation and more potential vehicle handling problems for the driver, as compared to a higher superelevation ratio.

The results of the analysis showed that curves having higher values of superelevation (> .035) and relatively low superelevation ratio values (< .25) were high accident locations more often than expected. These findings suggest the following:

- Curves of 1 degree or greater with a maximum superelevation below .035 have a greater likelihood of being high-accident locations.

- The proper transitioning of superelevations from the approach tangent to the curve is important. In particular, curves with a maximum superelevation of > .035, with less than 25 percent of the superelevation prior to the PC have a greater likelihood of being high-accident locations.

The findings from this analysis suggest that superelevation should be further studied from field data to be collected on a subset of curves in Washington State. A more in-depth analysis such as this would be important to better quantify the expected effect of improving superelevation on accidents.

5. <u>What criteria should be used for selecting curves to collect field superelevation data</u>? For the funds available for collecting field data in Washington on superelevation, it was decided to select sites from among the 1,039 curves where roadside data was also available. This would result in a sample of curves with a full range of available data variables. Further, it was essential to collect data for some curves with adequate superelevation and some curves with substandard superelevation, since the effect of substandard

superelevation could not be determined if all curves collected had adequate superelevation. Prior to data collection, it was not known which curves had deficient superelevation. Thus, counties were selected for data collection which contained a relatively large number of candidate sections and a range of curve conditions.

After all files were merged, extensive data checking and verification was conducted. This included:

- Printing frequency distributions for every variable and verifying and/or deleting data errors.
- Discussing selected data outliers with Washington DOT officials. Checks were made, for example, of the high-accident locations and for questionable degrees of curve and central angles.
- Verifying a sample of curve records with maps and other records.

Curve records were deleted from the analysis file where there were suspected data problems, errors, or unverifiable data values.

In addition to developing a file of 10,900 curves, a curve/tangent paired data base was created from the full analysis file. This consisted of selecting 3,427 of the 10,900 curves which had a tangent of equal or greater length directly after the curve, in addition to a buffer area of 0.05 mi (.08 km) after the preceding curve and before the next curve. Accidents for the tangent segments were obtained from the computerized accident file. The curve/tangent paired data file was discussed in chapter 5.

Data Base Characteristics

A summary of the curve sample is given in table 16 by degree of curve and length of arc. The definition of degree of curve used was that of degrees traveled per 100 ft (30 m) of arc. For example, if a roadway going northbound contains a curve of 900 ft (274 m) long before proceeding eastbound, then the road curved 90 degrees (north to east) over 900 ft (274 m), or 90 degrees/900 ft (274 m) = 10 degrees per 100 ft (30 m) of arc, which represents a 10 degree curve. Of the 10,900 curves in the data base, the most prevalent curvature groupings have degrees of curve of 2.01 to 5 degrees (33.25 percent), 5.01 to

Table 16. Distribution of Washington curves by degree of curve and length of arc.

DEGREE OF CURVE FREQUENCY PERCENT ROW PCT COL PCT	LENGTH OF ARC 0.010 - 0.050 MI	0.051 - 0.100 MI	0.101 - 0.200 MI	0.201 - 0.300 MI	OVER .30 MILES	TOTAL
0.5 DEG OR LESS	41*	58	74	27	52	252
	0.38	0.53	0.68	0.25	0.48	2.31
	16.27	23.02	29.37	10.71	20.63	
	1.64	1.85	2.31	2.26	6.08	
0.51 - 1 DEGREE	93	183	271	154	203	904
	0.85	1.68	2.49	1.41	1.86	8.29
	10.29	20.24	29.98	17.04	22.46	
	3.71	5.83	8.45	12.90	23.74	
1.01 - 2 DEG	120	381	577	316	266	1660
	1.10	3.50	5.29	2.90	2.44	15.23
	7.23	22.95	34.76	19.04	16.02	
	4.79	12.15	17.99	26.47	31.11	
2.01 - 5 DEG	457	979	1363	527	298	3624
	4.19	8.98	12.50	4.83	2.73	33.25
	12.61	27.01	37.61	14.54	8.22	
	18.24	31.21	42.49	44.14	34.85	
5.01 - 10 DEG	809	1064	788	164	36	2861
	7.42	9.76	7.23	1.50	0.33	26.25
	28.28	37.19	27.54	5.73	1.26	
	32.28	33.92	24.56	13.74	4.21	
10.01 - 20 DEG	581	379	120	6	0	1086
	5.33	3.48	1.10	0.06	0.00	9.96
	53.50	34.90	11.05	0.55	0.00	
	23.18	12.08	3.74	0.50	0.00	
20.01 - 30 DEG	199	62	14	0	0	275
	1.83	0.57	0.13	0.00	0.00	2.52
	72.36	22.55	5.09	0.00	0.00	
	7.94	1.98	0.44	0.00	0.00	
OVER 30 DEGREE	206	31	1	0	0	238
	1.89	0.28	0.01	0.00	0.00	2.18
	86.55	13.03	0.42	0.00	0.00	
	8.22	0.99	0.03	0.00	0.00	
TOTAL	2506	3137	3208	1194	855	10900
	22.99	28.78	29.43	10.95	7.84	100.00

* Cell contains number of curves, overall percent, row percent, and column percent, respectively.

10 degrees (26.25 percent), and 1.01 to 2 degrees (15.23 percent). Only 1,156 curves (10.6 percent) have curvatures of less than 1 degree while 513 (4.7 percent) have greater than 20 degrees of curvature.

In terms of curve length, the study sample was limited to curves of 100 ft, or .019 mi (30 m, or .031 km) or greater, since greater inaccuracies were expected to result in the locating of accidents accurately on extremely short curves (i.e., almost no margin for error in accident reporting), as discussed earlier. Of the 10,900 curves in the data base, 2,506 (22.99 percent) are .01 to .05 mi (.02 to .08 km) long, 3,137 (28.8 percent) curves are .051 to .100 mi (.082 to .161 km) long, and 3,208 (29.4 percent) are .101 to .200 mi (.163 to .322 km) long. In other words, 81.2 percent of the study curves are .20 mi (.32 km) or shorter. It is also interesting to note from table 16 the predominance of sharp curves which were short, as is often found in mountainous areas. On the other hand, mild curves tended to be more uniformly distributed over various lengths.

Of the Washington State curves in the data base, 2,895 (26.6 percent) are on principal arterials, 5,512 (50.6 percent) are on minor arterials, and 2,493 (22.9 percent) are on major collector streets (see table 17). In terms of the area type, 7,919 curves (72.7 percent) are on roads in rolling terrain, while 1,832 curves (16.8 percent) are in mountainous areas and 1,149 curves (10.5 percent) are in level terrain. These numbers likely indicate that the State-maintained road system in Washington consists largely of arterial routes in rolling terrain, which would explain the high frequency of horizontal curves in those categories.

The width of the surface width (i.e., two travel lanes) varied from 16 ft to 28 ft (4.9 m to 8.5 m) for curves in the data base, with nearly half (5,269 or 48.3 percent) of the curves having a 22 ft (6.7 m) roadway width (table 18). Roadway widths of 20 to 24 ft (6.1 to 7.3 m) accounted for 10,399 curves or 95.4 percent. Only curves with paved roadway surfaces were included in the data base.

Shoulder widths most often ranged between 2 and 4 ft (0.6 to 1.2 m) (6,654 curves or 61.0 percent), although 8-ft (2.4 m) shoulders were not uncommon

Table 17. Distribution of Washington curves by functional class and terrain.

ROADWAY FUNCTIONAL CLASS — TERRAIN

FREQUENCY PERCENT ROW PCT COL PCT	LEVEL	ROLLING	MOUNTAINOUS	TOTAL
PRINC ARTERIAL	214 1.96 7.39 18.62	2334 21.41 80.62 29.47	347 3.18 11.99 18.94	2895 26.56
MINOR ARTERIAL	595 5.46 10.79 51.78	3549 32.56 64.39 44.82	1368 12.55 24.82 74.67	5512 50.57
MAJOR COLLECTOR	340 3.12 13.64 29.59	2036 18.68 81.67 25.71	117 1.07 4.69 6.39	2493 22.87
TOTAL	1149 10.54	7919 72.65	1832 16.81	10900 100.00

Table 18. Distribution of Washington curves by surface width and inside shoulder width.

SURFACE WIDTH — SHOULDER WIDTH, INSIDE

FREQUENCY / PERCENT / ROW PCT / COL PCT	NO SHOULDER	1 FT	2 FT	3 FT	4 FT	5 FT	6 FT	7 FT	8 FT	9 - 12 FT	TOTAL
16 - 19 FT	2	0	237	20	9	0	5	0	0	0	273
	0.02	0.00	2.17	0.18	0.08	0.00	0.05	0.00	0.00	0.00	2.50
	0.73	0.00	86.81	7.33	3.30	0.00	1.83	0.00	0.00	0.00	
	1.32	0.00	9.53	1.03	0.40	0.00	0.60	0.00	0.00	0.00	
20 FT	0	83	628	245	294	56	39	0	11	11	1367
	0.00	0.76	5.76	2.25	2.70	0.51	0.36	0.00	0.10	0.10	12.54
	0.00	6.07	45.94	17.92	21.51	4.10	2.85	0.00	0.80	0.80	
	0.00	11.56	25.26	12.65	13.17	11.99	4.72	0.00	0.73	3.50	
21 FT	0	57	116	38	126	5	34	5	25	21	427
	0.00	0.52	1.06	0.35	1.16	0.05	0.31	0.05	0.23	0.19	3.92
	0.00	13.35	27.17	8.90	29.51	1.17	7.96	1.17	5.85	4.92	
	0.00	7.94	4.67	1.96	5.65	1.07	4.11	1.98	1.65	6.69	
22 FT	2	368	1043	1134	1091	233	437	60	826	75	5269
	0.02	3.38	9.57	10.40	10.01	2.14	4.01	0.55	7.58	0.69	48.34
	0.04	6.98	19.80	21.52	20.71	4.42	8.29	1.14	15.68	1.42	
	1.32	51.25	41.95	58.57	48.88	49.89	52.84	23.72	54.49	23.89	
23 FT	0	47	185	226	147	51	64	61	176	24	981
	0.00	0.43	1.70	2.07	1.35	0.47	0.59	0.56	1.61	0.22	9.00
	0.00	4.79	18.86	23.04	14.98	5.20	6.52	6.22	17.94	2.45	
	0.00	6.55	7.44	11.67	6.59	10.92	7.74	24.11	11.61	7.64	
24 FT	92	141	260	197	537	116	242	120	474	176	2355
	0.84	1.29	2.39	1.81	4.93	1.06	2.22	1.10	4.35	1.61	21.61
	3.91	5.99	11.04	8.37	22.80	4.93	10.28	5.10	20.13	7.47	
	60.93	19.64	10.46	10.18	24.06	24.84	29.26	47.43	31.27	56.05	
25 - 28 FT	55	22	17	76	28	6	6	7	4	7	228
	0.50	0.20	0.16	0.70	0.26	0.06	0.06	0.06	0.04	0.06	2.09
	24.12	9.65	7.46	33.33	12.28	2.63	2.63	3.07	1.75	3.07	
	36.42	3.06	0.68	3.93	1.25	1.28	0.73	2.77	0.26	2.23	
TOTAL	151	718	2486	1936	2232	467	827	253	1516	314	10900
	1.39	6.59	22.81	17.76	20.48	4.28	7.59	2.32	13.91	2.88	100.00

(1,516 curves). While not shown in the tables, the most common shoulder surfaces consisted of asphalt (8,442 curves), gravel (2,287 curves), concrete (24 curves), and soil (24 curves).

Spiral transitions exist on both ends of the curve for 1,927 curves (17.7 percent), are not used on 8,913 curves (81.8 percent), and are present on only one end of the curve at 60 curves (0.6 percent). The maximum vertical grade by curve (see table 19) varies widely with 1,105 curves (10.7 percent) on level grade, 4,478 curves (43.5 percent) on grades of >0 to 2 percent, 3,027 curves (27.8 percent) on grades of >2 to 5 percent, and 1,694 curves (15.5 percent) on grades of greater than 5 percent. A large portion of the curves with steep grades (i.e., above 3 percent) occur on relatively sharp curves (i.e., 2 to 20 degree curves).

The most prevalent Average Daily Traffic (ADT) ranges for these curves are 1,001 to 2,000 (30.6 percent), 2,001 to 5,000 (32.9 percent) and 501 to 1,000 (18.3 percent), as shown in table 20. ADT's of 500 or below occur at 1,222 curves (11.2 percent), while only 764 curves (7.0 percent) have ADT's of 5,000 or greater. It is apparent that curves in mountainous areas have generally lower traffic volumes than curves in flat or rolling areas. In fact, 86.5 percent (1,584 out of 1,832) of curves in mountainous areas have ADT's of 2,000 or less compared to 43.4 percent in level areas and 56.4 percent in rolling areas.

General Accident Characteristics

For the 10,900 curves in the Washington State data base, there were a total of 12,123 accidents. This is an average of 1.11 accidents per 5-year period, or 0.22 accidents per year per curve. Crashes by severity included 6,500 property damage only accidents (53.6 percent), 5,359 injury accidents (44.2 percent), and 264 fatal accidents (2.2 percent), as shown in table 21. A total of 8,434 people were injured and 314 were killed in these accidents.

The most common accident types were fixed-object crashes (41.6 percent) and rollover crashes (15.5 percent). In terms of road condition, wet pavement and icy/snowy pavement conditions each accounted for approximately 21.5 percent

Table 19. Distribution of Washington curves by degree of curve and maximum grade.

DEGREE OF CURVE — MAXIMUM GRADE

FREQUENCY / PERCENT / ROW PCT / COL PCT	FLAT	>0 - 1	>1 - 2	>2 - 3	>3 - 5	>5 - 7	OVER 7%	TOTAL
1 DEGREE OR LESS	88	473	188	117	131	57	2	1056
	0.85	4.59	1.82	1.14	1.27	0.55	0.02	10.25
	8.33	44.79	17.80	11.08	12.41	5.40	0.19	
	7.96	16.14	12.14	11.44	6.54	3.61	1.75	
1.01 - 2 DEG	105	582	287	175	285	152	5	1591
	1.02	5.65	2.79	1.70	2.77	1.48	0.05	15.44
	6.60	36.58	18.04	11.00	17.91	9.55	0.31	
	9.50	19.86	18.54	17.11	14.22	9.62	4.39	
2.01 - 5 DEG	322	1006	574	378	678	465	25	3448
	3.13	9.76	5.57	3.67	6.58	4.51	0.24	33.46
	9.34	29.18	16.65	10.96	19.66	13.49	0.73	
	29.14	34.33	37.08	36.95	33.83	29.43	21.93	
5.01 - 10 DEG	324	596	372	246	600	540	38	2716
	3.14	5.78	3.61	2.39	5.82	5.24	0.37	26.36
	11.93	21.94	13.70	9.06	22.09	19.88	1.40	
	29.32	20.34	24.03	24.05	29.94	34.18	33.33	
10.01 - 20 DEG	171	210	102	86	204	223	24	1020
	1.66	2.04	0.99	0.83	1.98	2.16	0.23	9.90
	16.76	20.59	10.00	8.43	20.00	21.86	2.35	
	15.48	7.17	6.59	8.41	10.18	14.11	21.05	
OVER 20 DEGREE	95	63	25	21	106	143	20	473
	0.92	0.61	0.24	0.20	1.03	1.39	0.19	4.59
	20.08	13.32	5.29	4.44	22.41	30.23	4.23	
	8.60	2.15	1.61	2.05	5.29	9.05	17.54	
TOTAL	1105	2930	1548	1023	2004	1580	114	10304
	10.72	28.44	15.02	9.93	19.45	15.33	1.11	100.00

FREQUENCY MISSING = 596

Table 20. Distribution of Washington curves by average daily traffic and terrain.

AVERAGE DAILY TRAFFIC TERRAIN

FREQUENCY PERCENT ROW PCT COL PCT	LEVEL	ROLLING	MOUNTAINOUS	TOTAL
100 OR FEWER VEH	0 0.00 0.00 0.00	26 0.24 74.29 0.33	9 0.08 25.71 0.49	35 0.32
101 - 500 VEH	11 0.10 0.93 0.96	830 7.61 69.92 10.48	346 3.17 29.15 18.89	1187 10.89
501 - 1000 VEH	77 0.71 3.87 6.70	1370 12.57 68.84 17.30	543 4.98 27.29 29.64	1990 18.26
1,001 - 2,000	411 3.77 12.32 35.77	2240 20.55 67.13 28.29	686 6.29 20.56 37.45	3337 30.61
2,001 - 5,000	512 4.70 14.27 44.56	2827 25.94 78.81 35.70	248 2.28 6.91 13.54	3587 32.91
5,000 - 10,000	124 1.14 19.71 10.79	505 4.63 80.29 6.38	0 0.00 0.00 0.00	629 5.77
10,000 - 15,000	14 0.13 12.39 1.22	99 0.91 87.61 1.25	0 0.00 0.00 0.00	113 1.04
15,001 - 20,000	0 0.00 0.00 0.00	22 0.20 100.00 0.28	0 0.00 0.00 0.00	22 0.20
TOTAL	1149 10.54	7919 72.65	1832 16.81	10900 100.00

Table 21. Summary of accident statistics on Washington State curve sample.

Variable	Frequency	Percent
Total accidents	12,123	100.0
PDO accidents	6,500	53.6
Injury accidents	5,359	44.2
Fatal accidents	264	2.2
People injured	8,434*	N.A.
People killed	314*	N.A.
Head-on accidents	517	4.3
Opposite direction sideswipe accidents	468	3.9
Fixed object accidents	5,045	41.6
Rollover accidents	1,874	15.5
Same direction sideswipe	139	1.1
Rear-end both moving	303	2.5
Other collision types	3,777	31.2
Dry road accidents	6,914	57.0
Wet road accidents	2,609	21.5
Snowy/icy road accidents	2,600	21.4
Daylight accidents	6,828	56.3
Dark, dawn, dusk accidents	5,295	43.7
Passenger car involvements	9,793	60.2**
Pickup truck involvements	4,541	27.9**
Semi-truck and trailer involvements	807	5.0**
Motorcycle involvements	448	2.8**
Other vehicle involvements	665	4.1**

*These are numbers of people injured or killed, and not the number of crashes in which someone was injured or killed.

**These represent vehicle involvement percentages since more than one vehicle is involved in some crashes.

of the accidents with the other 57.0 percent on dry pavement. Crashes at night accounted for 43.7 percent of curve accidents, which is probably higher than the percent of nighttime traffic volume. The most frequent vehicle types involved in curve crashes were passenger cars (60.2 percent) followed by pickup trucks (27.9 percent).

A summary of statistics for key accident and roadway variables in the curve data base is given in table 22. The 10,900 curves ranged from a minimum of 0.1 degree to 119 degrees (per 100 ft (30 m) of arc), with a mean of 6.8 degrees. There were a few "hairpin" curves on mountain roads which were verified based on discussions with Washington DOT officials and with assistance from detailed maps and photologs of the highway. Curve lengths ranged from 0.019 mi (.031 km) or 100 ft (30 m) to a maximum of 1.85 mi (2.98 km). The mean length was 0.13 mi (686 ft) (209 m), which reflects the large number of short curves in the data base. The mean central angle was 28.5 degrees, with a range from 0.18 degrees to 216.4 degrees. A few curves which had central angles exceeding 180 degrees existed on roadways which wound down mountainsides.

The average traffic volume was 2,209 with a wide range of 100 to 19,150. The maximum grade on the curves averaged 2.4 percent, while shoulder widths averaged about 4 ft (1.2 m) and ranged from 0 to 12 ft (3.7 m). The width of the roadway surface (i.e., two travel lanes) averaged 22.2 ft (6.8 m) and varied from 16 to 28 ft (4.9 to 8.5 m), which corresponds to 8 ft (2.4 m) lanes to 14 ft (4.3 m) lanes. Average roadside recovery distance was 7.4 ft (2.3 m), with roadside ratings (7 point scale of roadside hazard) averaging 4.7, which indicate that roadsides were of relatively high hazard for a large portion of the curves in the data base where such roadside data were available.

The mean accident rate for the curve sample was 2.79 crashes per million vehicle mi (1.61 km), with a range of 0 to 210.8. There were a few extreme accident rates which resulted from 1 or 2 accidents occurring on curves which were short and had low ADT's. For example, a 0.02 mi (.03 km) curve with one accident in 5 years and an ADT of 137 yields an accident rate of approximately 200 accidents per million vehicle miles (1.6 km). Accidents per 0.1 mi (0.16 km) per year averaged 0.2 and ranged from 0 to 9.5.

Table 22. Summary of statistics for selected variables.

Variable	No. of Cases	Minimum Value	Maximum Value	Mean	Standard Deviation
Degree of curve (degrees)	10,900	.10	119.4	6.8	8.1
Length of curve (mi)	10,900	.019	1.85	.13	.12
Central angle (degrees)	10,900	.18	216.4	28.5	23.2
Average daily traffic (ADT)	10,900	100	19,150	2,209	2,027
Maximum grade (%)	10,304	0	20	2.4	2.2
Outside shoulder width (ft)	10,900	0	12.0	4.0	2.4
Inside shoulder width (ft)	10,900	0	12.0	4.1	2.4
Roadway surface width (ft)	10,900	16	28	22.2	1.5
Roadside recovery area distance (ft)	1,039	0	28	7.4	4.6
Average roadside rating	1,039	2	7	4.7	.91
Accident rate (accs/mvm)	10,900	0	210.8	2.79	7.36
Accidents (per .1 mi (.16 km) per year)	10,900	0	9.5	0.2	0.4

Accident rates are shown for various severities and types of accidents in table 23. For example, the number of accidents per million vehicle mi (1.61 km) was found to be 1.48 for property damage only (PDO) accidents, 1.25 for non-fatal injury accidents, and .06 for fatal accidents. Such rates were 1.37 for fixed-object accidents, and 0.51 for rollover accidents. The rate of accidents <u>per million entering vehicles</u> (i.e., curve length is not used in this calculation) was .270 for total accidents, .144 for PDO accidents, .120 for injury accidents, and .006 for fatal accidents. The number of accidents per 5-year period is also given by accident type. For example, .17 rollover accidents are expected to occur per 5 years at an average highway curve in the Washington State data base, or (.17 ÷ 5 years =) .034 per year. In other words, a rollover accident occurs an average of once every (1 ÷ .034 =) 29.4 years for curves in the Washington curve data sample. Based on total accidents of 1.11 per 5 years, a curve accident is expected to occur an average of .222 per year, or one accident per 4.5 years. Of course, many curve sites have 0 accidents in a given 5-year period, and some curves have abnormally high accident experiences.

Table 23. Summary of accident rate measures for various accident severities and types - Washington curves data base.

Accident Variable	Accident Rate (Accs per MVM)	Accident Rate (Accs per MV)	Avg. No. of Accidents per 5 Years per Curve
Total accidents	2.79	.270	1.11
PDO accidents	1.48	.144	.60
Injury accidents	1.25	.120	.49
Fatal accidents	.06	.006	.02
Head-on accidents	.11	.010	.05
Opposite direction sideswipe acc.	.12	.010	.04
Fixed object accidents	1.37	.124	.46
Rollover accidents	.51	.051	.17
Same direction sideswipe	.02	.002	.01
Rear-end both moving acc.	.04	.004	.03
Other collision type acc.	.62	.068	.35

It was also considered informative to provide the distribution of curves by various accident frequencies. As shown in table 24, 6,073 of the 10,900 curves (55.7 percent) had no accidents in the 5-year period. Another 3,432 curves (31.5 percent) had 1 or 2 accidents, 985 curves (9.0 percent) had 3 to 5 accidents, and 307 curves (2.8 percent) had between 6 and 10 accidents in the 5-year period. A total of 84 curves had between 11 and 20 accidents, and only 19 of the 10,900 curves had more than 20 accidents in the 5-year period. Thus, the accident distribution is highly skewed toward low accident frequencies.

Determination of Important Variables

Before developing accident prediction models for horizontal curves, it was important to determine the accident types which were most related to curvature. Based on the results in chapter 5, for example, it was believed that either widening or flattening the curve would most likely reduce head-on and run-off-road accidents, with little or no effect on pedestrian, animal, and right-angle accidents. It is possible that rear-end accidents may also be reduced by flattening a curve, since vehicles would not need to slow down as much (from the tangent to the curve) on a mild curve compared to a sharp curve. In the earlier analysis of the curve/tangent paired data base (chapter 5), the accident types found to be most related to curves (as compared to tangents) were fixed-object, rollover, head-on, and opposite-direction sideswipe. This analysis based on degree of curvature was intended to further investigate the accident types which should be used for curve accident modeling and analyses.

For each curve segment in the data base, the number of accidents was summarized by type (e.g., head-on, rollover, fixed object), weather (dry, wet, snow/ice), light condition (daylight or dark), occupant injury (A-type, B-type, or C-type, or fatal injury), vehicle type (car, pickup, semitrailer, motorcycle), and driver sobriety (drunk or sober). Also, accidents were summarized by accident type for which an injury or fatality occurred (e.g., the number of head-on accidents involving at least one person injured or killed). For each of 34 accident types or categories (see table 25), regression models of the form

Table 24. Summary of accident frequency distribution.

TOTALACC

TERRAIN(RDWAY TERRAIN)

FREQUENCY / PERCENT / ROW PCT / COL PCT	LEVEL	MOUNTAINOUS	ROLLING	TOTAL
0	513 4.71 8.45 44.65	1235 11.33 20.34 67.41	4325 39.68 71.22 54.62	6073 55.72
1 - 2 ACCIDENTS	424 3.89 12.35 36.90	454 4.17 13.23 24.78	2554 23.43 74.42 32.25	3432 31.49
3 - 5 ACCIDENTS	145 1.33 14.72 12.62	110 1.01 11.17 6.00	730 6.70 74.11 9.22	985 9.04
6 - 10 ACCS	52 0.48 16.94 4.53	30 0.28 9.77 1.64	225 2.06 73.29 2.84	307 2.82
11 - 15 ACCS	9 0.08 15.00 0.78	3 0.03 5.00 0.16	48 0.44 80.00 0.61	60 0.55
15 - 20 ACCS	3 0.03 12.50 0.26	0 0.00 0.00 0.00	21 0.19 87.50 0.27	24 0.22
21 - 25 ACCS	2 0.02 22.22 0.17	0 0.00 0.00 0.00	7 0.06 77.78 0.09	9 0.08
26 - 30 ACCS	1 0.01 25.00 0.09	0 0.00 0.00 0.00	3 0.03 75.00 0.04	4 0.04
31 - 40 ACCS	0 0.00 0.00 0.00	0 0.00 0.00 0.00	1 0.01 100.00 0.01	1 0.01
41 - 50 ACCS	0 0.00 0.00 0.00	0 0.00 0.00 0.00	1 0.01 100.00 0.01	1 0.01
*OVER 50 ACCS	0 0.00 0.00 0.00	0 0.00 0.00 0.00	4 0.04 100.00 0.05	4 0.04
TOTAL	1149 10.54	1832 16.81	7919 72.65	10900 100.00

$$\log \text{accidents} = \beta_0 + \beta_1 (\text{ADT}) + \beta_2 (\text{length of curve}) + \beta_3 (\text{degree of curve}) + \varepsilon \quad (1)$$

and

$$\log \frac{\text{accidents}}{\text{million vehicle miles}} = \alpha_0 + \alpha_1 (\text{degree of curve}) + \eta$$

were fit to the data. The purpose of these models was to find which accident types were significantly related to degree of curve, while controlling for ADT and curve length.

In terms of accident frequency, only three of the accident types had a p-value above 0.001. These included same-direction sideswipe accidents ($p = .0176$), injury/fatal same direction sideswipe accidents ($p = .1642$) and injury/fatal rear-end both moving ($p = .0326$). This analysis indicates that nearly all accident types are significantly affected by the sharpness of the curve.

The R^2 value indicates the amount of variation in the accident grouping explained by curve sharpness (along with ADT and length of curve), although R^2 is also affected by the accident sample size. The accident types or groups with the highest R^2 values include total accidents as well as other accident classes with relatively large numbers of accidents such as dry weather accidents ($R^2 = .206$) passenger car accidents ($R^2 = .235$), and sober driver accidents ($R^2 = .225$).

Using accident rate (accidents per million vehicle mi (1.6 km)) as the dependent variable and repeating the regression runs, the results were basically similar. Using rates, all accident characteristics were significantly related to degree of curve ($p < .001$). The highest R^2 values were found for motorcycle accidents ($R^2 = .112$), same direction sideswipe injury/fatal accidents ($R^2 = .161$), and opposite direction sideswipe injury/fatal accidents ($R^2 = .108$).

The overall results of these analyses indicate that as curves become sharper, the frequency and rate of virtually all accident types and groupings increase (while controlling for ADT and length of curve). Thus, it would not

Table 25. Summary accident grouping related to curvature.

Accident Characteristics	Accident Frequency: P-Value for Curvature Effect	Accident Frequency: R^2	Accident Rate: P-Value for Curvature Effect	Accident Rate: R^2
Type				
Head-On	.0001	.054	.0001	.060
Opposite Direction Sideswipe	.0001	.042	.0001	.069
Fixed-Object	.0001	.147	.0001	.040
Rollover	.0001	.085	.0001	.037
Related (Combined 4 Types Above)	.0001	.204	.0001	.025
Same Direction Sideswipe	.0176	.020	.0001	.090
Rear End-Both Moving	.0010	.042	.0001	.056
Other Types	.0001	.162	.0001	.002
Total Accidents	.0001	.262	.0001	.011
Weather				
Dry Weather	.0001	.206	.0001	.008
Wet Weather	.0001	.118	.0001	.039
Snow/Ice	.0001	.116	.0001	.018
Light Condition				
Daylight	.0001	.198	.0001	.014
Dark	.0001	.188	.0001	.013
Crash Severity				
Injury	.0001	.177	.0001	.018
Fatal	.0001	.023	.0001	.092
A-Type Injury	.0001	.071	.0001	.046
B-Type Injury	.0001	.115	.0001	.025
C-Type Injury	.0001	.086	.0002	.040
Vehicle Type				
Passenger Car	.0001	.235	.0001	.007
Pickup Truck	.0001	.163	.0001	.013
Tractor Semi Trailer	.0001	.051	.0001	.053
Motorcycle	.0001	.019	.0001	.112
Other Vehicle	.0001	.045	.0001	.048
Total Vehicles	.0001	.267	.0001	.007
Sobriety				
Drunk Driver	.0001	.105	.0001	.041
Sober Driver	.0001	.225	.0001	.008
Unknown Driver Sobriety	.0001	.100	.0001	.020
Type x Crash Severity				
Head-On-Injury/Fatal	.0001	.041	.0001	.077
Opposite Direction Sideswipe (Inj./Fat.)	.0001	.024	.0001	.108
Fixed-Object-Injury/Fatal	.0001	.094	.0001	.050
Rollover-Injury/Fatal	.0001	.051	.0001	.054
Same Direction Sideswipe Inj/Fatal	.1642	.003	.0001	.161
Rear End Both Moving-Injury/Fatal	.0326	.022	.0001	.093

only be appropriate to use total accidents as the primary dependent variable in further analyses, but most other specific accident types or groupings could also be used for analysis of the effect of curvature, provided that there is an adequate accident sample.

Data Analysis/Model Building

There were, essentially, two major goals for the analysis of the Washington curve data. These goals were: (1) to estimate relationships between the roadway characteristics and accident experience on curves, and, (2) to develop these relationships into accident reduction factors (i.e., the percent reduction in accidents expected due to making certain types of curve improvements). The remaining discussion in this chapter relates to developing such accident relationships (goal 1). Accident reduction factors (goal 2) are discussed in chapter 8.

In pursuing goal 1, many different types of analyses were carried out on the data, and a logical accident predictive model was ultimately developed which fit the data quite well. It was then used for predicting effects of countermeasures on accidents. Some of the early analyses did not seem to lead to very useful results. Selected examples of these analyses will be discussed, but a complete discussion of all the analyses will not be given.

The data analysis and model development involved many different activities. These activities have been organized into the following topics for purposes of discussion:

- Initial regression models.
- Cluster analyses.
- Models within subsets.
- Linear accident rate models.
- Special analyses of curve-related variables.
- Non-linear estimating procedures.

- Development of model for accident reduction factors.
- Summary of analysis results.

Initial Regression Models

As was discussed earlier, accident types were determined which were curve related based on a series of regression analyses of the forms

$$\log(\text{Accidents}) = \beta_0 + \beta_1 \log(\text{ADT}) + \beta_2 \log(\text{Length}) + \beta_3 \text{ Degree} + \varepsilon \qquad (1)$$

and

$$\log(\text{Accidents/million vehicle miles}) = \alpha_0 + \alpha_1 \text{ Degree} + \eta \qquad (2)$$

fit to each of the different types of accidents of interest. Since over 50 percent of the Washington curves experienced no accidents over the 5-year observation period, the quantity 0.01 was added to each accident count before applying the log transformation. <u>All expressions of log in this model and others in this report refer to natural logarithms</u>.

At the next stage in the analysis, attempts were made to include other variables into models (1) and (2) for each of the different accident types. In general, variables were included one at a time in each regression model. If statistically significant variables were found, then the most significant one was retained in the model and the process repeated to attempt to add other variables. The list of potential variables for inclusion in the models included:

- Maximum grade for curve.
- Maximum superelevation*.
- Maximum distance to adjacent curve.
- Minimum distance to adjacent curve.
- Roadside recovery area*.
- Roadside rating scale*.
- Outside shoulder width.
- Inside shoulder width.
- Outside shoulder type.
- Inside shoulder type.
- Surface width.
- Surface type.
- Terrain type.
- Indicator of spirals = Presence of transition spiral

where * indicates that the variable was only available on a subset of the data. Analyses involving these variables are further discussed later in this chapter.

A shoulder width variable was found to be statistically significant for nearly every accident type, and outside shoulder width was usually slightly more significant than inside shoulder width. The two, in fact, were highly correlated. With shoulder width included in the model, surface width (i.e., width of the two travel lanes) was sometimes significant and sometimes not. Moreover, surface width was usually estimated to have a positive coefficient but on occasion had a negative one. From these results, the decision was made to use a single roadway width variable consisting of the sum of surface width, inside shoulder width and outside shoulder width. This variable will subsequently be referred to simply as width.

Using model (1), the only variables found to be statistically significant at levels approaching the 5 percent level were ADT, degree of curve, length of curve, and width. The model of this form estimated for total accidents was,

$$\text{Log (accidents} + .01) = -16.287 + \underset{(.029)}{1.280} \log \text{ADT} + \underset{(.033)}{1.102} \log \text{Length} + \underset{(.003)}{.048}\ \text{Deg} - \underset{(.005)}{.026}\ \text{Width} \qquad (3)$$

where standard errors are shown in parentheses below the regression coefficients. All coefficients were significant at the .0001 level. The model had an $R^2 = .264$. When the variable indicating presence of spirals was included, its estimated coefficient was .0057 with a standard error of .063 and corresponding p-value of .928. Thus, in this form, no significant effect for spirals was found. Models were also estimated with log transformations applied to other variables -- degree, width, etc., and models with various interaction effects were tested. None of these, however, seemed to yield any noticeable improvement over model (3) for total accidents.

It was of interest to further check the fit of model (3) in the sense of comparing actual and predicted values. Scatter plots were not very informative due to the very large sample size, the large overall scatter and the fact that many points fell on top of other points. An alternative method of examining the distribution of actual values relative to the predicted values that seemed more informative was to partition the range of predicted values into subintervals and then examine the distribution of actual values over each subinterval. For model (3), the first step was to generate predicted values of accidents using the model

$$\hat{A} = \text{Exp}\,(-16.287 + 1.280 \log \text{ADT} + 1.102 \log \text{Length} + .048\ \text{Deg} - .026\ \text{Width}) - .01 \qquad (4)$$

Table 26 shows the distributions of actual accidents over five ranges of predicted values, running from the smallest predicted values to the largest. The first line of table 26 considers curves where the predicted number of accidents was very small (< .10). Note that nearly half of the curves were in this lowest range. The mean predicted value for these curves was .034. The percentiles of actual values for these curves show that for more than 75 percent of these curves the actual value was 0 accidents, even though the mean observed value was .345. Thus, for this half of the data, model (4) does fairly well, namely, it predicts very small accident frequencies which usually

Table 26. Comparison of actual and predicted accidents using log transform model.

Range of Predicted Values($\hat{A}$)	N	Mean Predicted	Mean Actual	Actual Percentiles 25th	50th	75th
.01 - .09	5420	.034	.345	0	0	0
.10 - .24	2784	.150	.919	0	1	1
.25 - .53	1599	.355	1.83	0	1	3
.54 - .85	544	.662	3.03	1	2	4
> .85	543	1.76	5.69	2	4	7

correspond to 0 actual values. On the other hand, the last line of table 26 shows that even among the highest 5 percent (i.e., 543 of the 10,890 curves) of the predicted values, some of the predicted values are still less than 1 and the mean predicted value is only 1.76. This compares with 75 percent of the actual values having 2 or more accidents and 50 percent are 4 or more, with an actual mean of 5.69. This sort of behavior (i.e., the model underpredicting accidents in the higher ranges of predicted values) was found, generally, for the models fit using a log transformation including rate models of the model (2). The model form also underpredicts accidents for other accident categories to a considerable degree. Thus, these type models were unsatisfactory for our purposes, and several other alternative types of analyses were next considered, as described below.

Cluster Analyses

The idea behind the cluster analysis approach was that there might tend to exist groups of curves which clustered with respect to their roadway/roadside characteristics. Thus, the curves in one cluster would tend to have similar characteristics distinct from those in another cluster. The data might then be characterized in terms of empirical accident distributions over the clusters. A few standard routines were tried, but these did not seem to yield very meaningful clusters. Moreover, accident distributions over these clusters did not vary as much as it did over subsets obtained by partitioning the data on one or two variables.

Models Within Subsets

The fitting of models within subsets of the data was motivated by the fact that model (3) seemed to fit well over a portion of the range of the independent variables, namely, lower ADT and degree of curve values. It was thought, then, that more useful results might be obtained by fitting models of this same form within certain subsets of the data. This did not prove to be the case. Six ADT categories and four degree of curve categories were defined. Models were fit within each of these 10 subsets and also within each of the degree by ADT categories where sample sizes permitted.

Estimated model coefficients and their statistical significance varied substantially from subset to subset. Sometimes this variation seemed to be systematic (e.g, the estimated effects of ADT tended to increase with increasing ADT values through the lower range of ADT), but often this was not even the case. For the highest ADT categories, the effects of ADT were not statistically significant. Moreover, many of the within subset models fit quite poorly. Overall, the subsets, themselves, represented another form of clustering the data based on only two variables -- ADT and degree of curve. The models within the subses, however, did not seem to be yielding useful results.

Linear Accident Rate Models

An alternative type of model which seemed to provide a relatively good fit to the Washington State data was based on estimating a linear model for accident rate (per million vehicle miles) using a weighted least squares procedure. The weight function used was the product $w = (ADT)(Length)$. Thus, the estimated models were of the form

$$\text{Accident rate} = B_0 + B_1 \text{ Degree} + B_2 \text{ Width} + B_3 \text{ Spirals} + \ldots + \delta \qquad (5)$$

where δ is assumed to have mean zero and variance inversely proportional to w. This assumption agrees with intuition in the sense that accident rates on longer curves with higher ADT should be known with greater precision than those on short curves with low ADT.

Table 27 below shows estimated variances of total accident rate within 10 categories of increasing values of w. Categories were chosen to contain, roughly, equal numbers of observations. In the second column, $w^* = w/\text{million vehicle miles}$, and $\bar{w}^*$ is the mean value of this variable within the interval.

Table 27. Accident rate variance by weight (w) categories.

Category	$\bar{w}^*$	Total Accident Rate Variance(V)	$V^{-1}/\bar{w}^*$
1	.031	284.17	.1135
2	.080	85.77	.1457
3	.136	41.13	.1788
4	.192	26.18	.1989
5	.245	18.34	.2226
6	.355	17.14	.1643
7	.541	11.43	.1617
8	.766	6.44	.2027
9	1.122	4.36	.2044
10	2.945	2.86	.1187

Total accident rate variance (V), given in the next column, decreases from the first category to the last by a factor of nearly 100. The last column gives the inverse of the variance divided by $\bar{w}^*$ which remains relatively constant as it should under the assumptions on δ. It should be noted that accident rate models of the form (2) were also fit using the same weighted least squares procedure.

For total accident rate, the estimated model was

$$\begin{aligned}\text{Total acc. rate} &= \text{Total acc./million vehicle miles}\\ &= \underset{}{1.94} + \underset{(.008)}{.24}\ \text{Deg} - \underset{(.006)}{.026}\ \text{Width} - \underset{(.062)}{.25}\ \text{Spirals} \qquad (6)\end{aligned}$$

with all coefficients significant at the p = .0001 level. Thus, with this model spirals are estimated to be highly significant. Accident frequencies could be estimated by the model

$$\text{Total acc.} = (\text{ADT})(\text{Length})\ (1.94 + .24\ \text{Deg} - .026\ \text{Width} - .25\ \text{Spirals}) \qquad (7)$$

Subtracting these predicted values from the corresponding actual values, squaring, and summing led to the computation of the quantity, SS residual, which when divided by SS Total which is the sum of squares of the deviations of the actual values from the overall average, yielded

$$Q = \frac{\text{SS residual}}{\text{SS Total}} = .64$$

In the case of a least squares fit, $R^2 = 1-Q$. Since model (7) does not represent a least squares fit to total accidents, the total sum of squares is not partitioned into a sum of squares due to regression and a residual sum of squares. Still Q seems to be a meaningful quantity and 1-Q = .364 may be thought of as a sort of pseudo R^2.

Another way of examining the fit of model (7) is to generate a table similar to table 26 which shows the actual accident distributions over ranges of predicted values. These quantities are shown in table 28. A comparison with table 26 shows the linear rate model to fit the data much better than did the multiplicative model fit through log transformations. Tables comparing the linear rate model with other models are presented later.

Table 28. Comparison of actual and predicted total accidents from linear rate model(8).

Range of Predicted Values	N	Mean Predicted	Mean Actual	Actual Percentiles 25th	50th	75th
.01 - .49	4,397	.269	.296	0	0	0
.50 - .99	2,788	.719	.695	0	0	1
1.00 - 2.49	2,635	1.54	1.54	0	1	2
2.50 - 5.00	820	3.40	3.47	1	2	5
> 5.0	260	7.85	7.60	3	5	9
	10,900					

Table 29 contains results from fitting weighted linear models of the form (6) to other types of accident rates. In this table, the significance level of each estimated coefficient is shown below the coefficient. Using the procedure described earlier, attempts were made to include other variables and interaction terms in the models of table 29. From the analysis of the main data set, no other factors contributed significantly to these models. In

Table 29. Accident rate models.

Accident Type	Constant	Degree	Width	Spirals
Related acc.	1.67 .0001	.20 .0001	-.035 .0001	-.17 .0002
Fixed object acc.	1.28 .0001	.14 .0001	-.029 .0001	-.12 .0010
Injury acc.	.91 .0001	.12 .0001	-.013 .0001	-.11 .0029
Dry weather acc.	1.05 .0001	.13 .0001	-.011 .0043	-.23 .0001
Wet weather acc.	.28 .0009	.077 .0001	-.004 .0833	-.08 .0018
Daytime acc.	1.00 .0001	.14 .0001	-.012 .0018	-.13 .0019
Nighttime acc.	.93 .0001	.11 .0001	-.014 .0001	-.12 .0004

particular, neither of two variables of special interest, vertical grade and distance to adjacent curve, was found to have a consistently significant relationship with curve accidents. Two measures of distance to adjacent curve were included in the analyses: minimum distance to adjacent curve and maximum distance to adjacent curve, where each curve had a tangent distance on both ends (although this tangent distance may be zero for one or both sides of the curve for compound or reverse curves). If, for example, a curve had a 0.10-mi (0.16 km) tangent on one end and a 0.05-mi (0.08 km) tangent on the other end, its minimum and maximum value for distance to adjacent curve would be 0.05 and 0.10 mi (0.08 and 0.16 km), respectively.

When tested separately in various models as continuous variables, no significant effects were found at the 5 percent level for either variable. However, when the maximum distance to adjacent curve was expressed as a categorical variable for several distances (e.g., maximum tangent distance greater than 0.3 mi (0.5 km)), it was marginally significant ($p = .06$). Further analyses were not conducted, although there appears to be some evidence that tangents above a certain length may result in some increase in accidents on the curve ahead.

The effects of vertical grade on curve accidents were investigated based on testing the level of significance of the variable "maximum grade on the curve" for the various model forms. Maximum grade was not significant at the 5 percent level in most cases. In a few instances, it was marginally significant, but had a negative sign (i.e., higher grades resulted in lower accident rates). This may not be a true effect of grade, but could be the result of the grade variable interacting with one or more other roadway variables.

Special Analyses of Curve-Related Variables

In addition to testing various modeling techniques on the full 10,900 curves, several subsets of the main data set were also available which contained additional information, or which could be used for other types of analysis. For example, superelevation data were collected on a subset of 732 of the study curves. A second subset of 1,039 curves contained information on two measures of roadside hazard, a roadside rating scale and the average clear zone distance beyond the shoulder. The intersection of these two subsets consisted of 486 curves with information on all three variables.

A subset was also developed consisting of 3,427 curves for which there was an adjacent tangent section of length at least equal to the length of the curve. For these curves, accident data from the corresponding tangent section (of length equal to that of the curve) were appended to the existing curve data. This last subset is referred to as the "matched pairs data set," as was discussed in chapter 5. The results of some of these analyses are discussed below.

Analysis of Matched Pair Data: For the matched pairs data, accidents on the tangent sections could potentially be used as controls for accidents on the corresponding curved sections, thus, tending to remove effects of factors except those characterizing the curve itself. The linear rate model lends itself to this type of analysis. Model (6) with degree and spirals set equal to zero should represent a model for accident rates on tangents as a function of roadway width. A model of this form fit to data on the difference (i.e., curve accident rate - tangent accident rate) should result in the constant term and the width effect dropping out while the effects of degree and spirals should remain about the same. Specifically, in a model of the form

$$\text{Rate diff.} = \beta_0 + \beta_1 \text{ Degree} + \beta_2 \text{ Width} + \beta_3 \text{ Spirals} \tag{8}$$

it should be the case that

$$\beta_0 = 0,\ \beta_1 = .24,\ \beta_2 = 0, \text{ and } \beta_3 = -.25$$

for the estimates to be consistent with those of model (6). When model (8) was fit to the rate differences on the matched pairs data set, the estimated model was

$$\text{Rate diff.} = \underset{(.404)}{-.186} + \underset{(.020)}{.190} \text{ Degree} - \underset{(.011)}{.0007} \text{ Width} - \underset{(.120)}{.174} \text{ Spiral} \tag{9}$$

The coefficients β_0, β_2, and β_3 do not differ significantly from the values specified above, but β_1 (the degree effect) is significantly lower.

Numerically, however, the values .19 versus .24 are reasonably close. Thus, results from the matched pairs data seems to be in reasonably good agreement with those from the complete data set. This close agreement lends support to the relative effects of degree of curve, width, and presence of spiral on accidents.

Estimation of Superelevation Effect: As discussed earlier, of the 10,900 curves in the Washington State curves file, superelevation data were collected for 732 of those curves. The effect of superelevation on curve accidents was considered to be an important question to be addressed with the Washington data base. The superelevation deviation variable was constructed as (optimal superelevation) - (actual superelevation), where optimal superelevation was determined from the AASHTO Design Guide as a function of degree of curve and terrain type.[15] Table 30 shows results from analyses aimed at estimating the effects of superelevation deviation. The first set of model coefficients on the left are the original coefficients from estimating model (6) on the full data set.

Table 30. Estimation of superelevation effects.

	Full Data		Superelevation Subset					
Model			I		II		III	
Parameter	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
Constant	1.94	.0001	1.63	.0125	1.52	.0204	1.53	.0001
Degree	.24	.0001	.28	.0001	.28	.0001	.28	.0001
Width	-.026	.0001	-.030	.0738	-.029	.0854	-.026	*
Spiral	-.25	.0001	.12	.4874	.08	.6258	-.25	*
Sup. Def.					8.51	.0628	9.52	.0364

The next set, I, represents a reestimation of this model on the superelevation subset. The results are quite different, with spirals having a nonsignificant effect and the width effect becoming only marginally significant. Next, set II illustrates what happens when superelevation deviation is added to the model. Finally in set III, the effects of width and spirals were set at their respective values from the full data set (namely, -.026 and -.25, respectively), and a model containing only degree, superelevation deviation and an intercept fit to the residuals after removing the width and spiral effects. This last model, which combines information from the full data set with information from the superelevation subset, represents our best estimate of a model containing effects for both spirals and superelevation. This model is as follows:

$$\text{Total acc. rate} = 1.53 + .28 \text{ Deg.} - .026 \text{ Width} - .25 \text{ Spiral} + 9.52 \text{ Sup. Def} \tag{10}$$

Superelevation deviation, spirals, and roadway width are all correlated. Superelevation deviation is significantly correlated with width, but not with spirals. The presence of spirals is strongly correlated with width on the superelevation subset; curves having spirals were wider by an average of 5 ft (1.5 m) than those not having spirals. Superelevation deviation tended to decrease as width increased (i.e., wider curves had less deficiencies in superelevation), and was about 10 percent less on curves having spirals.

Models estimated over the large data set contained roadway width and spirals as competing variables and in most cases both variables were found to be statistically significant. Some of the effects that are attributed to these variables might, however, be due to superelevation.

To get an idea of the magnitude of the effect of superelevation relative to accident reduction, the model under set III of table 30 was used to calculate a percent reduction in crashes corresponding to a reduction of .02 in superelevation deviation with "typical" values for the other variables, namely degree = 3°, width = 30 ft (9.1 m), no spiral, and .3 million vehicle mi (.5 million vehicle km) of traffic. These calculations yielded an accident reduction of 10.6 percent.

Analyses were also carried out to address the question of whether "too much" superelevation was associated with higher accident rates or frequencies. No evidence was found to support such a conjecture. This may best be seen from figure 5, which shows a scatter plot of total accident rate residuals (i.e., observed-predicted rates) with degree and roadway width removed, plotted against maximum superelevation. A nonparametric regression curve fit to the data using the LOWESS procedure is also shown. The slightly downward slope of the curve shows higher superelevation values to correspond to lower accident rates throughout the range of superelevation values. More specifically, the right-hand tail of the curve does not increase as it should if too much superelevation caused accidents.

Estimation of Effects Due to Roadside Condition: Data were obtained for analysis of roadside hazard (i.e., roadside hazard rating and roadside recovery area distance) for 1,039 curves of the 10,900 in the Washington State curves data base. None of the analyses involving roadside rating scale or clear recovery area showed either of these variables to be significantly associated with curve accidents. These results may be due, in part, to the limited variability of these quantities in the data. Figure 6 shows that nearly 80 percent of the rated curves had roadside ratings of 4 or 5.

Non-Linear Estimation Procedures

Along with the other analytic procedures, multiplicative models similar to model (1) were also estimated using nonlinear least squares procedures; in particular, SAS PROC NLIN. The basic model considered was

$$\text{Acc} = C_o\ (\text{ADT})^{C_1}\ (\text{Length})^{C_2}\ C_3^{\text{Degree}}\ C_4^{\text{Width}}\ C_5^{\text{Spiral}} + \varepsilon$$

This model is of the same basic form as model (1) but with a different error structure.

Initial attempts at estimating models using non-linear procedures were unsuccessful due to the large amount of time required for convergence with such a large data sample. However, a model successfully estimated for total accidents was

$$\text{Total acc.} = 3.17 \times 10^{-6}\ (\text{ADT})^{1.21}\ (\text{Length})^{.89} \times (1.042)^{\text{Degree}}\ (.9646)^{\text{Width}}\ (.781)^{\text{Spiral}} \qquad (11)$$

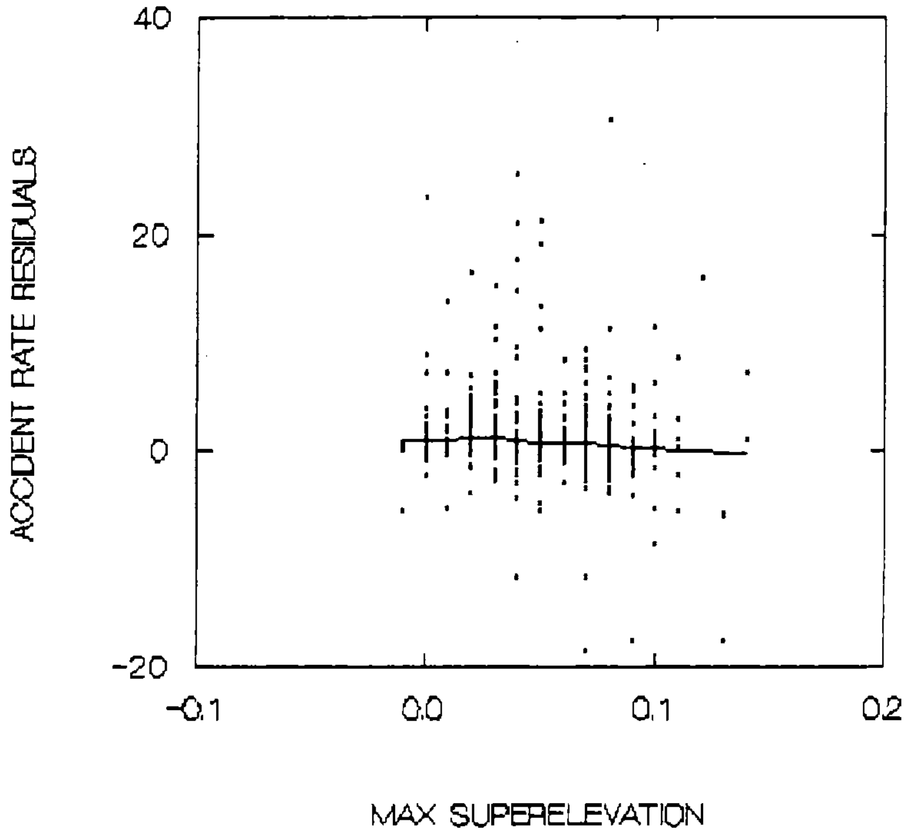

Figure 5. Accident residuals by superelevation.

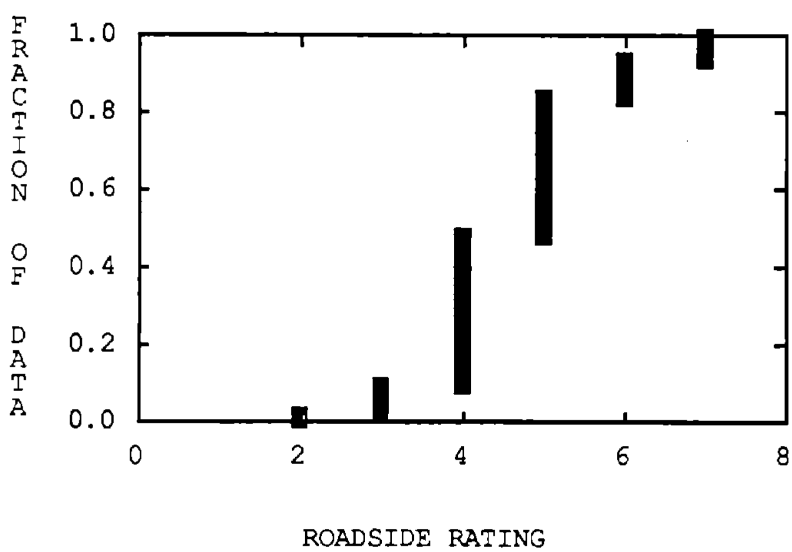

Figure 6. Distribution of roadside hazard rating.

where, as before, the variable, spiral, takes the value 1 to indicate the presence of a spiral and the value 0 for no spiral. All model coefficients were significant at the 5 percent level. The ratio of residual sum-of-squares to total sum-of-squares for this model was Q = .638 (or a pseudo R^2 of .362), very similar to that obtained for the linear rate model. Other comparisons showed the fit of model (11) to be quite comparable to that of the linear model (7). Models of the form (11), when fit to other accident type data (e.g., fixed object accidents), failed to converge, as did slightly different models fit to total accident data.

Development of Models for Accident Reduction Factors

While the linear rate models described in detail above seemed to fulfill goal 1 of the opening paragraph of this section, namely, to describe relationships between accidents on curves and roadway characteristics, models of this form were not useful for estimating accident reductions due to roadway improvements. In particular, the improvement of curve flattening involves reducing the degree of the curve while increasing the curve length. The product of length times degree or central angle remains, essentially, constant for this procedure. The accident prediction model (7) contains the product degree x length x ADT, and, therefore, is not suitable for the estimation of changes of this type.

A model which represents an extension of a model developed by TRB, allows for determining the effects of curve flattening, roadway widening, and of adding spirals.[10] This model was fit to the data on total curve accidents and was of the form

$$\begin{aligned}\text{Total acc.} = \; & [\alpha_1 \text{ (Length x Volume)} + \alpha_2 \text{ (Degree x Volume)} \\ & + \alpha_3 \text{ (Spiral x Volume)}] \, (\alpha_4)^{\text{Width}} + \varepsilon \qquad (12)\end{aligned}$$

In model (12), Volume is ADT expressed in millions of vehicles over the 5 year period of observation. The width effect α_4 was reparemeterized as

$$\alpha_4 = e^{-\rho}$$

The model parameters were estimated by choosing a value for ρ in the interval $0 \leq \rho < .10$, fitting the regression model

$$\text{Accidents} = \alpha_1 \text{ (Length x Vol x } e^{-\rho \cdot w} + \alpha_2 \text{ (Deg. Vol. x } e^{-\rho \cdot w}$$
$$+ \alpha_3 \text{ (Spiral x Vol x } e^{-\rho \cdot w} + \varepsilon ,$$

then searching on ρ to find the value which minimized the error sum-of-squares. This process led to the estimated model

$$\text{Total acc.} = [1.55 \text{ (Length)(Vol.)} + .014 \text{ (Deg.)(Vol.)}$$
$$- .012 \text{ (Spiral)(Vol.)}] \ (.978)^{(\text{Width}-30)} \qquad (13)$$

α_1 and α_2 were statistically significant at $p = .0001$. For α_3, $p = .140$. No significance level or standard error was available for α_4 or $\hat{\rho} = .022$. Even though the coefficient of spirals was not found to be statistically significant at the .05 level in model (13), it was retained in the model, since it was found to be an important factor in numerous other analyses. The error sum-of-squares ratio, Q was computed to be Q = .649 for model (12), or a pseudo R^2 of .351. This value is very close to that for the linear model (7) for accident frequencies (i.e., .36) as well as for the multiplicative model (11) (i.e., .362).

Table 31 shows mean values of actual <u>accident rates</u> per million vehicle miles, and predicted rates for both the linear model (6) and model (13) divided by (ADT)(L), within categories of curves defined by degree, width, and spirals. Actual and predicted total <u>accident frequencies</u> are presented in table 32 in a similar format.

Summary of Analysis Results

In summary, most of the analyses discussed in this chapter were based on linear regression models of accident rates estimated by a weighted least squares procedure. The product of traffic volume (ADT) times curve length was taken as the weight factor. The appropriateness of the weighted analysis was suggested both by engineering logic and statistical theory, and was borne out empirically. Conceptually, this type of model may be thought of as a

Table 31. Mean values of actual and predicted accident rates.

	Degree	No Spiral			Spiral		
		Width			Width		
		< 29	28-35	> 35	< 28	28-35	> 35
Actual rate	< 1°	2.08	1.63	1.56	.84	.82	1.21
Predicted rate (7)*		1.47	1.31	1.10	1.24	1.08	.90
Predicted rate (13)**		1.87	1.61	1.35	1.70	1.49	1.28
Sample size		247	375	399	11	24	100
Actual rate	1°- 1.99°	1.73	1.70	1.09	1.67	1.69	1.21
Predicted rate (7)		1.71	1.56	1.09	1.45	1.32	1.13
Predicted rate (13)		2.02	1.77	1.43	1.77	1.58	1.34
Sample size		477	457	255	55	125	291
Actual rate	2°- 2.99°	1.80	1.94	1.64	1.48	1.60	1.15
Predicted rate (7)		1.95	1.82	1.61	1.67	1.56	1.37
Predicted rate (13)		2.23	1.95	1.57	1.84	1.66	1.40
Sample size		404	358	167	61	96	222
Actual rate	3°- 3.99°	2.07	2.02	1.47	2.30	1.65	1.35
Predicted rate (7)		2.21	2.06	1.85	1.95	1.81	1.62
Predicted rate (13)		2.55	2.15	1.69	1.98	1.77	1.48
Sample size		563	384	136	70	114	196
Actual rate	4°- 4.99°	2.76	2.14	1.99	2.69	2.40	1.58
Predicted rate (7)		2.45	2.30	2.10	2.17	2.05	1.86
Predicted rate (13)		2.84	2.43	1.97	2.07	1.84	1.55
Sample size		330	260	79	49	55	80
Actual rate	5°- 9.99°	3.10	2.90	3.30	3.52	2.69	2.16
Predicted rate (7)		3.21	2.96	2.70	2.80	2.72	2.31
Predicted rate (13)		4.06	3.13	2.50	2.36	2.21	1.73
Sample size		1511	809	169	122	138	112
Actual rate	10°-14.99°	4.93	4.41	5.75	5.03		
Predicted rate (7)		4.39	4.19	3.88	4.09	**	**
Predicted rate (13)		6.09	4.93	3.93	3.61		
Sample size		429	143	22	22		
Actual rate	≥ 15°	7.24	8.43	13.32	8.28		
Predicted rate (7)		8.09	6.82	7.54	5.52	**	**
Predicted rate (13)		14.98	9.67	9.35	4.22		
Sample size		782	132	25	24		

*(7) = Values computed from model (7)
**(model 13)/ADT x L
**Cells with sample sizes of less than 10 curves.

Table 32. Mean values of actual and predicted accident frequencies (accs/5 years).

	Degree	No Spiral			Spiral		
		Width			Width		
		< 29'	28-35'	> 35'	< 28'	28-35'	> 35'
Actual frequency	< 1°	.70	1.21	1.95	1.09	.79	2.14
Predicted freq. (7)*		.62	1.00	1.93	1.39	1.36	1.54
Predicted freq. (13)**		.76	1.19	2.31	1.91	1.87	2.18
Sample size		247	375	399	11	24	100
Actual frequency	1°- 1.99°	.58	1.11	1.56	1.07	1.36	2.24
Predicted freq. (7)		.63	1.10	1.92	.88	1.25	2.18
Predicted freq. (13)		.67	1.18	1.97	1.06	1.47	2.58
Sample size		477	457	255	55	125	291
Actual frequency	2°- 2.99°	.60	1.14	2.05	.75	1.67	2.17
Predicted freq. (7)		.63	1.09	1.94	.90	1.75	2.26
Predicted freq. (13)		.66	1.09	1.79	.98	1.81	2.29
Sample size		404	358	167	61	96	222
Actual frequency	3°- 3.99°	.52	1.14	1.46	1.34	1.75	2.44
Predicted freq. (7)		.52	1.10	2.00	.99	1.73	2.85
Predicted freq. (13)		.54	1.04	1.69	.97	1.63	2.52
Sample size		563	384	136	70	114	196
Actual frequency	4°- 4.99°	.54	.97	1.47	.84	1.87	2.05
Predicted freq. (7)		.58	1.01	1.67	.83	1.82	2.19
Predicted freq. (13)		.60	.93	1.35	.76	1.56	1.78
Sample size		330	260	79	49	55	80
Actual frequency	5°- 9.99°	.62	1.20	2.03	1.01	1.60	2.27
Predicted freq. (7)		.66	1.14	1.69	1.11	1.51	2.29
Predicted freq. (13)		.70	1.02	1.34	.89	1.17	1.62
Sample size		1511	809	169	122	138	112
Actual frequency	10°-14.99°	.67	1.17	1.82	.64		
Predicted freq. (7)		.71	1.28	1.32	.62	***	****
Predicted freq. (13)		.82	1.23	1.10	.51		
Sample size		429	143	22	22		
Actual frequency	≥ 15°	.59	1.73	2.40	1.21		
Predicted freq. (7)		.61	1.36	1.73	1.24	***	***
Predicted freq. (13)		.95	1.64	1.85	.86		
Sample size		782	132	25	24		

**Cells with less than 10 curves.
*(7) = Values computed from model (7)
**(model 13)/ADT x L

continuous variable analogue of a weighted analysis-of-variance model for accident rates with factors such as degree of curve, road width, etc.

Statistically significant effects were consistently found for degree of curve, road width (lane width plus shoulder width), and spirals. Another variable of interest - distance from last curve - was not found to be significant in any model when treated as a continuous variable. When treated as a categorical variable, a marginally significant ($p = .06$) effect was found indicating that the truly isolated curves may have slightly higher accident rates. This type of effect is examined further in chapter 7 using the four-State curves data base.

Information on superelevation was available for only a small subsample of the Washington curves. Analyses carried out on this subsample revealed some evidence of a positive correlation between superelevation deficiency and accident rate. It was also found that superelevation was intercorrelated with roadway width and spirals, that is, more superelevation was generally found on curves with spirals and on curves with wider roadways. While attempts were made to determine the isolated effects of each curve feature on accidents, such isolated effects are not always clear. For example, the use of spiral transitions may be beneficial partly because of the better likelihood of highway designers to also provide good superelevation at curve sites with spirals.

Thus, based on the analysis of 10,900 horizontal curves in Washington State, the variables found to have a significant effect on accidents are traffic volume, degree of curve, length of curve, roadway width, the presence of spiral transitions, and superelevation. The effect of roadside condition on curve accidents could not be properly quantified with this data base as discussed earlier. An accident prediction model was developed which can be used to determine accident reduction factors expected due to various curve improvements (e.g., curve flattening, curve widening, adding spiral transitions). The model and accident reduction factors developed from the Washington State data base corresponds with that data sample which is mostly non-isolated curves. Accident relationships for isolated curves were developed from the FHWA four-State data base, as discussed in the next chapter.

CHAPTER 7 - COMPARISON OF WASHINGTON WITH FOUR-STATE DATA MODEL

Chapter 6 involved an analysis of data from 10,900 horizontal curves in Washington State (and related data subsets), which led to the development of accident predictive models as a function of roadway and geometric features. The curve variables found to have a significant relationship with accidents included ADT, degree of curve, length of curve, roadway width, presence of spiral transitions, and superelevation. To validate some of the models developed using the Washington State data base, the separate four-State data base developed in a 1983 FHWA study (and discussed in chapter 3) was examined. The comparison of models from those two data bases is presented in this chapter.

The four-State curves data base consists of accident, traffic, and geometric data for 3,304 curve sections and 244 tangent sections for selected sections in Ohio, Florida, Illinois, and Texas, plus supplemental data for the subset of 333 high- and low-accident curve sites. After data verification and deletion of questionable data, 3,277 of the 3,304 original curve sections were available for analysis.

A listing of data variables for the full data set and high/low accident data set are given in figure 7. Note that the full four-State data set contains information on accident experience, degree of curve, ADT, curve length, roadway width, etc., but not on superelevation, presence of spiral, or roadside features. While the high/low accident data base does contain information on superelevation, roadside hazard (as well as degree of curve, length of curve, roadway width, ADT, etc.), it does not contain curves with the full range of accident experience (i.e., it only includes the high-accident and low-accidents sites). Thus, the full curve sample (3,277 curves) is more appropriate than the high/low data set for developing accident predictive models for comparison with the Washington State accident models, and that was the data base which was analyzed and is discussed further in this chapter.

The four-State data base differed from the Washington State data base in several respects. Some of the most notable differences were:

<u>Full Curves Data Base</u>

<u>Data Elements</u>:

1. State: Florida, Illinois, Ohio, and Texas
2. County
3. Route
4. Beginning Milepost
5. Ending Milepost
6. Beginning Curve Milepost
7. Ending Curve Milepost
8. Direction of Curve: Left or Right
9. Degree of Curve
10. Length of Curve
11. Roadway Width
12. Surface Width
13. Shoulder Type: Dirt, Lawn, Concrete
14. ADT
15. Total Accidents at Site
16. Single Vehicle Accidents
17. Multi-Vehicle Accidents
18. Nighttime Accidents
19. Fatal Accidents
20. Accident Rate
21. Single Vehicle Rate
22. Multi-Vehicle Accident Rate
23. Nighttime Accident Rate
24. Fatal Accident Rate
25. Degree of Curve
26. Shoulder Width
27. Site Length

<u>High/Low Accident Data Base</u>

<u>Data Elements</u>:

1. State
2. High or Low Accident Site
3. Degrees
4. Minutes
5. Seconds
6. Length of Curve
7. Pavement Rating
8. Rate of Change of Superelevation
9. Maximum Superelevation
10. Superelevation in Curve
11. Roadside Rating
12. Segment Width in Curve
13. Degree of Curve
14. Ratio of Superelevation at the Point of the Curve to the Maximum Superelevation

Figure 7. List of data variables from the four-State curve data base.

- While the Washington State data base contained curves with all levels of ADT, the four-State base generally (i.e., with some exceptions) contained curves with ADT's > 1,500 vehicles per day.

- Each curve record in the Washington State data base consisted of a single curve segment plus transition spirals with corresponding geometric, traffic, and roadway data. Each curve segment in the four-State data base consisted of one curve embedded in a larger roadway segment (i.e., generally 0.61 mi (1 km) segment lengths consisting of a curve and adjacent tangents). Thus, in general, the four-State data base included accidents on curves plus adjacent tangents, while the Washington data base contained accidents only on the curve.

- Curves in the four-State data base were essentially "isolated" curves (i.e., minimum tangent lengths of .124 mi (.20 km) on each side of the curve). In contrast, the Washington curves data sample included mostly non-isolated curves; that is, a vast majority of the curves had other curves within a few tenths of a mi (km). No attempt was made to eliminate curves because of their proximity to adjacent curves.

- Curves in the four-State data base had no information on spiral transitions or superelevation, but did contain seemingly reliable information on accidents, ADT, degree of curve, length of curve, roadway width, etc., which were also available with the Washington State data base.

Comparison of Data Characteristics

The roadway and accident statistics are summarized in table 33 for the Washington State and four-State data bases. The average ADT was higher on curves in the four-State data base (3,178 vs. 2,209) due to site selection criteria used in that study (i.e., generally selecting curves with a minimum of 1,500 ADT). Average curve lengths were about the same for the two data bases (.132 vs. .169 mi) (.21 vs. .27 km). However, the average length of a segment (e.g., curve plus adjacent tangents) was .631 mi (1.02 km) for the four-State data base, almost five times the length of the average Washington State curve. This longer segment length and higher ADT resulted in a greater number of accidents per year (1.31) for the curve plus tangent segments in the four-State data base, compared to an average of .22 accidents per year for the Washington State curves.

The roadway widths (i.e., width of lanes plus shoulders) were also greater for the four-State data base (36.6 ft vs. 30.4 ft) (11.2 vs. 9.3 m) due primarily to wider shoulders. However, curves in the Washington data base were sharper on average with a degree of curve of 6.8, compared to 3.4 for the four-State data base. This seems reasonable, since most sharp curves are typically located in mountainous terrain with short tangents between curves. The four-State sample omitted curves with short tangents, which logically would have omitted many of the sharpest curves. Central angles were also larger on average (28.7 degrees) for the Washington curve sample, compared to the four-State data base (19.7 degrees), which again may be expected because of the curve sampling procedures.

Table 33. Comparison of basic roadway and accident statistics for the Washington and four-State curves data bases.

Data Variable	Washington State Curves Data Base	Four-State Curves Data Base
Number of Curve Sections	10,900	3,277
Average ADT	2,209	3,178
Average Curve Length (mi)	.132	.169
Average Length of Total Section (mi)	.132	.631
Average Number of Total Accidents per Year	0.22	1.31
Average Number of Total Accidents per Five Years	1.11	6.55
Average Lane Width (ft)	11.1	11.4
Average Shoulder Width (ft)	4.1	6.9
Average Roadway (Lane plus Shoulder) Width	30.4	36.6
Average Degree of Curve (Degrees)	6.8	3.4
Average Central Angle (Degrees)	28.7	19.7
Average Total Accident Rate (Accs/MVM)	2.79	1.82
Average Total Accident Rate (Accs/MV)	0.27	1.14
Average Accidents per Mile per Year	1.99	2.09

The average accident rate (using total accidents) per million vehicle mi (1.6 km) was 2.79 for Washington State curve sample, compared to 1.82 for the four-State data base. Such a higher rate would be expected due to the greater average degree of curve with the Washington data base. Also, the use of tangent segments with curve segments (for the four-State data base) would be expected to result in a somewhat lower segment accident rate compared to the accident rate on curves alone (i.e., as used in the Washington curves data base). The average accident frequency (i.e., number of accidents per mi (1.61 km) per year) was approximately the same for the two data bases (1.99 vs. 2.09). This may be the result of higher accident rates for the Washington curves which are offset by the higher ADT's (with correspondingly higher accident frequencies) on segments from the four-State data base.

The accident rates for the two data bases were compared for various degrees of curve, as illustrated in figure 8 and given in table 34. For both data bases, accident rates generally increase as degree of curve increases, as expected. Accident rates were quite similar between the Washington and four-State data bases for curves with degree of curvature below 12. Above 12 degrees, the accident rate becomes increasingly greater for the Washington data base.

The differing accident rates above 12 degrees may be due to the fact that sharper curves are typically shorter than mild curves. Thus, since each curve segment in the four-State data base consists of one curve with its adjacent tangents (totaling a fixed .61 mi (1 km) length), the sharpest curves in that data base would, therefore, consist largely of tangents, which would reduce the overall accident rate of those segments. For example, consider a 20 degree curve which is .02 mi (.03 km) long in the four-State data base. The total segment length would be .61 mi (1 km), leaving .59 mi (.95 km) of tangent or 97 percent of the total segment length. Thus, the accident rate of the curve segment would be influenced heavily by the greater amount of tangent. A 1 degree curve of .30 mi (.48 km) would consist of only .31 mi (.50 km) of tangent, approximately 51 percent of the total segment length. Thus, since mild curves are typically longer than sharp curves, the accident rates for the mild curve segments will correspond more closely to a curve accident rate for .61 mi segments in the four-State data base.

It should also be remembered that the curves in the four-State data are all somewhat isolated, and an isolated curve may be expected to have a slightly higher accident rate than a similar curve which exists in a series of curves. This offsetting factor could partly explain the similarity in accident rates between the two data bases for low degrees of curve.

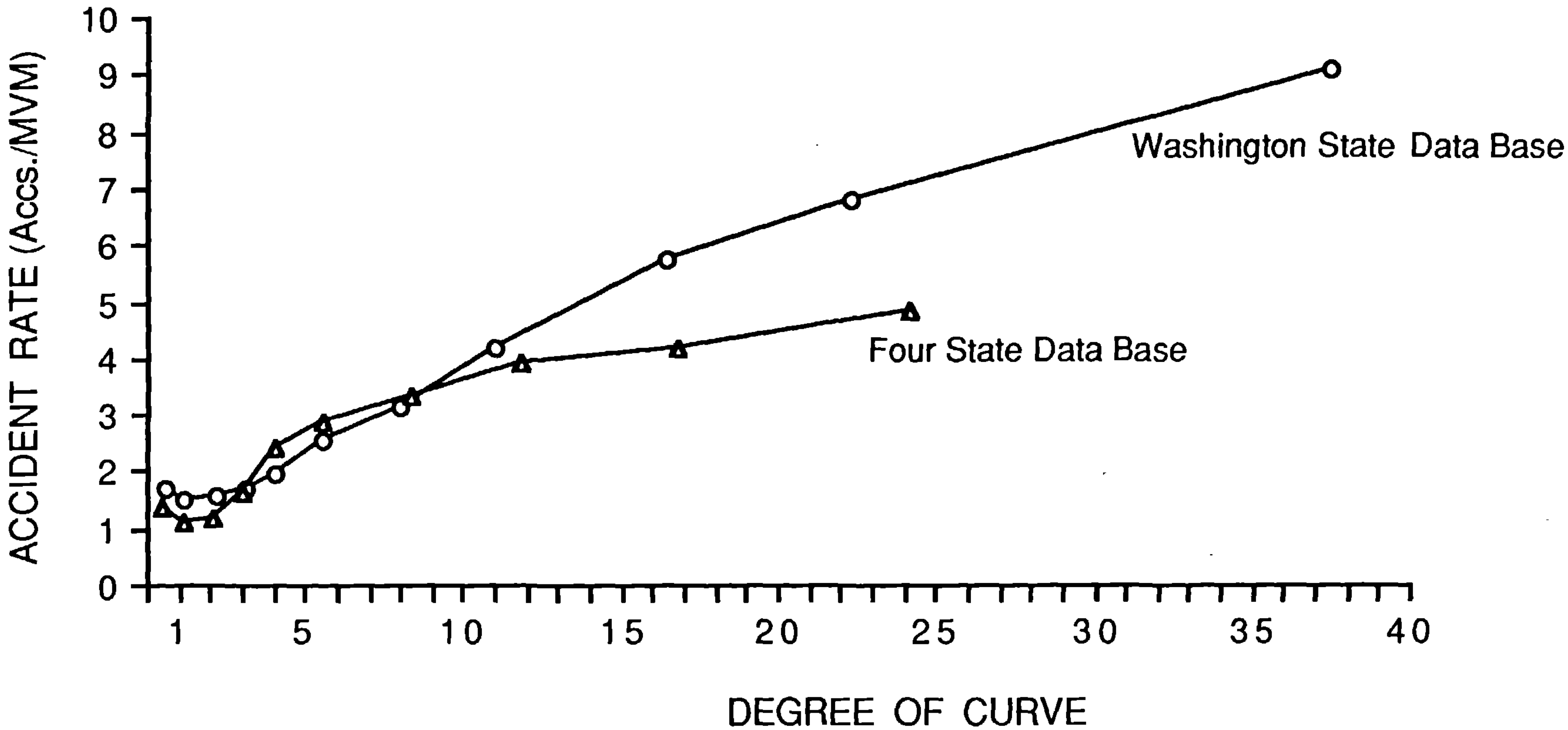

Figure 8. Plot of accident rate by degree of curve for two curve data bases.

Table 34. Comparison of accident rates by degree of curve for the Washington and four-State curves data bases.

Degree of Curve	Washington State Data Base			Four-State Data Base		
	No. Sites	Mean Degree of Curve	Accident Rate (Acc/MVM)	No. Sites	Mean Degree of Curve	Accident Rate (Acc/MVM)
> 0 to < 1	396	.55	1.72	527	.47	1.36
1 to 1.99	1,254	1.20	1.48	932	1.13	1.14
2 to 2.99	1,620	2.16	1.60	593	2.07	1.17
3 to 3.99	1,171	3.15	1.72	239	3.05	1.64
4 to 4.99	1,378	4.08	1.95	211	4.05	2.41
5 to 6.99	1,669	5.59	2.53	293	5.55	2.85
7 to 9.99	1,085	7.95	3.12	249	8.32	3.32
10 to 14.99	1,280	11.04	4.17	174	11.75	3.94
15 to 19.99	335	16.42	5.77	38	16.74	4.18
20 to 29.99	405	22.34	6.80	21	24.18	4.83
30 to 49.99	266	37.45	9.10	__*	__	__
≥ 50	41	68.63	12.80	__	__	__

__* = No data exist in these cells.

Also of interest is a slight increase in accident rate for the lowest degree of curve (i.e., $<$ 1 degree) which was found for both data bases. While this trend may not be expected, one possible explanation is that some drivers may not readily distinguish very flat curves from tangents. If this is true, some drivers may react with last-minute steering reactions and/or "driver overshoot" could be slightly more of a problem on very mild curves (less than 1 degree) than on more recognizable curves of 1 or 2 degrees. If this problem is indeed occurring on curves of $\leq$ 1 degree, improved delineation and/or signing may help drivers to more readily recognize the presence of a curve and react more appropriately.

Various traffic and roadway features were also compared between the two data bases by degree of curve, as shown in table 35. The general findings show the four-State data base has generally higher ADT's and wider shoulders than the Washington data base for a given degree of curve. Lane widths, curve lengths, and central angles are roughly comparable for the two data bases, although some variation exists by degree of curve (e.g., curves less than 1 degree are longer in the Washington State data base than the four-State data base ((.271 mi vs. .197 mi) (.43 vs .32 km)).

Comparison of Accident Models

Attempts were made to develop accident predictive models for the four-State data sample to compare with the Washington models described in chapter 6. Using the four-State data base, a model of the linear rate form, estimated by weighted least squares, fit the data quite well. The estimated model was:

$$\hat{\text{A}}\text{cc. rate/million veh. miles} = 2.694 + .223 \text{ Degree} - .044 \text{ Width}, \quad (14)$$

where Width was the sum of surface width and shoulder widths. All coefficients were significant at the $p = .0001$ level. Accident frequencies were then predicted using:

$$\hat{\text{A}}\text{cc} = (\text{Vol.})(\text{Section Length})(2.694 + .223 \text{ Degree} - .044 \text{ Width}). \quad (15)$$

Comparing predicted accident frequencies with actual values yielded a sum-of-squares ratio of

Table 35. Comparison of traffic and roadway features by degree of curve for two curve data base.

Degree of Curve (Degrees)	Washington State Data Base					Four-State Data Base				
	ADT	Lane Width (ft)	Shoulder Width (ft)	Curve Length (mi)	Central Angle (Degrees)	ADT	Lane Width (ft)	Shoulder Width (ft)	Curve Length (mi)	Central Angle (Degrees)
> 0 to < 1	3,218	11.5	6.2	.271	8.4	3,180	11.7	7.7	.197	5.1
1 to 1.99	2,707	11.3	5.3	.206	12.9	3,250	11.9	7.5	.221	13.2
2 to 2.99	2,591	11.2	4.8	.177	19.2	3,101	11.8	7.2	.198	21.7
3 to 3.99	2,550	11.2	4.6	.155	23.8	3,385	11.5	7.3	.181	29.2
4 to 4.99	2,243	11.1	4.1	.132	25.9	3,030	11.3	6.4	.140	30.0
5 to 6.99	2,055	11.1	3.8	.115	31.1	3,221	11.0	5.9	.098	28.3
7 to 9.99	1,857	11.1	3.4	.091	35.5	3,221	10.3	4.8	.054	23.4
10 to 14.99	1,791	10.9	2.9	.068	37.8	2,853	10.1	4.8	.057	34.9
≥ 15	1,331	10.8	2.4	.045	57.5	3,081	10.1	4.5	.053	53.6

$$Q = \frac{\text{SS error}}{\text{SS total}} = .54$$

or a pseudo R^2 of $1-Q = .46$.

Table 36 shows the distribution of actual values over five ranges of predicted values. The fit of the model seems quite adequate over a much larger range of values than were available in the Washington State data. Comparisons

Table 36. Comparison of predicted and actual accident distributions.

Range of Predicted Accidents ($\hat{A}$)	N	Means: Predicted	Means: Actual	Actual Percentiles: 25th	50th	75th
$\leq$ 2.0	1,165	1.46	1.64	0	1	2
2.01 to 3.0	790	2.48	2.37	1	2	3
3.01 to 5.0	846	3.86	3.99	2	3	5
5.01 to 8.0	440	6.22	6.00	3	5	8
> 8.0	284	12.47	12.83	5	9	16

of the estimated effects for degree of curve and roadway width are shown in table 37. The table shows model coefficients along with their standard errors in parentheses. The estimated degree of curve effects are virtually identical. While the difference in the estimated width effects is statistically significant, they are certainly of the same order of magnitude.

Table 37. Comparison of model coefficients (standard errors).

Data Base	Variable: Degree	Variable: Width
Washington	.240 (.008)	-.026 (.006)
four-State	.223 (.009)	-.044 (.006)

While differences in the model coefficients of table 37 are statistically significant, they do seem to be of, roughly, the same order of magnitude. Given the differences between the two data sets, the results in terms of accident rates per million vehicle mi (1.61 km) seem reasonably comparable.

A model similar to model (13) given earlier in chapter 6 (and having the same form as the model in TRB Special Report 214) was also fit to the four-State curves data base. The estimated model was:[10]

$$\hat{Acc} = [1.28 \text{ (Section Length)(Volume)} + .141 \text{ (Degree)(Volume)}] \, (.980)^{\text{Width}-30} , \qquad (16)$$

where the length and degree effects are significant at the $p = .0001$ level. In this form, the estimated degree effect is much larger than it was from the Washington data (i.e., .141 from the four-State curve sample vs. .014 from the Washington State sample).

It was conjectured that a possible reason for the large differences in the estimated coefficients of the (Degree) x (Volume) term in these models might be due to the fact that the four-State data contained only isolated curves, while a great majority of the Washington curves were not isolated. Further, it was believed that sharper curves would likely result in more of a driver expectancy problem (and more accidents) if they are isolated (i.e., curves located at the end of a long tangent) than if they are one curve in a series of curves. To investigate this idea, a series of analyses were run on subsets of the Washington data where the curves were restricted to be separated by increasingly longer distances. The results of these analyses are summarized in table 38. For these analyses the simplified model:

$$Acc = \beta_1 \, (L \cdot V) + \beta_2 \, (D \cdot V) + \varepsilon \qquad (17)$$

was fit to the data subsets.

From table 38, it is seen that as the Washington curves become more isolated, the estimated Degree x Volume effect from model (17) does tend to

Table 38. Changes in estimated degree x volume effects as a function of minimum distance between (Washington) curves.

Minimum Distance Between Curves	Subset Size (N)	Estimated Coefficient for Degree x Volume in Model (17)
No restriction	10,900	.016
D $\geq$ .15 mi.	2,714	.033
D $\geq$ .300 mi.	1,212	.050
D $\geq$ .450 mi.	638	.062
D $\geq$ .600 mi.	389	.074
D $\geq$ .700 mi.	303	.072

increase and become more in line with the results obtained from the four- State data.

In terms of the effect of roadway width (W) on accidents, the four-State model had the term $(.980)^{(W-30)}$, while the term $(.978)^{(W-30)}$ was in the Washington State model. These terms are virtually identical and would result in approximately the same accident reduction factors for a given amount of widening. For example, widening a 30-ft (9.1-m) roadway to 36 ft (11.0 m) would yield an accident reduction (AR) factor of 11.4 percent based on the four-State model, and 12.5 percent based on the Washington model. Due to the similarity of the roadway width effects, it was not considered justified to produce separate AR factors for roadway widening for isolated vs. non-isolated curves. Instead, accident reduction factors presented in chapter 8 are based on the Washington State model, since that model is for a large sample consisting of curve-only segments (not curves plus tangents) and does not exclude curves based on length of tangent adjacent to the curve.

In summary, the results between the various studies are reasonably consistent in terms of the roadway variables most related to accidents and the signs of the coefficients (i.e., whether a variable has a positive or negative effect on accidents). While the magnitudes of the coefficients for degree of curve differ for the two curve data bases, these differences appear to be due at least in part to the fact that the four-State data base consists of isolated curves and the Washington State data base is mostly non-isolated curves. In fact, the coefficient (i.e., accident effect) for degree of curve is considerably higher for isolated curves (four-State data base) than non-isolated curves (Washington State data base). This agrees with the assumption that a sharp curve at the end of a long tangent (i.e., a possible driver expectancy problem) will often result in more accidents, compared to a similar curve on a generally winding section with shorter tangents.

As discussed in the next chapter, two separate sets of accident reduction factors (AR factors) were developed for curve flattening projects. One set of AR factors is for isolated curves (based on the model for the four-State curve model) and the other set of AR factors corresponds to non-isolated curves (based on the Washington State curve model). In terms of effects from roadway widening, results were relatively similar between the four-State and Washington State curve data bases. Therefore, only one set of accident reduction factors is needed for curve widening improvements. The accident reduction factors for various curve improvements are given in the next chapter.

CHAPTER 8 - ACCIDENT REDUCTION FACTORS

This chapter describes the development of accident reduction factors (i.e., percent reductions in accidents) which are expected due to various curve-related improvements. Accident reduction factors (AR factors) for most of the curve improvements (e.g., curve widening, curve flattening, adding spiral transitions, improving deficient superelevation) are based primarily on the analysis of the Washington State data base. AR factors are also provided for the curve flattening improvements for isolated curves (i.e., curves with minimum tangents of .124 mi on each end), based on an analysis of the FHWA four-State data base of horizontal curves.

Accident Predictions

As discussed in chapter 6, several computer models were produced from the Washington State curves data base which predicted the number or rate of accidents on curves with reasonable accuracy. However, the model that was used in the development of accident reduction factors for roadway widening, curve flattening (non-isolated curves), and the addition of a spiral transition was as follows:

$$A = [\ (1.55)\ (L)(V) + .014\ (D)(V) - (.012)\ (S)(V)\ ]\ (.978)^{W-30} \qquad (13)$$

where,

A = Number of total accidents on the curve in a 5-year period

L = Length of the curve in mi (1.6 km)

V = Volume of vehicles in million vehicles in a 5-year period passing through the curve (both directions)

D = Degree of curve

S = Presence of spiral transitions on both ends of the curve, where S = 0 if no spiral exists, and S = 1 if spirals do exist

W = Width of the roadway on the curve in ft (.3048 m)

This model form was chosen for several reasons. First of all, it predicts accident frequencies quite well, compared to actual accident means for various data subsets (about as well as the linear model). Also, the interaction of traffic and roadway variables are reasonable, and make sense in terms of accident occurrences on curves. Note that both D and L are used in the model, since both the degree of curve and length of curve are needed to characterize a curve and define the curve central angle.

A similar model form for curve accidents was discussed in reference 10 as:

A_c = AR_s (L)(V) + K(D)(V), where

A_c = Number of accidents on the curve

AR_s = Accident rate on a straight highway section

K = A constant derived for the coefficient for degree of curve (where K=.0336 as found in that analysis)

The first component in the model ($AR_s \cdot L \cdot V$) was used by the authors to represent a steady-state effect of turning, which is directly proportional to the vehicle mi of travel around the curve but is independent of the curvature. The second component of the model ($K \cdot D \cdot V$) was termed the transitional component and is proportional to the traffic volume and degree of curve. This component of the model represents the expected accidents at the ends of the curve due to driver loss of control related to the sharpness of the curve. This model form was calibrated by the authors for K using data from the four-State curve data base and used to compute accident reduction factors for various curve flattening improvements.(2)

While the model form in reference 10 was considered to be a reasonable form for computing curve flattening effects, there was also a need to incorporate the effects of curve width, presence of spiral, and/or other roadway variables found to be significant. Incorporating these other variables in the model would allow for also estimating the accident effects of other curve improvements (e.g., widening the curve). Thus, that basic model form was used in addition to adding effects of road width and spiral based on the Washington State analysis.

To illustrate the results of the chosen accident prediction model, the number of curve accidents per 5 years, A_p, was computed for various values of degree of curve, central angle, length of curve, ADT, and roadway width, as shown in table 39. Note that each combination degree of curve and central angle defines a curve length, since,

$$I = \text{Central angle} = (D)(L)(52.8), \text{ or}$$

$$L = \frac{I}{D(52.8)}$$

where

I = central angle of curve (in degrees)
D = degree of curve (in degrees)
L = length of curve (in mi (1.61 km))

When L is expressed in ft,

$$L = \frac{I}{D} \times 100$$

Thus, for example, a 1-degree curve with a central angle of 10 degrees would correspond to a curve length of $\frac{I}{D} \times 100 = \frac{10}{1} \times 100 = 1{,}000$ ft (305 m). Similarly, values of L are given for each <u>combination</u> of D and I in table 39.

For a 5-degree curve with a 50-degree central angle, an ADT of 2,000 and a 22-ft (6.7-m) roadway width, the model predicts 1.59 curve accidents per 5 years. Under similar conditions (i.e., 5-degree curve, 50-degree central angle, and ADT of 2,000) with a 40-ft (12.2-m) roadway width, the predicted number of curve accidents (A_p) in a 5-year period would be 1.06. Throughout the table, A_p decreases with increasing road width, whereas A_p increases as ADT increases and as central angle increases.

One seemingly illogical trend in the table requires discussion. We would expect, for example, that accidents would increase as degree of curve increases (for equal curve lengths, road widths, etc.) Notice that for a given ADT, road width and central angle, A_p <u>decreases</u> in some cases for higher degrees of curves. For example, consider the column in the table with 1,000 ADT and a roadway width of 34 ft (10.4 m). For a central angle of 30 degrees, values of A_p are 1.50 for a 1-degree curve, .41 for a 5-degree curve, .38 for a 10-degree curve, and .75 for a 30-degree curve. This is because the A_p values represent those accidents within the curve itself and, for a given central angle, curve lengths are longer for milder curves. As in the previous example for a 30-

Table 39. Predicted number of curve accidents (A_p) per 5-year period from the model (13) based on traffic volume and curve features.

Predicted Number of Accidents (A_p) per 5 year period

Degree of Curve (D)	Central Angle (I)	(Length of Curve in ft.)* (L)	ADT = 500				ADT = 1,000				ADT = 2,000				ADT = 5,000			
			Roadway Width (w)				Roadway Width				Roadway Width				Roadway Width			
			22	28	34	40	22	28	34	40	22	28	34	40	22	28	34	40
1	10	(1,000)	.34	.29	.26	.22	.67	.59	.51	.45	1.34	1.18	1.03	.90	3.36	2.94	2.57	2.25
	30	(3,000)	1.00	.85	.75	.65	1.95	1.71	1.50	1.31	3.91	3.42	2.99	2.62	9.77	8.55	7.48	6.54
	50	(5,000)	1.62	1.41	1.24	1.08	3.24	2.83	2.48	2.17	6.47	5.66	4.95	4.34	16.18	14.15	12.39	10.84
5	10	(200)	.14	.12	.10	.09	.28	.25	.22	.19	.56	.49	.43	.38	1.40	1.23	1.08	.94
	30	(600)	.26	.24	.20	.18	.54	.47	.41	.36	1.07	.94	.82	.72	2.69	2.35	2.06	1.80
	50	(1,000)	.40	.35	.30	.27	.79	.69	.61	.53	1.59	1.39	1.22	1.06	3.97	3.47	3.04	2.66
10	10	(100)	.18	.16	.14	.12	.37	.32	.28	.25	.74	.64	.57	.50	1.85	1.62	1.41	1.24
	30	(300)	.25	.22	.19	.17	.50	.44	.38	.33	1.00	.87	.76	.67	2.49	2.18	1.90	1.67
	50	(500)	.31	.27	.24	.21	.63	.55	.48	.42	1.25	1.10	.96	.84	3.13	2.74	2.40	2.10
	90	(900)	.44	.39	.34	.30	.88	.77	.68	.59	1.76	1.54	1.35	1.18	4.41	3.86	3.38	2.96
30	10	(33)	.47	.41	.36	.31	.94	.82	.72	.63	1.87	1.64	1.44	1.26	4.69	4.10	3.59	3.14
	30	(100)	.49	.43	.38	.33	.98	.86	.75	.66	1.96	1.71	1.50	1.31	4.90	4.29	3.75	3.28
	50	(167)	.51	.45	.39	.34	1.02	.89	.78	.69	2.05	1.79	1.57	1.37	5.11	4.47	3.92	3.43
	90	(300)	.55	.48	.42	.37	1.11	.97	.85	.74	2.22	1.94	1.70	1.48	5.54	4.85	4.24	3.71

$$\text{*Length} = \frac{\text{Central Angle}}{\text{Degree}} \times 100$$

1 ft = 0.3048 m

degree central angle, values of L are 3,000 ft (914 m) for a 1-degree curve, 600 ft (183 m) for a 5-degree curve, 300 ft (91 m) for a 10-degree curve, and 100 ft (30 m) for a 30-degree curve. Thus, in that example, with a 30-degree central angle, accidents per 1,000 ft (305 m) of curve are .5 for a 1-degree curve, .68 for a 5-degree curve, 1.27 for the 10-degree curve, and 7.5 for a 30-degree curve. Thus, the model predicts that accidents per given length of curve increase as degree of curve increases, as expected. In summary, A_p values in table 39 should not be used to estimate the accident effects of curve flattening, since the original and new alignment of the roadway must be properly accounted for (as described in more detail in a later section).

The combined effects of roadway and traffic variables on curve accidents are illustrated in figures 9 through 13, as developed from accident prediction model (13). For example, for an ADT of 2,000 on curves with a 30-ft (9.1-m) roadway and no spiral (i.e., a typical situation), the relationship between degree of curve and curve length on accidents is given in figure 9. Notice that increases in accidents occur as degree of curve increases, and accidents increase as curve length increases. The relationship of degree of curve and roadway widths on crashes is shown in figure 10 for a curve length of .10 mi (.16 km), an ADT of 2,000 and no spiral. Accidents decrease slightly with increasing roadway width for each degree of curve category. For a 20-degree curve under these conditions, widening the curve from 20 ft (6.1 m) to 30 ft (9.1 m) will reduce accidents from about 2 (accidents per 5 years) down to about 1.6, a 20 percent reduction.

The effect on total crashes of ADT combined with degree of curve is shown in figure 11. Notice the more rapid increase in accidents for higher degree of curve as ADT increases and the linear increase in accidents as ADT increases within each curvature category. Likewise, accidents increase linearly for various roadway widths as ADT increases, as shown in figure 12. Finally, the effect of spirals on accidents is given in figure 13 for degree of curve values of 1 through 10. According to the model, accidents are consistently lower for curves with spiral transitions than for curves without spirals. The specific accident reduction factors for curve flattening, roadway widening, adding a spiral transition, and improving deficient superelevation are given in the following sections.

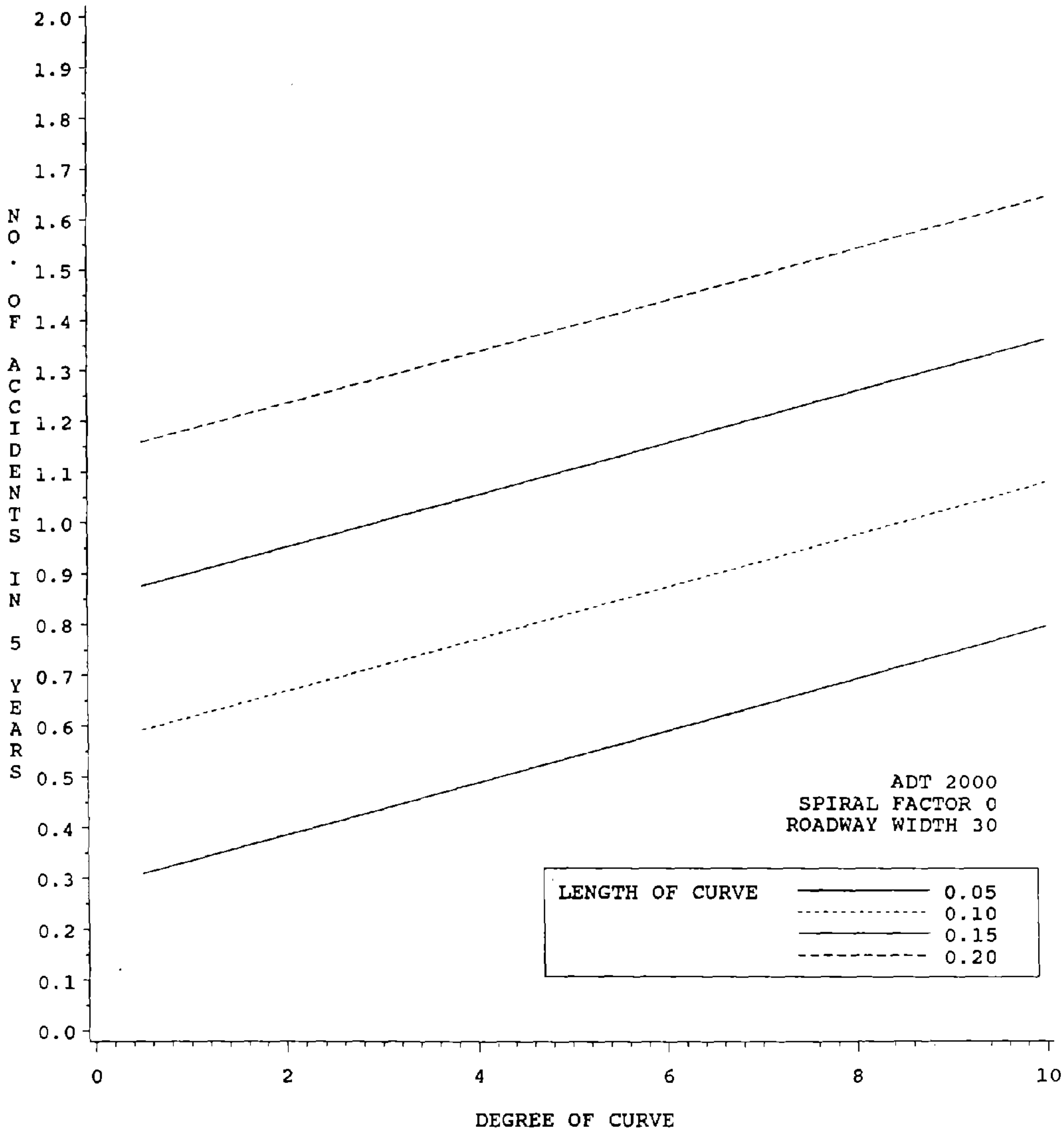

Figure 9. Plot of predicted accidents in 5 years for degree of curve and curve length.

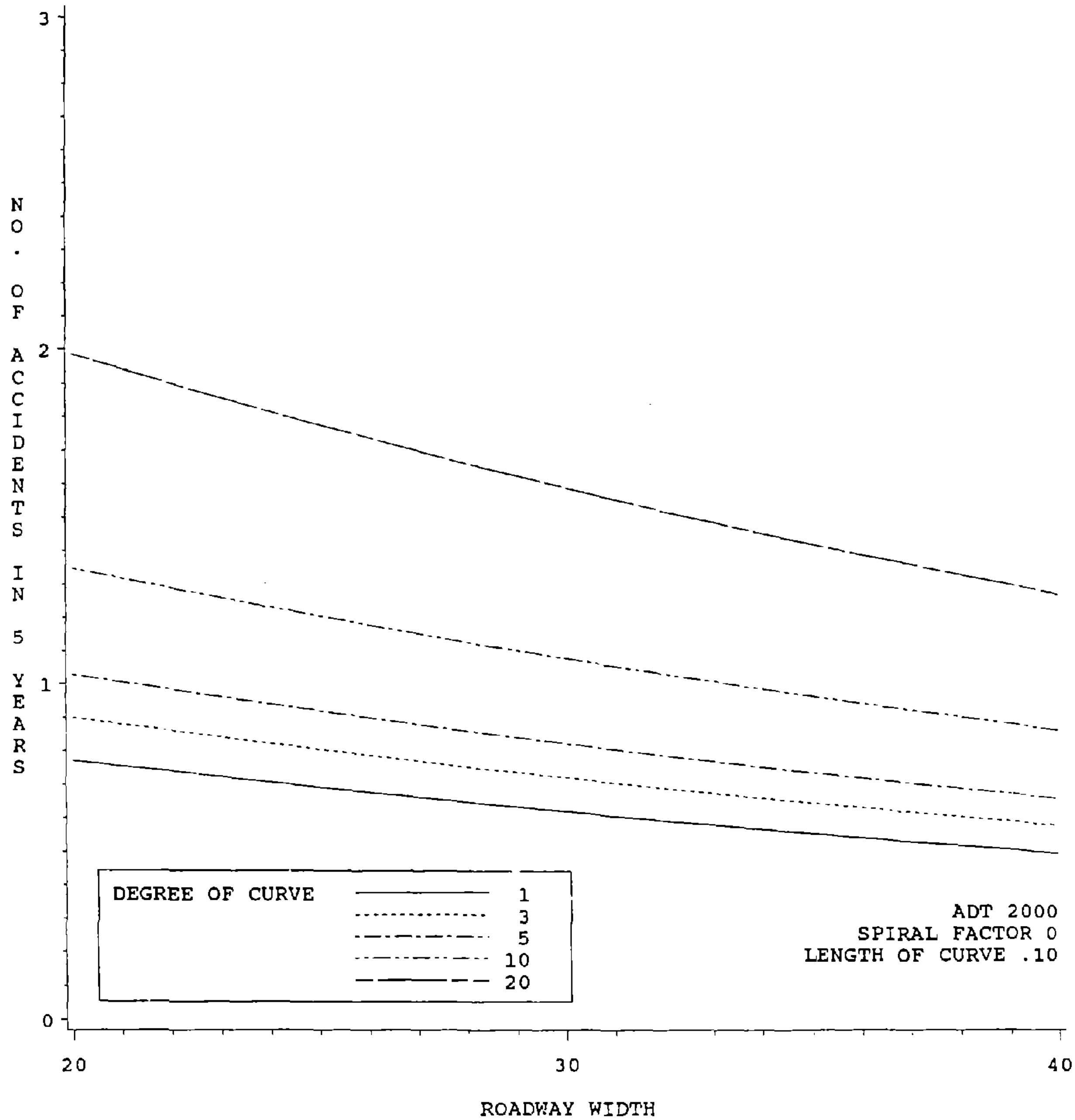

Figure 10. Plot of predicted accidents in 5 years for degree of curve and road width.

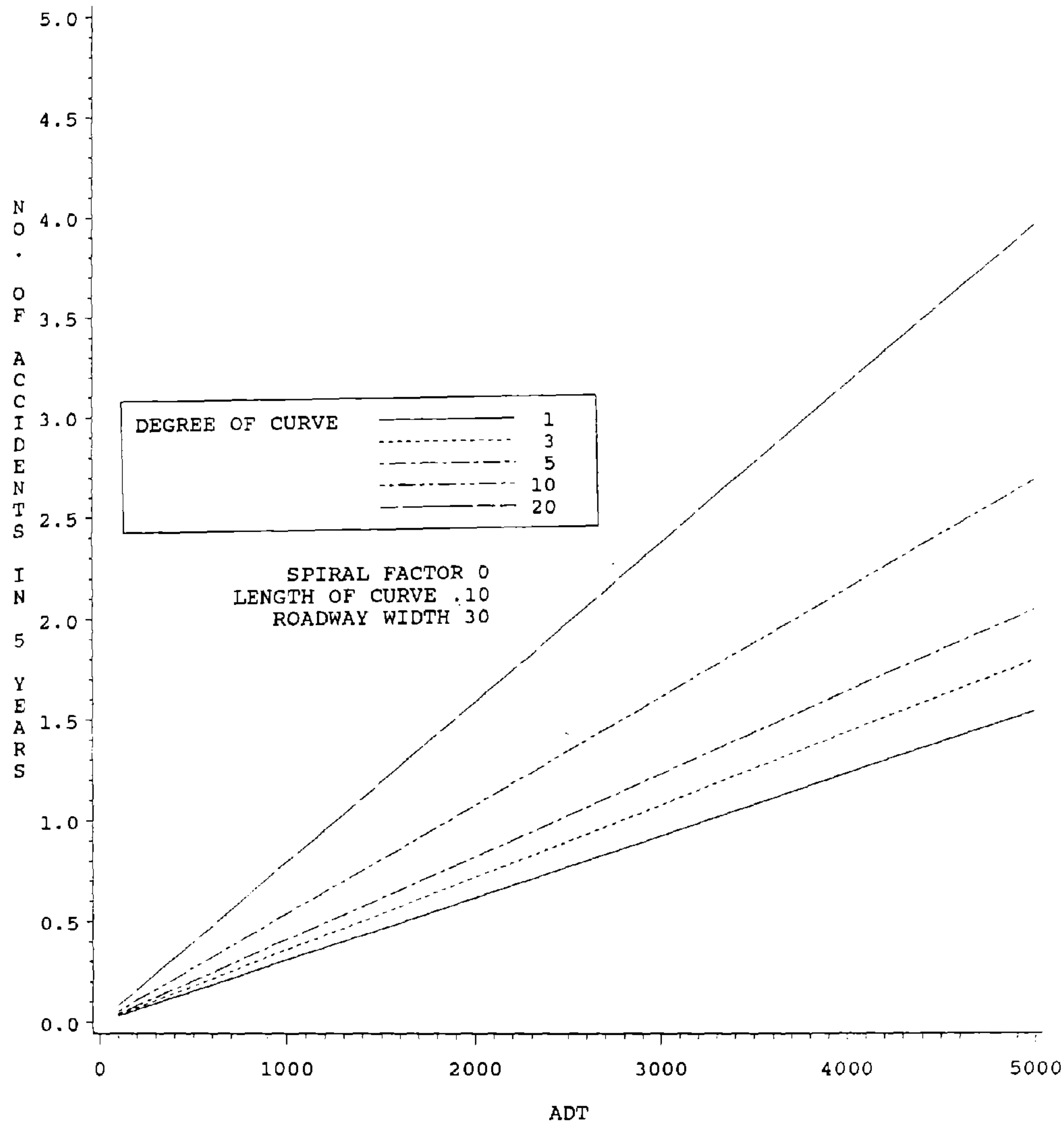

Figure 11. Plot of predicted accidents in 5 years for degree of curve and ADT.

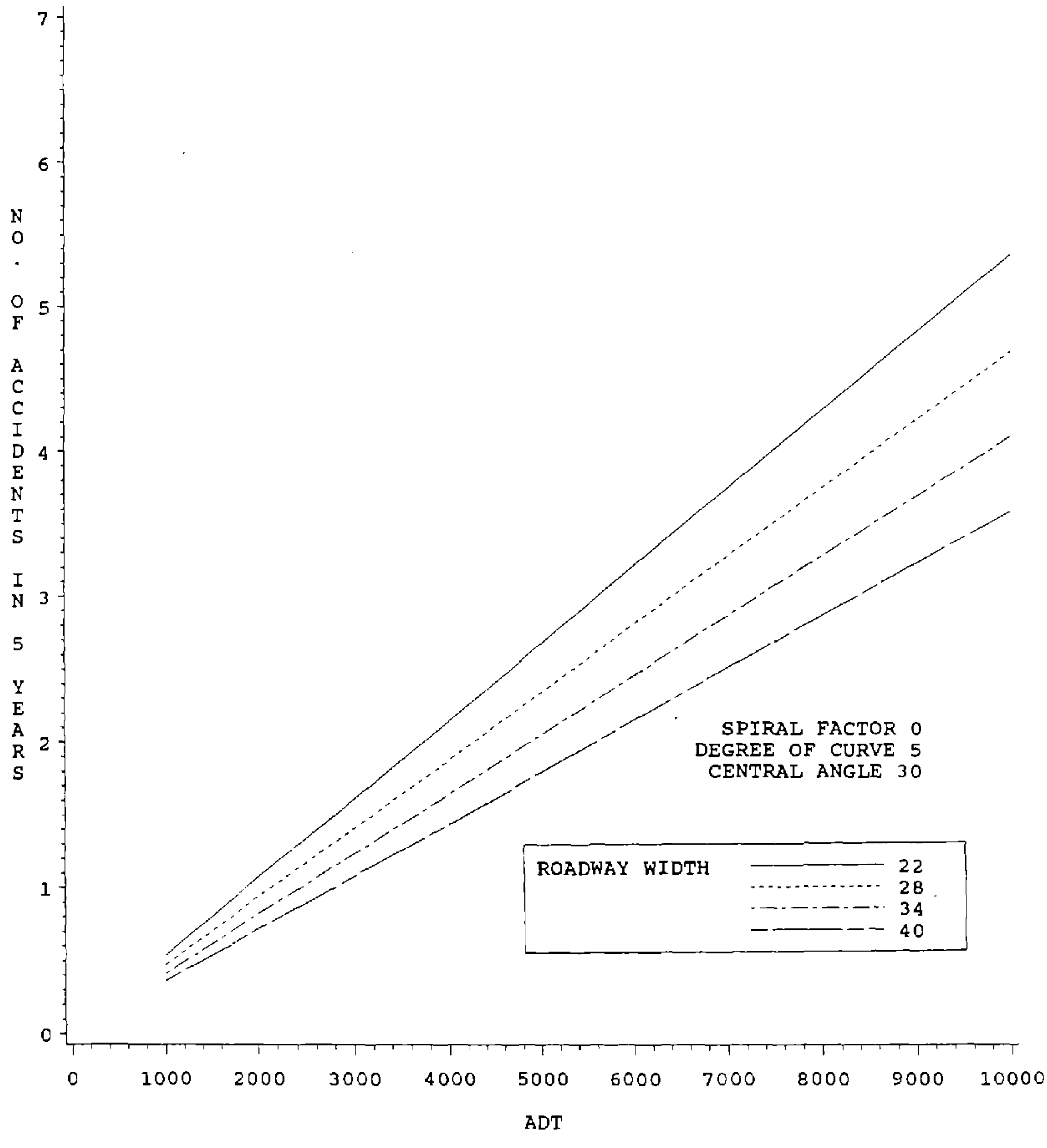

Figure 12. Plot of predicted accidents in 5 years for road width and ADT.

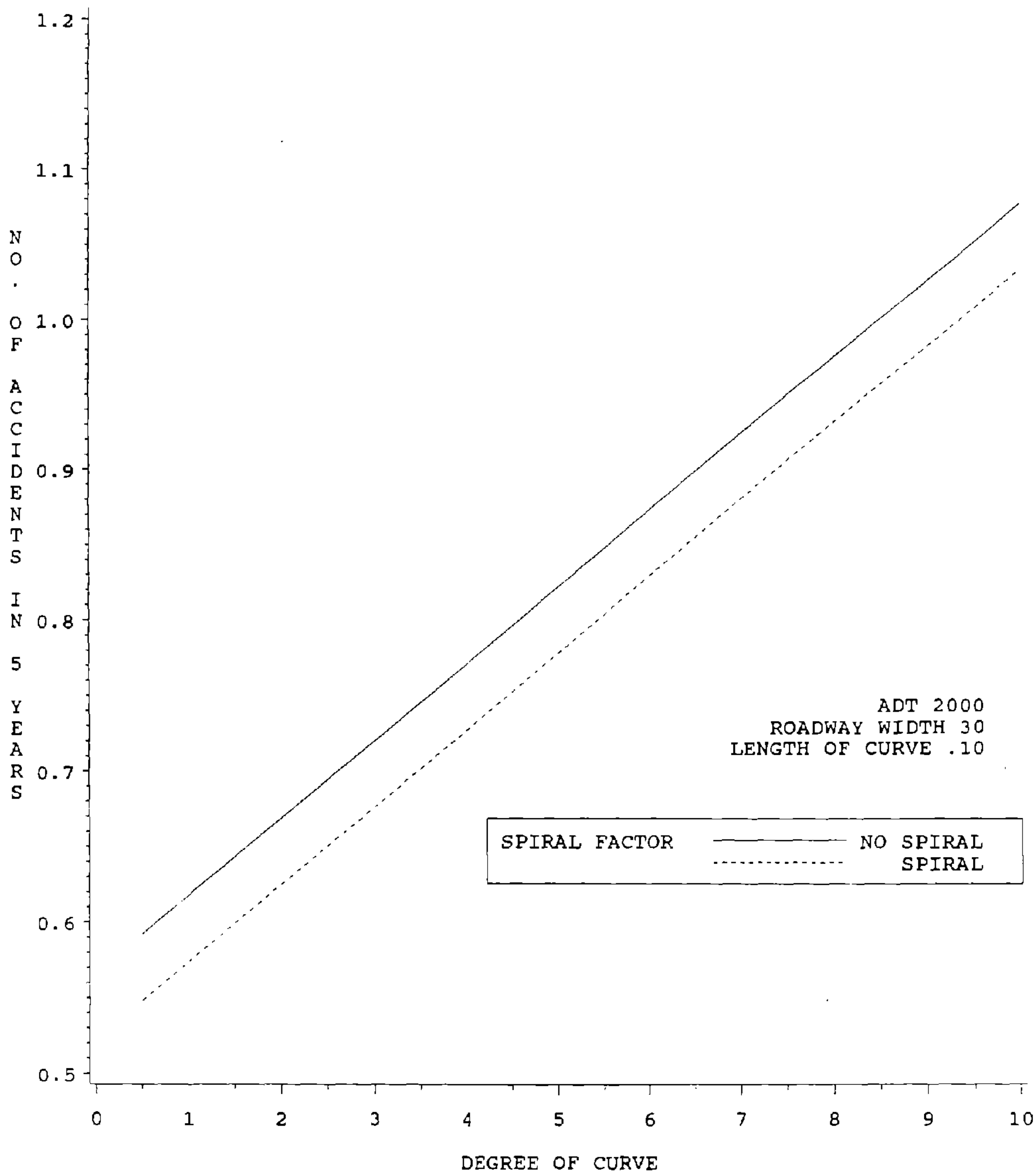

Figure 13. Plot of predicted accidents in 5 years for degree of curve and spiral presence.

Curve Flattening Effects

To use the predictive model for estimating the effects on crashes of curve flattening, consider the sketch in figure 14 of an original curve (from the PC_o to PT_o) and a newly constructed flattened curve (from PC_n to PT_n). To compute the accident reduction due to the flattening project, we must compute the accidents in the before and after condition from common points. Curve flattening reduces the overall length of the highway but increases the length of the curve, assuming that the central angle remains unchanged. Thus, we must compare accidents in the after condition between PC_n and PT_n along the new alignment with accidents in the before condition between PC_n and PT_n along the old alignment.

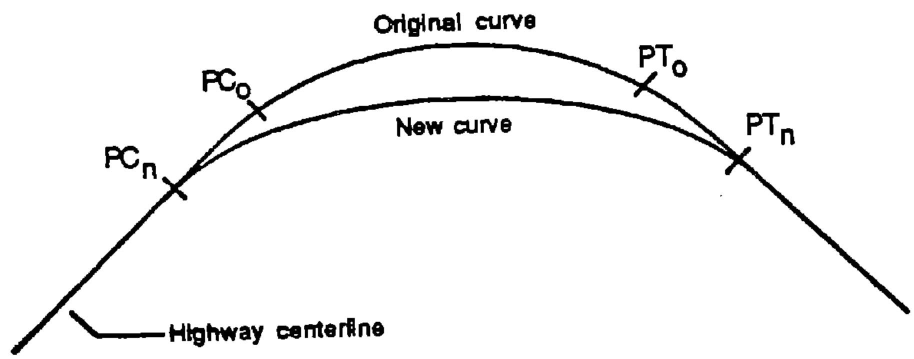

Figure 14. Illustration of curve alignment before and after flattening.

The number of accidents on the new curve (A_n) is computed using model (13) with the new degree of curve D_n, new curve length (L_n), new roadway width W_n, and new spiral condition, S_n, or

$$A_n = [(1.552)(L_n)(V) + .014(D_n)(V) - (.012)(S_n)(V)](.978)^{(W_n-30)} \qquad (13)$$

To compute accident reduction due to curve flattening, we must determine the accidents on the old curve alignment (A_o) by adding the accidents on the old tangent segments A_T to the accidents on the old curve A_{oc}. The lengths of the tangent segments (T_1 and T_2 in figure 16) are computed as (L_n - L_o + L), where L is the amount by which the highway alignment is shortened (between PC_n and PT_n) due to the flattening project and is expressed as:[10]

$$\Delta L = [(2.17 \tan I/2) - (I/52.8)] [(1/D_n) - 1/D_o)] ,$$

or

$$\Delta L = (2) (\tan I/2) (R_n - R_o) \tag{18}$$

where ΔL is given in mi, I in degrees and tan I/2 in radians. As discussed in reference 10, ΔL is very small for central angles of 90 degrees or less.

The number of accidents on the tangent (A_T) portions on the old alignment is computed based on model (13) as:

$$A_T = (1.55) (L_n - L_o + \Delta L) V (.978)^{(W_o - 30)} \tag{19}$$

The accidents on the old alignment = accidents on the old curve (A_{oc}) plus the accidents on the old tangent segments (A_T), i.e.,

$$A_o = A_{oc} + A_T = [(1.552) L_oV + (.014) D_oV - (.012) S_oV] (.978)^{(W_o - 30)} + [(1.552) (L_n - L_o + \Delta L) V] (.978)^{(W_o - 30)} \tag{20}$$

The accident reduction factor for curve flattening (AR_F) is equal to

$$AR_F = \frac{A_o - A_n}{A_o}$$

Thus, the percent reduction in accidents may be computed as the difference between accidents on the <u>old</u> <u>alignment</u> (A_o) and the accidents on the <u>new</u> <u>alignment</u> (A_n) divided by the accidents on the old alignment (A_o). However, to apply the AR factors in this form, one must know the number of accidents on the old alignment (i.e., accidents on the old curve plus the tangent portions, A_T). This number of accidents may not be easily determined from a practical standpoint.

A more simplified expression of the AR factor would be one which can be multiplied by the number of accidents on only the old curve (A_{oc}). The expression for this AR factor would then be:

$$AR_R = \frac{A_o - A_n}{A_{oc}} \tag{21}$$

where AR_R = the revised accident reduction factor. Note that the denominator, A_{OC}, in this expression represents accidents on the old curve only. Thus, for a given flattening project (e.g., flattening from a 25-degree curve to a 10-degree curve), one should simply multiply AR_R times the number of accidents on the old curve to compute the estimated number of accidents reduced.

Accident reduction percentages for curve flattening using model 21 are given in table 40 for various combinations of central angle and degree of curve before and after flattening. AR factors are provided for both isolated curves (from the four-State model) and non-isolated curves (from the Washington State model), where isolated curves are considered to have tangents of at least 650 ft (198 m), or .124 mi (.20 km) or greater on each end. AR factors are higher for flattening isolated curves, compared to non-isolated curves. Flattening a 20-degree curve to an 8-degree curve with a 30-degree central angle would reduce curve accidents by approximately 52 percent for non-isolated curves, or 59 percent for isolated curves. As expected, the greater the curve flattening, the higher the accident reductions.

It is also useful to mention that, for a given amount of curve flattening, the percent reduction in accidents is slightly larger for lower central angles than for greater central angles. For example, flattening a 20-degree non-isolated curve to 10 degrees will reduce accidents 48 percent for a 10-degree central angle, but by only 41 percent for a 50-degree central angle. However, it should be remembered that a 50-degree central angle curve would be expected to have a greater number of total accidents than a 10-degree central angle for a given degree of curve (all else being equal). Thus, the net number of accidents reduced may be greater on a 50-degree central angle than a 10-degree central angle for a given flattening improvement. For example, for a 25-degree curve with a 50-degree angle, and ADT of 1,000 (V = 1.825), a 30-ft (9.1-m) width with no spiral, the curve length would be:

$$L = \frac{I}{D\ (52.8)} = \frac{50}{25\ (52.8)} = .038 \text{ mi } (.061 \text{ km}).$$

The predicted accidents (A_p) using model (13) would be:

$$A_p = [(1.55)\ (L)(V) + .014\ (D)(V) - (.012)\ (S)(V)]\ .978^{(W-30)}, \text{ or}$$

Table 40. Percent reduction (AR) and total accidents due to horizontal curve flattening -- non-isolated and isolated curves.

Degree of Curve		Central Angle in Degrees									
		10		20		30		40		50	
Original (Do)	New (Dn)	Non-Isolated	Isolated*	Non-Isolated	Isolated	Non-Isolated	Isolated	Non-Isolated	Isolated	Non-Isolated	Isolated
30	25	16	17*	16	17	16	17	15	16	15	16
30	20	33	33	32	33	31	33	31	33	30	33
30	15	49	50	48	50	47	50	46	50	46	50
30	12	59	60	57	60	56	60	55	60	55	60
30	10	65	67	64	66	63	66	62	66	61	66
30	8	72	73	70	73	69	73	68	73	68	73
30	5	82	83	80	83	79	83	78	83	78	83
25	20	19	20	19	20	18	20	18	20	17	20
25	15	39	40	38	40	36	40	36	40	35	40
25	12	50	52	49	52	48	52	46	52	46	51
25	10	58	60	56	60	55	60	54	59	53	59
25	8	66	68	64	68	62	68	61	67	60	67
25	5	77	80	75	80	74	79	72	79	72	79
20	15	24	25	23	25	22	25	21	25	20	24
20	12	38	40	36	40	35	40	34	39	33	39
20	10	48	50	45	50	44	49	42	49	41	49
20	8	57	60	54	60	52	59	51	59	50	59
20	5	71	75	68	74	66	74	64	74	64	74
15	10	30	33	28	33	26	33	25	32	24	32
15	8	43	46	40	46	37	46	35	45	34	45
15	5	61	66	56	66	53	65	51	65	50	65
15	3	73	79	68	79	64	78	63	78	63	78
10	5	41	49	36	48	32	48	29	47	28	47
10	3	58	69	50	68	45	67	43	66	42	66
5	3	22	37	15	35	13	33	11	32	11	31

*Isolated curves include curves with tangents of 650 ft (.124 mi) or greater on each end.

$$A_p = [(1.55)(.038)(1.825) + (.014)(25)(1.825) - (.012)(0)(1.825)] \times (1)$$

A_p = $\boxed{.75}$ accidents per 5 years on the curve for a 50-degree central angle and 25-degree curve

For a central angle of 10 degrees and a 25-degree curve, (all other factors being equal)

$$L = \frac{I}{D\ (52.8)} = \frac{10}{25\ (52.8)} = .0076 \text{ mi., and}$$

$$A = [(1.55)(.0076)(1.825) + (.014)(25)(1.825) - 0] \times (1)$$

$$= .022 + .639 = \boxed{.66}$$ accidents per 5 years on the curve for a 10-degree central angle and 25-degree curve

Thus, the net reduction in accidents would be greater for a given flattening project for high central angles than for low central angles.

It should also be mentioned that a wide variety of curve flattening projects are provided in table 40, including the flattening of 30-degree curves to much flatter (e.g., 5 and 10 degree) curves. Although less than 10 percent of the Washington curves data base had curves of 30 degrees or sharper, it is the sharpest curves which typically have the greatest accident problems, and thus are most in need of flattening. Flattening of a sharp curve, however, may be more practical on roadway sections where a sharp or poorly designed curve is experiencing an abnormally high accident experience within a roadway section.

Roadway Widening Improvements

The widening of the roadway lanes or shoulders and shoulder surfacing are other geometric curve improvements which were considered in terms of their effects on accidents. Accident reduction percentages were first developed based on inputting various roadway widths into accident prediction model (13). Accident reductions range from 4 percent for 2 ft (0.6 m) of total roadway widening (e.g., for widening a 24 ft (7.3 m) roadway to 26 ft (7.9 m)) to 36 percent for 20 ft (6.1 m) of total roadway widening.

The predictive model alone did not allow for further determining the accident restrictions which would result from widening the lanes vs. adding paved shoulder vs. adding unpaved shoulder. This is because the variable "total roadway width" was the only width-related variable in the final accident prediction model (instead of lane width, paved shoulder width, and unpaved shoulder width). However, based on the previous safety literature, it is fairly clear that the roadway width effects on crashes will vary, depending on the type of widening. The FHWA cross-section study, for example, provided accident reductions for widening lanes, compared to widening paved or unpaved shoulders.(3) From that study, the accident predictive model for two-lane, rural roads (based on approximately 5,000 mi (8,050 km) of road in 7 States) was as follows:

$$AO/M/Y = 0.0019\ (ADT)^{0.8824}\ (0.8786)^{W}\ (0.9192)^{PA}\ (0.9316)^{UP}\ (1.2365)^{H}\ (0.8822)^{TER1}\ (1.3221)^{TER2} \tag{22}$$

where:

AO/M/Y = related accidents (i.e., single-vehicle plus head-on plus opposite direction sideswipe plus same direction sideswipe accidents) per mi (1.61 km) per year,

ADT = average daily traffic,

W = lane width in ft (.3048 m),

PA = average paved shoulder width in ft (.3048 m),

UP = average unpaved (i.e., gravel, stabilized, earth, or grass) shoulder width in ft (.3048 m),

H = median roadside hazard rating (where a rating of 1 represents a low level of hazard and a 7 represents a high level of hazard for a run-off-road vehicle)

TER1 = 1 if flat, 0 otherwise, and

TER2 = 1 if mountainous, 0 otherwise.

Based on model (22), accident reduction factors were estimated for various amounts of lane widening and widening of paved and unpaved shoulders. It should be remembered, however, that the AR factors developed in that study are for widening on rural roadway <u>sections</u>, which include tangents, as well as curves. Thus, there was a need to determine the most likely effects of widening lanes, paved shoulders, and unpaved shoulders on <u>curves only</u>. To accomplish this, results were used from the accident prediction model 13 (i.e., accident effects of roadway width on curves) combined with the relative influence of lane widening vs. paved and unpaved shoulder widening from reference 3. This process for refining the accident reductions from the curve accident predictive model (13) is described below.

From the effectiveness estimates from the cross-section study, ratios were computed of effectiveness for equal amounts of widening by type of improvement. For example, from the cross-section study, 2 ft (.6 m) of lane widening per side reduces accidents by 23 percent, compared to 16 percent for paved shoulders and 13 percent for unpaved shoulders. The ratio of effectiveness of lane widening to paved shoulder widening is 1.44, and the ratio of effectiveness of paved to unpaved shoulder widening is 1.23. Across the width range given in the cross-section study, the average ratios are 1.41 and 1.17 respectively.[3]

From the Washington State distribution of lane and shoulder widths on two-lane rural roads, the number of ft (.3048 m) of lane and shoulder widening was compiled which was needed to bring all lanes to widths of 12 ft (3.7 m) and shoulders of widths of 16 ft (4.9 m). Widening to these levels would mean 19 percent of the improvements were to lanes and 81 percent to shoulders. Based on these percentages and the ratios of effectiveness for the various types of widening, AR factors were computed for each type of roadway widening.

As shown in table 41, a 5 percent reduction in accidents would be expected due to 2 total ft (.6m) of lane widening (i.e., 1 ft (.3 m) per side) such as from two 10-ft (3.0-m) lanes to two 11-ft (3.4-m) lanes. For 8 total ft (2.4-m) of lane widening (e.g., widening two 8 ft (2.4 m) lanes to 12 ft (3.7 m)), a 21 percent reduction in curve accidents would be expected. The table only provides values for up to 4 ft (1.2 m) of lane widening per side (i.e., up to 8 total ft (2.4 m) of widening). This is because widening lanes beyond 12 ft (3.7 m) is considered to be adding to the shoulder width, and lane widths less than 8 ft (2.4 m) fall outside the limits of this data base.

Widening paved shoulders by 2 ft (.6 m) (1 ft (.3 m) on each side) would result in a 4-percent accident reduction, while a 33-percent reduction would be expected for adding two 10-ft (3.0-m) paved shoulders. Accident reductions for unpaved shoulders are slightly less than for paved shoulders. Accident reductions range from 3 to 29 percent for widening of unpaved shoulders from 1 to 10 ft (.3 to 3.0 m), respectively.

Table 41. Percent reduction in accidents due to lane widening, paved shoulder widening, and unpaved shoulder widening.

Total Amount of Lane or Shoulder Widening (ft)		Percent Accident Reduction		
Total	Per Side	Lane Widening[1]	Paved Shoulder Widening	Unpaved Shoulder Widening
2	1	5	4	3
4	2	12	8	7
6	3	17	12	10
8	4	21	15	13
10	5	*	19	16
12	6	*	21	18
14	7	*	25	21
16	8	*	28	24
18	9	*	31	26
20	10	*	33	29

1 ft = 0.3048 m

[1]Values of lane widening correspond to a maximum widening of 8 ft (2.4 m) to 12 ft (3.7 m) for a total of 4 ft (1.2 m) per lane, or a total of 8 ft (2.4) of widening.

The values in table 41 need to be applied properly to account for the amount and type(s) of widening. For example, assume that a 20 ft (6.1 m) roadway (two 10-ft (3.0-m) lanes with no shoulder)) was to be widened to 32 ft

(9.8 m) of paved surface. Assuming that the lanes would be widened to 12 ft (3.7 m), then two 4-ft (.9-m) paved shoulders would also be added. Thus, table 41 indicates a 12-percent accident reduction due to widening the lanes a total of 4 ft (1.2 m) (from 20 ft (6.1 m) to 24 ft) (7.3 m)). Then, 8 ft (1.8 m) of total shoulder paving would correspond to an accident reduction of 15 percent. The resulting accident reduction factor for both widening improvements would not be the sum of the two accident reduction factors. The correct procedure for combing two or more accident reduction factors is discussed later in this chapter.

Spiral Improvement

Based on the statistical analysis and modeling efforts described earlier, the presence of spiral transitions on a curve was generally found to have a significant effect in reducing accident frequencies on curves. The magnitude of the effect was studied from the selected predictive model (13) as well as from other analyses. Depending on the degree of curve and central angle, the effect of having a spiral was found to range from about 2 percent to 9 percent based on the predictive model. The influence of central angle and degree of curve was generally a function of the form of the model.

An overall reduction of 5 percent was determined to be the most representative effect of adding spiral transitions to a curve in view of the predictive model and other related analyses. While one may expect that spiral transitions are more beneficial on sharp curves than mild curves, such a differential effect was not adequately supported from the analysis. In summary, a 5-percent reduction in crashes was the value deemed most likely for the effect of adding spiral transitions.

Superelevation Improvements

The previous analyses and modeling also revealed that inadequate superelevation (i.e., not enough superelevation compared to AASHTO Greenbook criteria) will result in increased curve accidents. Correcting this superelevation deficiency (or "superelevation deviation") will likely result in a significant reduction in curve accidents. The precise magnitude of the effect was difficult to quantify due to the interaction of superelevation with other roadway features. However, using one model form, the typical accident reduction which may result from correcting a superelevation deviation of .02 was approximately 10 to 11 percent. For superelevation deviations of greater than .02, even higher accident reductions may be possible. Having more superelevation than AASHTO criteria was not found to be associated with increased accidents on curves. A separate analysis of the FHWA four-State curve data base also revealed that further benefits may result from more gradual transition of superelevation beginning prior to the beginning of the curve.

The correction of superelevation deviation during a routine 3R project would involve providing sufficient additional asphalt and engineering design to upgrade the superelevation to the AASHTO and State specifications. While the cost of correcting superelevation may be a substantial increase in the cost of a routine pavement overlay on the curve, the relative cost would generally be much less than the cost of curve flattening or curve widening. Thus, because of the potential accident reduction, it is desirable to upgrade superelevation deviations on curves as a routine measure when roadways are repaved.

Combining Accident Reduction Factors

When two or more curve improvements are to be made as part of the same overall project, the combined effect of the AR factors must not be simply added. Instead, the overall accident reduction (AR) should be computed as follows:

$$AR = 1 - (1-AR_1)(1-AR_2)(1-AR_3)(1-AR_4) \ldots \qquad (23)$$

where:

AR_1 = the accident reduction factor of the first improvement

AR_2 = the accident reduction factor of the second improvement

AR_3 = the accident reduction factor of the third improvement, etc.

Consider, for example, an improvement involving curve flattening, lane widening, plus widening paved shoulder, with individual AR factors of 25 percent, 12 percent, and 15 percent, respectively. The overall (AR) would be computed as:

$$AR = 1 - (1-.25)\ (1-.12)\ (1-.15)$$

$$= 1 - (.75)\ (.88)\ (.85)$$

$$= .439$$, or a 44 expected percent reduction in accidents.

CHAPTER 9 - ROADSIDE OBSTACLE ANALYSIS

Overall Philosophy of Modeling Obstacle Accidents

A fixed object crash occurs when two situations occur:

1. A vehicle runs off the road.

2. A fixed object is in its path.

Factors related to a vehicle running off the road (situation 1 above) might include traffic volumes, width of road, horizontal and vertical curvature, pavement characteristics, superelevation, etc. The effects of these factors should be the same for all types of fixed objects. With respect to situation 2 above (i.e., a fixed object in the vehicle's path), factors include number, extent, and location of fixed objects. Extended objects may have different effects than point objects; i.e., it is not so clear that there should be differences due to type of object.

Some philosophy with respect to estimating models for fixed-object crashes also seems to be in order. First, we note that accident data of the type considered here are highly variable. Thus, to any given set of conditions describing the roadway and environment, there exists a wide distribution of accident counts or accident rates (accidents per mi (1.61 km) per yr, or accidents per vehicle mi (1.61 km) per yr). This means that while crashes may be statistically associated with variables relating to the roadway and roadside, a data analysis will, generally, not uniquely determine specific models which "explain" the data. More typically, a variety of models may be about equally consistent with the data. In the analyses which follow, an attempt was made to use as much information as possible from the data to estimate models that seem reasonable, logical, and consistent with the data.

As accident counts and accident rates increase, the variances of the count and rate distributions also tend to decrease. The log transformation tends to stabilize these variances. For this reason, and for their general versatility, log linear models were the basic type considered. We also note that accident rates are known with greater precision as road segment length, observation period, and ADT increase. With this in mind, weighted least squares analyses were used, with the weight function chosen proportional to the product segment length x years x ADT.

Preliminary Analysis

In order to estimate the effects of various roadway and roadside features on accident frequency, a model was first developed for all fixed object accidents. The data base needed for this analysis was the cross-section data base, which contains detailed roadside obstacle data along with traffic, accident, and roadway data covering nearly 5,000 miles (8,050 km) for 1,940 roadway sections in 7 States.(3) The initial step in this model development was a regression analysis with log (fixed object accidents + .1) as the dependent variable. Independent variables included:

- Log ADT.
- Lane width (W).
- Shoulder width (SW).
- Recovery distance (REC).
- Two dummy variables indicating rolling terrain and mountainous terrain (TERR).

Accidents were actually accidents/mi (1.6 km) per year and the analysis used a weighted regression with weight given by the product W = (C) (section length)(years)(ADT). The constant C was chosen so that weights summed to N = 1,939.

In the first analysis, only ADT and recovery distance (REC) were statistically significant. In particular, neither lane width (W) nor shoulder width (SW) was significant. Subsequent analyses involved trying certain other model forms and other variable combinations. When a model was run using measures of horizontal (HC) and vertical curvature (VC) in place of the terrain variables, statistically significant effects were found for W, SW, and REC, as well as the curvature variables (i.e. HC and VC). The curvature variables, however, were only available for 1,080 of the 1,939 roadway sections.

The next step was to again fit the original model, this time using the restricted data set, (i.e., the 1,080 sections). In this model, two opportune things happened. All variables, (ADT, W, SW, REC, and TERR) were significant and seemingly reasonable; and the coefficient (i.e. exponent) of ADT did not differ significantly from the value 1.0.

The effects of ADT, W, SW, and TERR were fixed at the values obtained from the last analysis using the restricted data set and these effects removed from the dependent variable. A model was then run on the complete data set fitting the adjusted dependent variable to a function containing only a constant and an effect due to REC. Both of these coefficients were similar in this last model to what they were in the original model.

Combining the results of these last two analyses yielded the model:

Fixed object accidents per mi (1.6 km) per yr =

$$.025(\text{ADT})(.88)^{\text{W}}(.95)^{\text{SW}}(.94)^{\text{REC}} \times \text{TERR} \qquad (24)$$

$$\text{where TERR} = \begin{cases} 1 \text{ if flat terrain} \\ 1.2 \text{ if rolling or mountainous.} \end{cases}$$

The fact that the estimated effects for SW and REC are essentially equal suggests that the two could be combined. The sum (SW + REC) is a measure of the distance from the travel lane to the fixed objects, which is used in the models for specific fixed objects which follow. The question is: How well does this model fit the full data set? When the first model was fit to the data, the resulting squared multiple correlation coefficient was $R^2 = .304$. When the nonsignificant variables (W, SW, TERR) were removed from the model, this value only dropped to an $R^2 = .303$.

With a regression model, the total sum of squares of the dependent variable about its mean value is partitioned into two parts: a sum of squares due to the regression, and a residual or error sum of squares. The quantity R^2 can be expressed as

$$R^2 = 1 - \frac{\text{SS error}}{\text{SS total}}$$

For a predictor function that has not been obtained through a least squares procedure, it is not necessarily true that the total sum of squares can be expressed as the sum of an error sum-of-squares plus a sum of squares due to the predictor. Still, the ratio of the error sum-of-squares to the total sum-of-squares of the dependent variable about its mean is a meaningful quantity, and

$$\tilde{R}^2 = 1 - \frac{\text{error sum-of-squares}}{\text{total sum-of-squares}}$$

can still be taken as a measure of goodness-of-fit. Note that $\tilde{R}^2$ can take on negative values if the predicted values do not fit the data as well as the mean value.

For the predictor function given in model (24) (i.e., by fixing the effects due to ADT, W, SW, and TERR), the error sum-of-squares is 3,958 compared with a total sum-of-squares of 5,565. These yield a pseudo-R^2 value of

$$\tilde{R}^2 = .289.$$

Thus, it seems that the predictor from model (24), fits the complete data set nearly as well as does the function representing the least-squares-fit (R^2 = .303). This fact is further clarified by figures 15 through 17. Figure 15 is a scatterplot where the dependent variable (log accident rate) is plotted on the vertical axis. The horizontal axis is the (weighted) least squares predictor function from the model. If this model fit the data exactly, all points would lie on a line at 45 degrees. Obviously, this is not the case, and figure 15 shows the wide distribution of accident rate values for any given predicted value.

The X-axis of figure 15 was then divided into eight intervals containing, roughly, equal numbers of data points, and the distribution of y-values over each interval summarized by a box and whisker plot. These are shown in figure 16. The boxes cover the range from the 25th to the 75th percentile points of the distribution of log (fixed object accs/mi (1.61 km) per yr), and the (dashed line) whiskers extend to the 5th and 95th percentiles. The dashed line across the box is the median value and the + is the mean. The solid line drawn across the box is the mean value of the predicted values from the function given in model (24) again showing that these predicted values fall well within the central part of the distribution of actual accident rates.

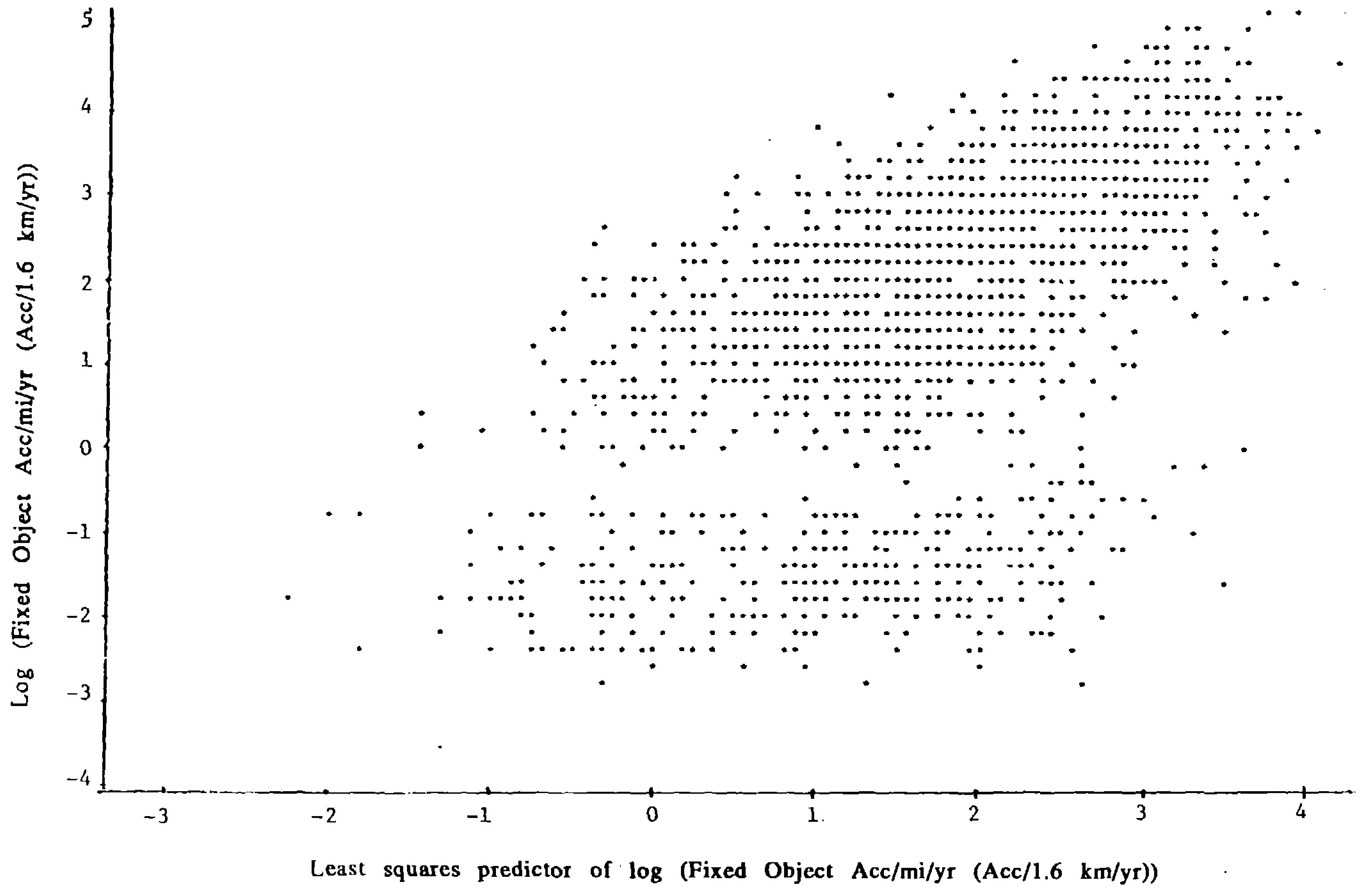

Figure 15. Scatter plot of accidents versus the least squares predictor.

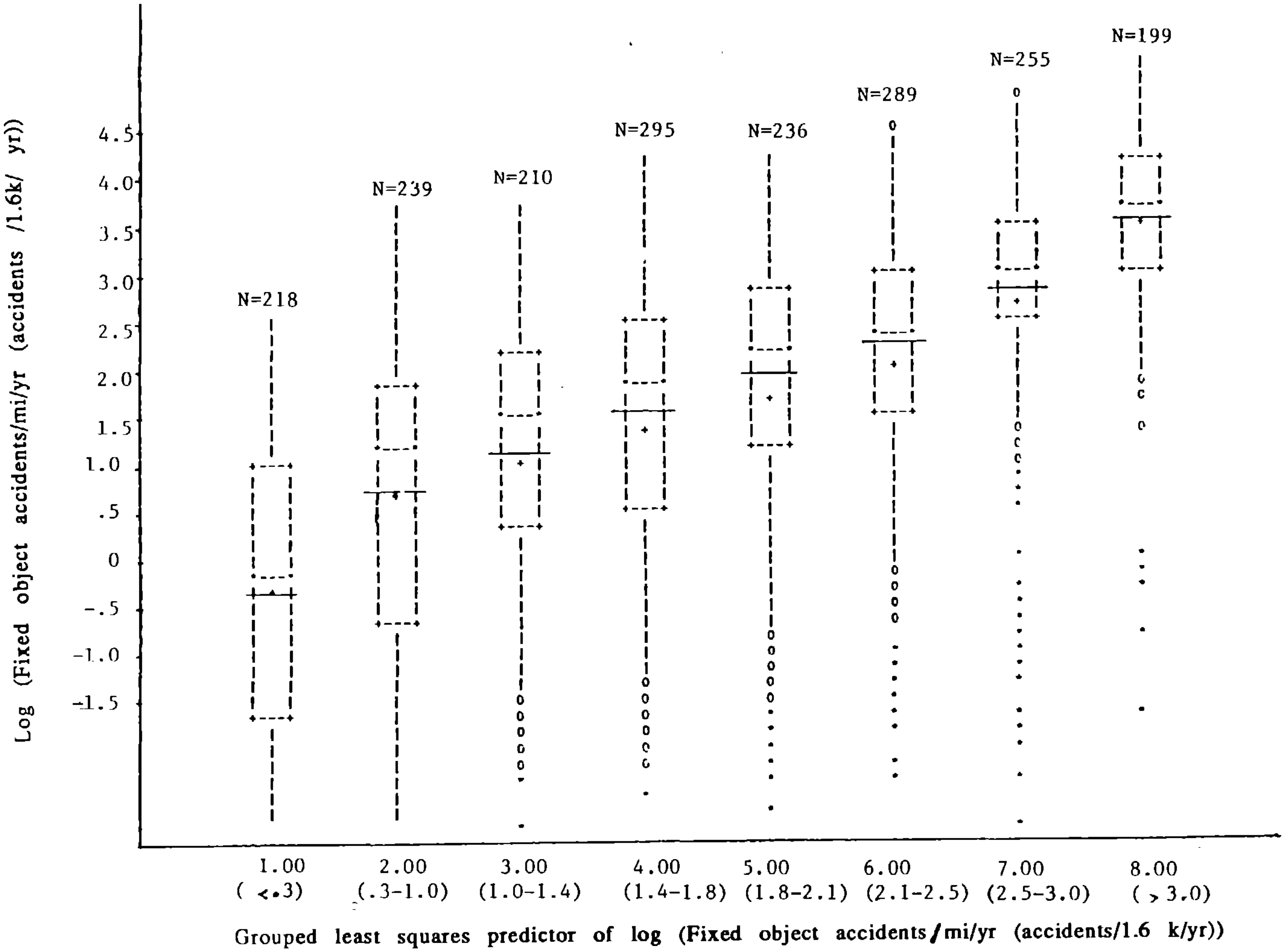

Figure 16. Box plot of log accident rates vs. predicted log accident rate distributions.

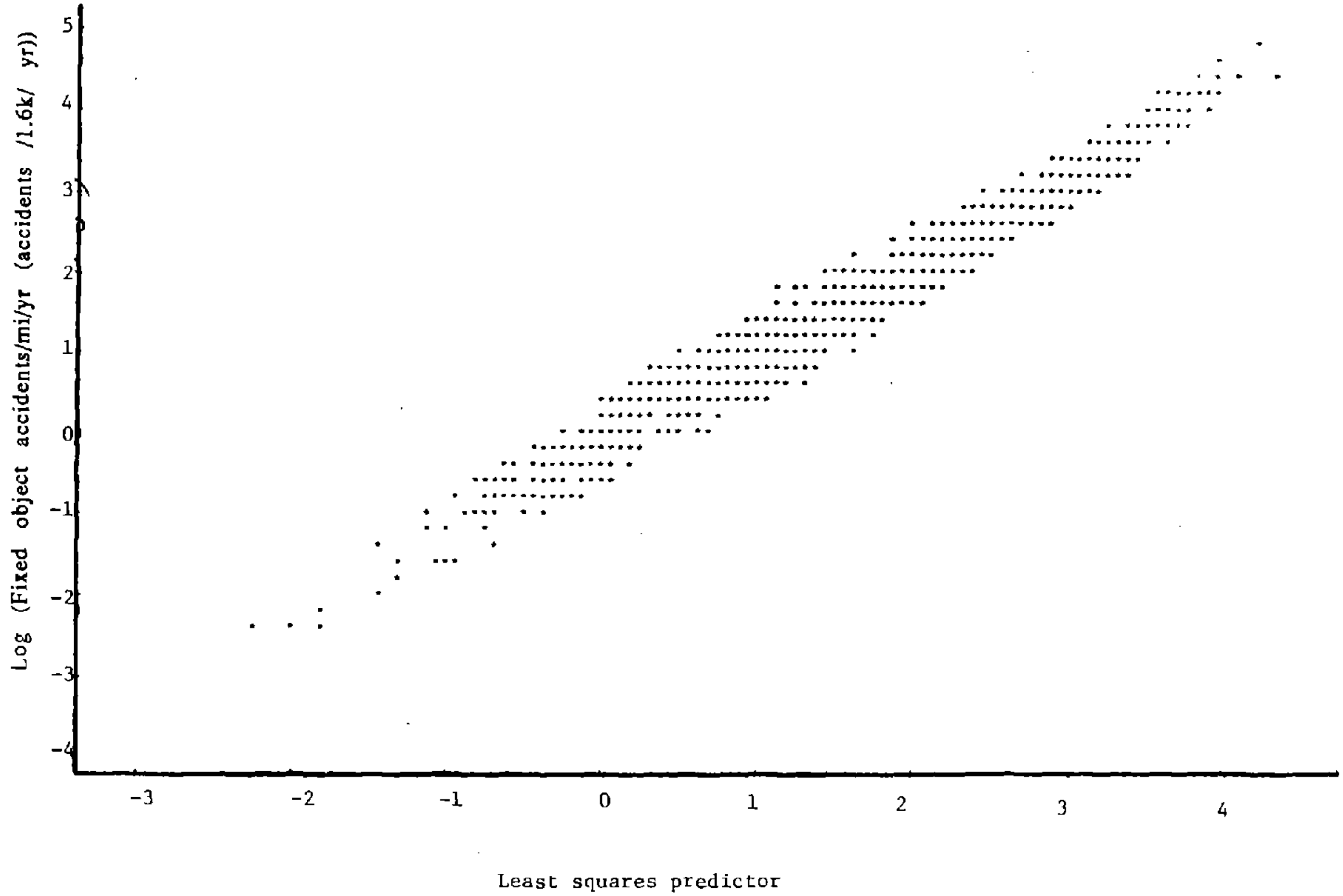

Figure 17. Scatter plot after adjustment.

Finally, figure 17 is a scatterplot of predicted values from the two predictor functions. From here on, the effects of ADT, W, and TERR are fixed at those given by model (24) and removed from the dependent variables prior to any additional modeling. This figure shows that variation in accidents is reduced when controlling for those other roadway variables.

Models for Specific Fixed Objects

The data included information on four types of fixed point objects, utility poles, culverts, signs, and mailboxes. For each road section we have:

- Number of accidents/mi/yr for each object type (where 1 mi = 1.6 km).
- Number of such objects/mi (where 1 mi = 1.6 km).
- Average distance of objects of that type from edgeline.

To develop a model for utility pole accidents, we first adjust the accident variable as follows:

$$\text{Y pole} = \frac{[(\text{Pole accidents/mi/yr})(\text{mi})(\text{yr}) + .01]}{[(\text{ADT})(\text{mi})(\text{yr})(.88)^{W} \times \text{TERR}}$$

$$\text{where TERR} = \begin{cases} 1 \text{ if terrain = flat} \\ 1.2 \text{ if terrain = rolling or mountainous]} \end{cases}$$

Then we fit the log linear model

$$\log\ (\text{Y pole}) = \beta_o + \beta_1(\text{poles/mi}) + \beta_2(\text{avg. dist. of poles}),$$

or some variation of this such as using log (distance) rather than distance. Note that the effects of ADT, W, and TERR have been factored out of the dependent variable prior to additional modeling. Increasing the accident counts by .01 eliminates problems of using the log transformation on a variable which sometimes takes on zero values. The amount .01 could be subtracted from the predicted accident numbers, but this seems unnecessary. The estimated model coefficients were:

β_o (constant) = -9.77.
β_1 (poles/mi) = .047.
β_2 (avg.dist.) = -.145.

All coefficients were statistically significant with p-values of .0001. The value of R^2 for this model was R^2 = .257, which seems quite high considering that the effects of ADT, W, and TERR had already been removed.

Combining the effects of this model with the fixed effects leads to model for pole accidents, namely

$$\text{Pole accident/mi/yr} = (.00006)(\text{ADT})(.88)^{W}(1.05)^{\text{poles/mi}} (.865)^{\text{avg.dist}}\ (\text{TERR}) \tag{25}$$

$$\text{where TERR} = \begin{cases} 1 \text{ if flat terrain} \\ 1.2 \text{ if rolling or mountainous.} \end{cases}$$

since 1.05 = exp (.047) and .865 = exp. (-.145). A pseudo-R^2 (i.e., in $\tilde{R}^2$) was calculated for the entire model at $\tilde{R}^2$ = .366.

Following the same procedure, models were fit to the data on culvert accidents, sign accidents, and mail box accidents. The results of these analyses are shown in table 42.

Table 42. Model coefficients and standard errors for point objects.

Coefficient (p-value)	Object Type		
	Culvert	Sign	Mailbox
Constant	-13.3	-13.0	-12.9
Number/mi	.103 (.0001)	.024 (.0002)	.107 (.0001)
Avg. dist.	-.015 (.240)	.047 (.0011)	-.038 (.0300)
R^2	.045	.012	.095

1 mi = 1.61 km

The model for pole accidents seems quite reasonable, but the results shown in table 42 requires explanation. Poles per mi (1.61 km) and reported pole accidents occur with much greater frequency than the other object types. Culverts and culvert accidents are relatively rare. For both signs and mailboxes, there was relatively little variability in average distance from pavement edge. All of these facts may lead to situations where a least squares fit may not provide very meaningful results.

In an attempt to improve the situation, the four object types were combined and an overall object distance effect estimated. The estimated distance effect was -.050 with p = .0004. This effect was, in turn, fixed and removed from the dependent variable, and the models refit for mailboxes, culverts, and signs. Each of these models contained only a constant term and an effect for the number of objects per mi. The results are given in table 43, which also contains results concerning models for extended object accidents. These models for extended fixed object crashes were developed in a similar manner with effects of ADT, W, and TERR fixed. The pseudo-R^2 values for the fit of each predictor is also given in table 43. The models are shown in table 43 in a multiplicative form for accident rates (per mi (1.61 km) per-yr). The models, themselves, were all fit to log (accident rates).

Table 43. Models for fixed object accident rates (i.e., accidents per mi (1.61 km) per yr).

Object Type	Model	R^2
Utility Poles	$(.00006)(ADT)(.88)^W(1.05)^N(.865)^D(1.2)^T$	.366
Mailboxes	$(.000003)(ADT)(.88)^W(1.11)^N(.95)^D(1.2)^T$	.159
Culverts	$(.000003)(ADT)(.88)^W(1.11)^N(.95)^D(1.2)^T$	.049
Signs	$(.00001)(ADT)(.88)^W(2.01)^N(.95)^D(1.2)^T$	.108
Trees	$(.00002)(ADT)(.88)^W(1.04)^C(.92)^D(1.2)^T$	.153
Guardrails	$(.00002)(ADT)(.88)^W(1.10)^C(.86)^D(1.2)^T$	.248
Fence/Gate	$(.00001)(ADT)(.88)^W(1.06)^C(.93)^D(1.2)^T$	.160

where,

ADT = average daily traffic
W = lane width in ft (.3048 m)
N = number per mi of fixed object (of specified type)
C = percent coverage of roadside by fixed object
D = average distance of objects from edge of travel lane in ft (.3048 m)

$$T = \begin{cases} 1 \text{ if mountainous or rolling terrain,} \\ 0 \text{ if flat} \end{cases}$$

1 mi = 1.61 km

Accident Reductions from Roadside Obstacle Improvements

The accident predictive models given in table 43 were used to estimate the number of accidents for each obstacle type for various ADT values, distance of the obstacles from the road, and density of obstacles (i.e., number of point objects per mile or percent coverage of longitudinal objects). For most situations, the numbers of accidents of a given obstacle type were quite small. For example, estimated utility pole accidents are shown for mountainous areas in table 44. The minimum number of pole accidents (per mi (1.61 km) per year) was .003 for a section with 1,000 ADT, 12-ft (3.7-m) lanes, 20 ft (6.1 m) pole offset, and 30 poles per mi (per 1.61 km). The maximum of 8.44 pole accidents occurred for 80 poles per mi (1.61 km), 9 ft (2.7-m) lane widths, 10,000 ADT, and 2-ft (.6-m) pole offset. For most conditions, however, predicted pole accidents are less than one per mi (1.61 km) per year.

Similar summaries of predicted accidents are given for mailboxes, culverts, signs, trees, guardrails, and fences in tables 45 through 50. For all types of obstacles, crashes increase with increasing ADT and obstacles per mi, and also increase with decreasing shoulder width and obstacle offset. Estimated numbers of obstacle accidents are generally low, except for ADT's above 5,000 and with obstacle offsets of 5 ft (1.5 m) or less.

It should be emphasized that these predicted crashes in tables 45 through 50 by obstacle type represent averages for various combinations of conditions, but not the high-accident outlyers where considerably higher accident

Table 44. Number of utility pole accidents per mi per year predicted from model (24).[1]

ADT	Lane Width (ft)	N = 30 Poles Per Mi				N = 50 Poles Per Mi				N = 80 Poles Per Mi			
		Pole Distance from Road (ft)				Pole Distance from Road (ft)				Pole Distance from Road (ft)			
		2	5	10	20	2	5	10	20	2	5	10	20
1,000	9	.07	.05	.02	.01	.20	.13	.06	.01	.84	.55	.26	.06
	12	.05	.03	.01	.003	.13	.09	.04	.01	.58	.37	.18	.04
2,000	9	.15	.10	.04	.01	.39	.25	.12	.03	1.69	1.09	.53	.12
	12	.10	.07	.03	.01	.27	.17	.08	.02	1.15	.74	.36	.08
5,000	9	.37	.24	.12	.03	.98	.63	.31	.07	4.22	2.73	1.32	.31
	12	.25	.16	.08	.02	.67	.43	.21	.05	2.88	1.86	0.90	.21
10,000	9	.74	.48	.23	.05	1.96	1.27	.61	.14	8.45	5.47	2.65	.62
	12	.50	.33	.16	.04	1.33	.86	.42	.10	5.76	3.73	1.80	.42

[1] Note: These values are for rolling and mountainous areas only.

1 ft = 0.3048 m
1 mi = 1.61 km

Table 45. Number of mailbox accidents per mi per year predicted from model (24).[1]

ADT	Lane Width (ft)	N = 25 Mailboxes Per Mi			N = 50 Mailboxes Per Mi		
		Mailbox Distance from Road (ft)			Mailbox Distance from Road (ft)		
		2	5	10	2	5	10
2,000	9	.028	.024	.019	.380	.325	.252
	12	.019	.016	.013	.259	.222	.172
5,000	9	.070	.060	.046	.949	.813	.630
	12	.048	.041	.032	.647	.554	.429
10,000	9	.140	.120	.093	1.898	1.627	1.259
	12	.095	.082	.063	1.293	1.109	.858

[1] Note: These values are for rolling and mountainous areas only.

1 ft = 0.3048 m
1 mi = 1.61 km

Table 46. Number of culvert accidents per mi per year predicted from model (24).[1]

ADT	Lane Width (ft)	N = 10 Culverts Per Mi			N = 20 Culverts Per Mi		
		Culvert Distance from Road (ft)			Culvert Distance from Road (ft)		
		2	5	10	2	5	10
2,000	9	.006	.005	.004	.017	.014	.011
	12	.004	.003	.003	.011	.010	.008
5,000	9	.015	.013	.010	.041	.036	.028
	12	.010	.009	.007	.028	.024	.019
10,000	9	.029	.025	.019	.083	.071	.055
	12	.020	.017	.013	.056	.048	.037

[1] Note: These values are for rolling and mountainous areas only.

1 ft = 0.3048 m
1 mi = 1.61 km

Table 47. Number of sign accidents per mi per year predicted from model (24).[1]

ADT	Lane Width (ft)	N = 25 Signs Per Mi			N = 50 Signs Per Mi		
		Sign Distance from Road (ft)			Sign Distance from Road (ft)		
		2	5	10	2	5	10
2,000	9	.009	.008	.006	.011	.010	.007
	12	.006	.005	.004	.008	.007	.005
5,000	9	.022	.019	.015	.028	.024	.019
	12	.015	.013	.010	.019	.016	.013
10,000	9	.044	.038	.029	.056	.048	.037
	12	.030	.026	.020	.038	.033	.025

[1]Note: These values are for rolling and mountainous areas only.

1 ft = 0.3048 m
1 mi = 1.61 km

Table 48. Number of tree accidents per mi per year predicted from model (24).[1]

ADT	Lane Width (ft)	N = 20% Coverage of Trees				N = 30% Coverage of Trees				N = 60% Coverage of Trees			
		Tree Distance from Road (ft)				Tree Distance from Road (ft)				Tree Distance from Road (ft)			
		2	5	10	20	2	5	10	20	2	5	10	20
1,000	9	.014	.011	.007	.003	.021	.016	.011	.005	.067	.053	.035	.015
	12	.010	.007	.005	.002	.014	.011	.007	.003	.046	.036	.024	.010
2,000	9	.028	.022	.015	.006	.042	.032	.021	.009	.135	.105	.069	.030
	12	.019	.015	.010	.004	.028	.022	.015	.006	.092	.071	.047	.021
5,000	9	.070	.055	.036	.016	.104	.081	.054	.023	.338	.263	.174	.075
	12	.048	.037	.025	.011	.071	.055	.036	.016	.230	.179	.118	.051
10,000	9	.141	.110	.072	.031	.209	.162	.107	.046	.676	.527	.347	.151
	12	.096	.075	.049	.021	.142	.111	.073	.032	.461	.359	.237	.103

[1] Note: These values are for rolling and mountainous areas only.

1 ft = 0.3048 m
1 mi = 1.61 km

Table 49. Number of guardrail accidents per mi per year predicted from model (24).[1]

ADT	Lane Width (ft)	N = 10% Coverage of Guardrail				N = 30% Coverage of Guardrail				N = 60% Coverage of Guardrail			
		Guardrail Distance from Road (ft)				Guardrail Distance from Road (ft)				Guardrail Distance from Road (ft)			
		2	5	10	20	2	5	10	20	2	5	10	20
1,000	9	.01	.01	--	--	.10	.06	.03	.01	1.71	1.09	.51	.24
	12	.01	.01	--	--	.07	.04	.02	.01	1.17	.74	.35	.16
2,000	9	.03	.02	.01	--	.20	.12	.06	.03	3.42	2.18	1.02	.48
	12	.02	.01	.01	--	.13	.08	.04	.02	2.33	1.48	.70	.33
5,000	9	.07	.05	.02	.01	.49	.31	.15	.07	8.55	5.44	2.56	1.20
	12	.05	.03	.01	.01	.33	.21	.10	.05	5.83	3.71	1.74	.82
10,000	9	.15	.09	.04	.02	.98	.62	.29	.14	17.10	10.88	5.11	2.41
	12	.10	.06	.03	.01	.67	.42	.20	.09	11.66	7.41	3.49	1.64

[1]Note: These values are for rolling and mountainous areas only.

1 ft = 0.3048 m
1 mi = 1.61 km

Table 50. Number of fence accidents per mi per year predicted from model (24).[1]

ADT	Lane Width (ft)	N = 20% Coverage of Fences				N = 40% Coverage of Fences			
		Fence Distance from the Road (ft)				Fence Distance from the Road (ft)			
		2	5	10	20	2	5	10	20
2,000	9	.021	.017	.012	.006	.034	.027	.019	.009
	12	.014	.012	.008	.004	.023	.019	.013	.006
5,000	9	.053	.042	.029	.014	.068	.054	.038	.018
	12	.036	.029	.020	.010	.046	.037	.026	.012
10,000	9	.105	.085	.059	.029	.169	.136	.095	.046
	12	.072	.058	.040	.019	.115	.093	.064	.031

[1]Note: These values are for rolling and mountainous terrain only.

1 ft = 0.3048 m
1 mi = 1.61 km

experience may occur. Thus, when considering obstacle accidents on a given curve (or series of curves), the best measure of obstacle accidents would be the actual accidents on that curve in recent years. The expected effect of obstacle improvements may then be estimated from the model or from other research sources. Accident benefits may be computed and used along with costs for roadside improvements, which will compete for funding along with curve flattening, curve widening, and other curve or roadway improvements. The expected accident reductions due to various obstacle improvements may be estimated as discussed below.

Utility Pole Improvements

Improvements which may be considered for reducing the number of utility pole crashes include relocating the poles farther from the roadway, increasing pole spacing, removing the poles and undergrounding the utility lines, and multiple pole use (i.e., removing poles on one side of the road and using poles on the other side of the road to carry multiple electric and/or utility lines). On rural roads with relatively low traffic volumes, undergrounding of utility lines is often not practical, however. For reducing crash severity, breakaway utility poles are currently being tested for future use on a more widespread basis.

The accident prediction models were used to produce accident reduction factors for relocating utility poles, as well as for clearing or relocating other roadside obstacles, as shown in table 51 and illustrated in figure 18. These were computed by plugging values into the model for various obstacle distances and then calculating the percent change in accidents due to higher distances from the road. Note that the percent accident reduction is given for various amounts of relocation from 3 to 15 ft (0.9 to 4.6 m) and is independent of ADT and the number of obstacles per mi. For example, relocating utility poles 3 ft (.9 m) further from the road (e.g., from 5 to 8 ft (1.5 to 2.4 m), or from 15 to 18 ft (4.6 to 5.5 m)) will be expected to reduce utility pole accidents by 35.3 percent. Increasing pole distance by 10 and 15 ft (3.0 and 4.6 m) give an expected accident reduction of 76.5 percent and 88.6 percent, respectively.

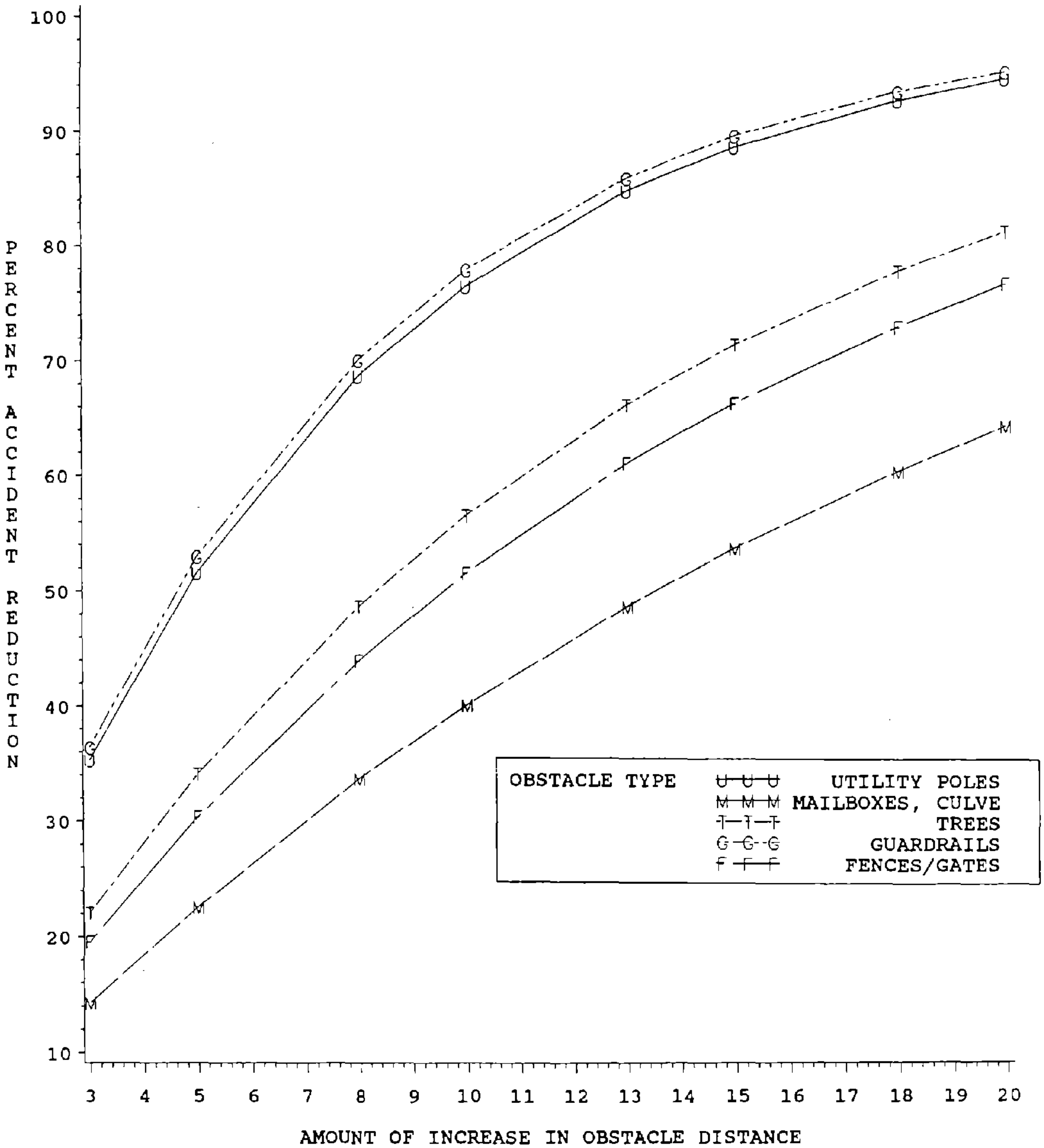

Figure 18. Accident reduction factors for increasing obstacle offsets.

Table 51. Percent reductions in specific types of obstacle accidents due to clearing or relocating obstacles further from the roadway.

Amount of Increase in Obstacle Distance from Roadway (feet)	Utility Poles	Obstacle Type			
		Mailboxes, Culverts, and Signs	Trees	Guardrails	Fences/ Gates
3	35.3	14.3	22.1	36.4	19.6
5	51.6	22.6	34.1	53.0	30.4
8	68.7	33.7	48.7	70.1	44.0
10	76.5	40.1	56.6	77.9	51.6
13	84.8	N.F.	66.2	N.F.	N.F.
15	88.6	N.F.	71.4	N.F.	N.F.

1 ft = 0.3048 m
*N.F. = Generally not feasible to relocate obstacles to specified distances.

Such reductions in utility pole accidents were compared with corresponding reductions from a 1983 FHWA study.(16) That study analyzed traffic, accident, roadway, and utility pole data for over 2,500 mi (4,025 km) of roads in four States, and a corresponding Utility Pole Users Guide and computer program were developed for computing benefits and costs for various types of utility pole improvements on specific roadway situations.(30) Accident reductions were determined for utility pole relocation, as well as other utility-pole improvements. Accident reductions from that study are given for various pole placements before and after relocation for ADT of 1,000, pole densities of 20, 40, and 75 poles per mi (1.61 km). Comparisons can be made between accident reductions in that study and the current study (for ADT = 1000 and 40 poles/mi (1.61 km) as shown in table 52.

The accident reductions between the current model and the 1983 FHWA study are reasonably similar for small pole offsets (e.g., 2 ft (.6 m) from the road) in the before period. As the initial offset increases, the current study estimates for accident reduction remained constant, whereas the estimates vary considerably in the 1983 FHWA study. These trends are due to the different forms of the models. Concerning utility pole improvements, the 1983 FHWA study

Table 52. Comparison of accident reductions due to utility pole relocation for current study and 1983 FHWA study.(16)

Increase in Offset (feet)	Pole Offset		Percent Reduction in Accidents	
	Before	After	Current Study	1983 FHWA Study
3	3 5 9	6 8 12	35.3	36 26 18
5	3 5 7 15	8 10 12 20	51.6	47 37 30 18
10	2 5 10 15	12 15 20 25	76.5	69 52 38 31
15	2 5 10	17 20 25	88.6	75 61 48

should be used, since it allows for considering many roadway factors and a variety of utility pole improvements. Also, a user's guide and computer program are available for computing accident benefits and project costs for a wide range of roadway conditions.

Mailboxes, Culverts and Signs

Due to the forms of the models and the resulting coefficients in the models, the accident reduction factors were determined to be similar for the equivalent amount of increases in offset for mailboxes, culverts, and signs, as described earlier. However, one must understand the practicality of relocating such obstacles before applying the models to the proposed improvements. For example, in rural areas mailboxes are typically located just off the shoulder next to a driveway entrance so they can be reached easily from a mail delivery vehicle.

Although relocating the mailboxes further from the road would be expected to reduce the frequency of mailbox accidents, such relocation is simply not practical in many situations. A more promising alternative which would affect crash severity but not crash occurrences would be to make use of mailboxes with light posts or breakaway design in place of the heavy steel or wooden posts (or multiple posts). Recent research has documented the injury reduction from breakaway mailbox posts.[31]

Placement of signs is largely a function of their readability to drivers, so in some respects should not be placed too far from the road. Even though sign posts present a roadside obstacle, sign placement must be within the driver's cone of vision to be useful. Again, the use of breakaway sign posts is highly desirable, where practical, to minimize the severity of impacts between motor vehicles and the posts.

Culvert headwalls can result in serious injury or death when struck at moderate or high speeds on rural roadways. While relocating such culverts may be feasible under certain conditions, the ideal solution would be to reconstruct the drainage facilities so that they are flush with the roadside terrain and present no obstacle to motor vehicles. Such designs essentially would eliminate culvert accidents, although run-off-road vehicles could still strike other obstacles (e.g., trees) beyond the culverts or rollover on a steep sideslope (see discussion of sideslope in a later section).

<u>Trees</u>

On rural two-lane roads, trees are often the fixed object struck in run-off-road accidents. While highway designers and safety engineers have often considered tree removal as a countermeasure to reduce tree accidents, they often had little, if any, basis for estimating the effect of such tree removal projects on accidents.

As shown earlier in table 51, tree accidents would be reduced by an estimated 22.1 percent for every 3 ft (.9 m) of additional distance that trees are removed from the roadside. For clearing trees by 10 ft (3.0 m) (e.g., cutting back trees from an 8 ft (2.4 m) distance from the road to 18 ft (5.5 m)), a 56.6-percent reduction in tree accidents would be expected. A reduction of 71.4 percent in tree accidents would be expected due to cutting back trees by an additional 15 ft (4.6 m) (e.g., from 10 ft (3.0 m) initially back to 25 ft (7.6 m)). These values assume that by clearing trees from the roadside, run-off-road vehicles would have additional recovery area, and, there would not be a steep sideslope or other rigid obstacles within that roadside area for vehicles to strike. Since tree accidents are quite prevalent on rural, two-lane roads, and particularly on curved road sections, clearing of trees is often an effective countermeasure to reduce roadside accidents.

Guardrail

Guardrail is installed along roadways to shield a vehicle from striking a more rigid obstacle or from rolling down a steep embankment. When installed, guardrail is generally placed directly beyond the roadway or outside shoulder and positioned at the greatest practical distance from the roadway to reduce the incidence of guardrail impacts. Thus, it is often not feasible to relocate guardrail further from the roadway along a section, unless some flattening of the roadside occurs. However, when it is feasible to flatten roadsides to a relatively mild slope (e.g., 4:1 or flatter) with appropriate removal of obstacles, then guardrail may no longer be needed since the guardrail presents an obstacle which vehicles can strike. The accident reductions in table 51 for guardrail placement illustrate the crash benefits from relocating guardrail.

Fences/Gates

Fences and gates are sometimes placed by private property owners just beyond the highway right-of-way, which can present a hazard to run-off-road vehicles. The effect of relocating fences according to the accident model is a 19.6 percent accident reduction for 3 ft (.9 m) of relocation, 44.0 percent for 8 ft (2.4 m) of relocation, and 51.6 percent for 10 ft (3.0 m) of relocation. Unfortunately, having fences relocated further from the roadway could require a highway agency to purchase more right-of-way along a route, which could be quite expensive.

Roadside Slope

For the current curve study, no specific analysis was conducted on the cross-section data base which dealt with roadside slope. That is because the FHWA cross-section study did quantify the effect of roadside slope on single-vehicle accidents using that same data base.(3) Field-measured sideslope data were collected for 1,776 mi (2,859 km) of two-lane roadways in three States

(Alabama, Michigan, and Washington), and corresponding accident, traffic, and roadway data, accident relationships were determined for sideslopes.

Based on the predicted accident relationship with sideslope, a table was produced of the reductions in single-vehicle accidents most likely to occur due to sideslope flattening. As shown in table 53, flattening an existing 2:1 sideslope to 6:1 should reduce single vehicle crashes by 21 percent, whereas flattening it to 3:1 would reduce accidents by only 2 percent. Flattening a 3:1 sideslope to 7:1 or flatter should result in a 26-percent reduction in single-vehicle accidents.

Estimates of accident reductions are also given for <u>total</u> accidents, as derived from information in reference 3. For example, single-vehicle accidents represent 57 percent of total accidents on horizontal curves on two-lane rural roads (based on the Washington curves data base). Further, sideslope improvements are expected to primarily affect single vehicle (i.e., fixed object and rollover) accidents. Thus, a sideslope flattening project which reduces single vehicle accidents by X percent, should reduce total accidents by .57 X percent. For example, flattening a 3:1 sideslope to 5:1 would be expected to result in a 14 percent reduction in single vehicle accidents, or a reduction of (14) x (.57) = 8 percent in total accidents for an average distribution of curve accidents.

The accident reductions for sideslope flattening and for other roadside improvements in this chapter were based on the cross-section data base, which consists of sections of rural, two-lane roads on a variety of terrain (flat, rolling, and mountainous) in seven States. The predictive models and accident reductions developed from this data base pertain to tangent sections as well as curved roadway sections. Thus, if one assumes that sideslope flattening and other roadside improvements would be more effective on curve sections than on combined tangent/curve sections, then the accident reductions in this chapter may be somewhat conservative. It should be mentioned, however, that for the roadside obstacle models given earlier, a factor was included to account for whether a section was in rolling or mountainous areas, and thus, to hopefully make the results as appropriate as possible for applying to roadway improvements on horizontal curves.

Table 53. Effects of sideslope flattening on single-vehicle and total accidents.[1]

Sideslope in Before Condition	Sideslope in After Condition							
	4:1		5:1		6:1		7:1 or Flatter	
	SV Accs.	Total Accs.	SV Accs.	Total Accs.	SV Accs.	Total Accs.	SV Accs.	Total Accs.
2:1	10	6	15	9	21	12	27	15
3:1	8	5	14	8	19	11	26	15
4:1	0	-	6	3	12	7	19	11
5:1	-	-	0	-	6	3	14	8
6:1	-	-	-	-	0	-	8	5

[1]Note: The percent reductions in single-vehicle accidents were taken directly from reference 3. Percent reductions in total accidents were derived based on information from that report.

CHAPTER 10 - ANALYSIS OF VEHICLE OPERATIONS ON CURVES

The four previous chapters have all involved analyses of accident data related to horizontal curves (and/or curve sections) on rural, two-lane roads. Such analyses were conducted primarily to quantify the effects on accidents of various geometric and roadway improvements on curves, such as curve flattening, curve widening, adding spiral transition curves, improving superelevation, and various types of roadside improvements. The purpose of this chapter is to better quantify the effects of curve geometrics on vehicle operations.

One of the primary objectives of this overall study was to "determine horizontal design criteria appropriate for traffic operations anticipated on various highway sections, as affected by speed" and other operational variables of interest. There was interest in determining certain curve design criteria which would lead to effective improvement of safety and overall traffic operations at current curve sites. More specifically, this study effort focused upon certain operational variables such as speed reduction and encroachment characteristics and their relationship to varying classifications of curve design.

The data analyzed in this chapter originated from the FHWA New York Surrogate study and included both operational and nonoperational roadside and curve characteristics. This database was developed for the FHWA in 1985 and consists of accidents, geometrics, vehicle operations and roadway features for 78 curve sites in New York State.[4] The operational variables considered in this particular analysis included speed reduction which was calculated from speed measured 250 ft (76 m) prior to the midpoint of the curve and then measured at the curve midpoint. The desired measure of speed reduction was the difference between the two measurements. Other operational variables were centerline encroachment and edgeline encroachment rates (i.e., encroachments per hour per ADT). As encroachments obviously occur from either the inside lane or the outside lane of a curve, the encroachment data were categorized according to each of these lane characteristics.

Referred to in this text as nonoperational variables, certain geometric and roadway features which were analyzed included degree of curvature, length of curve, superelevation error, vertical alignment (grade), and roadside hazard rating. To address the issue concerning effects of nonoperational data on vehicle operations, descriptive statistical analyses as well as model-based statistical analyses were utilized. More specifically, the analysis involved the following steps.

Descriptive analyses were conducted for the New York State surrogate database, which included frequency listings for operational and nonoperational variables of interest, as well as Pearson X^2 measures of association. The frequency listings proved to be useful in determining the formation of category levels for certain variables later chosen to be categorized. Pearson X^2 measures of association were calculated between each operational variable and each nonoperational variable, and the significance of each association was determined (see table 54).

Table 54. Measures of association between operational and non-operational variables.

Roadway Feature	Speed Reduction	Centerline Encroachment		Edgeline Encroachment	
		Inside	Outside	Inside	Outside
Degree of Curve	3.6* 0.028+	2.1 0.331	6.1 0.002	2.4 0.095	0.7 0.498
Curve Length	0.3 0.718	0.5 0.611	4.5 0.011	1.5 0.224	0.6 0.545
Superelevation Error	2.7 0.068	1.1 0.338	0.5 0.631	6.2 0.042	0.5 0.583
Shoulder Width	1.8 0.160	0.7 0.493	0.7 0.498	0.7 0.518	0.6 0.549
Grade	1.1 0.297	10.8 0.001	6.3 0.013	1.7 0.062	0.0 0.921
Roadside Hazard: Outside	1.1 0.320	1.2 0.301	0.7 0.515	0.3 0.726	0.1 0.883
Roadside Hazard: Inside	2.3 0.102	2.4 0.097	0.3 0.740	0.5 0.582	0.3 0.740

*X^2/df +p-value

To summarize these results using $\alpha = 0.05$, average speed reduction was found to be significantly associated with degree of curvature. Centerline encroachments on the inside lane were significantly associated with grade. Centerline encroachments on the outside lane were significantly associated with degree of curvature, curve length, and grade. Edgeline encroachments on the inside lane were significantly associated with superelevation error and 'nearly' significantly associated with degree of curve (p-value of 0.095) and grade (p-value of 0.062). Edgeline encroachments on the outside lane had no significant association with any of the nonoperational variables but was nevertheless examined in further model-based analyses.

These measures of association, which are essentially correlation statistics, are useful indicators in determining which nonoperational variables (e.g., degree of curve) might best account for the amount of variation in the operational variable values (e.g., speed reduction). The modeling of this variation in these operational variables was a primary goal of this investigation. Therefore, univariable regression analyses were conducted using the information obtained from the Pearson X^2 analyses.

First, plots of actual values were constructed of each operational variable (vertical axis) versus each promising nonoperational variable (horizontal axis). Five of these plots using degree of curve as the non-operational variable are shown in figures 19 through 23. As is evident from these plots as well as for all other plots examined, there is a considerable amount of dispersion in the data. This problem will be addressed later, but first univariable modeling results are discussed.

Several univariable models were considered. However, out of all models analyzed only two of these models are noteworthy. Based on R^2 values and significance of parameter estimates (using SAS PROC GLM), these two models were centerline encroachments from the outside lane versus degree of curve and average speed reduction versus degree of curve. These results are listed in table 55. The estimates are for degree of curve effects on the operational variables listed at the left margin. The p-values are associated with the hypothesis that the estimate is essentially zero (i.e., no effect).

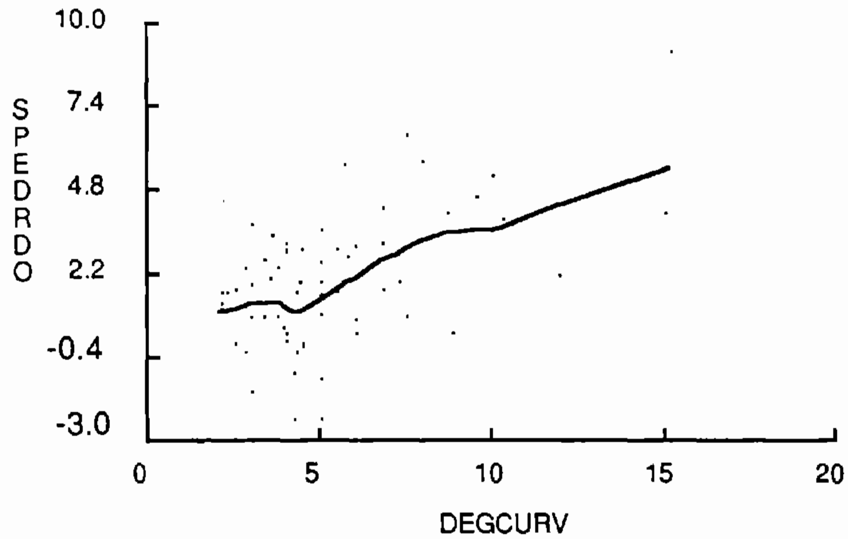

Figure 19. Speed reduction vs. degree of curve.

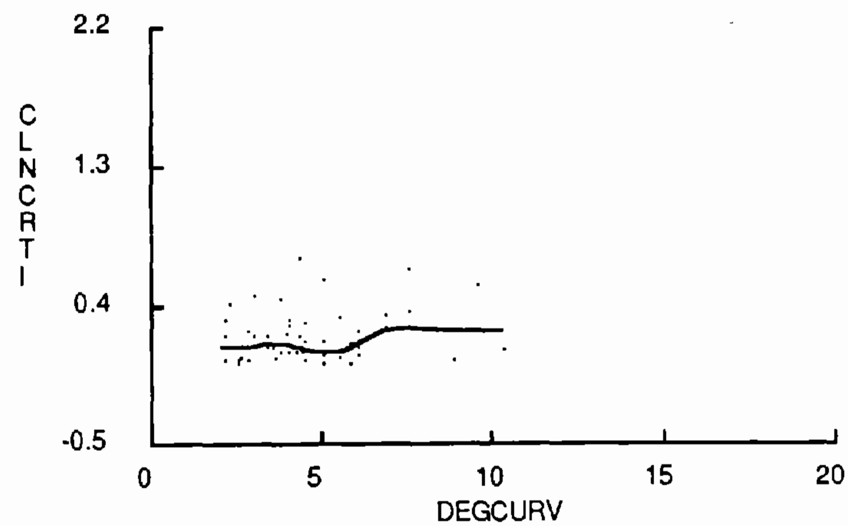

Figure 20. Centerline encroachment rates from inside vs. degree of curve.

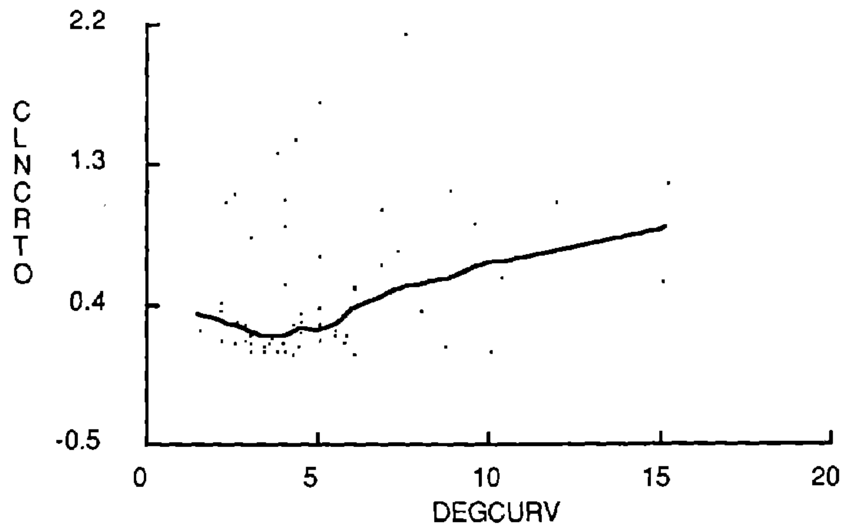

Figure 21. Centerline encroachment rates from outside vs. degree of curve.

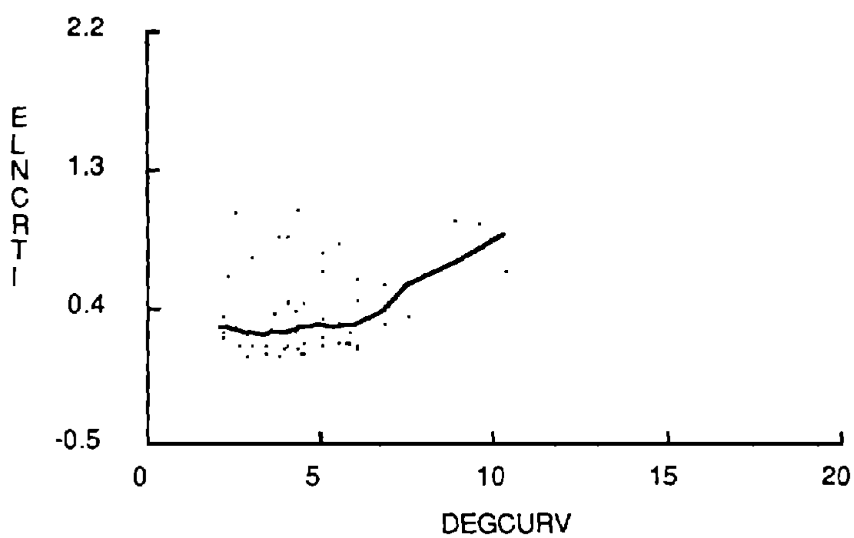

Figure 22. Edgeline encroachment rates from inside vs. degree of curve.

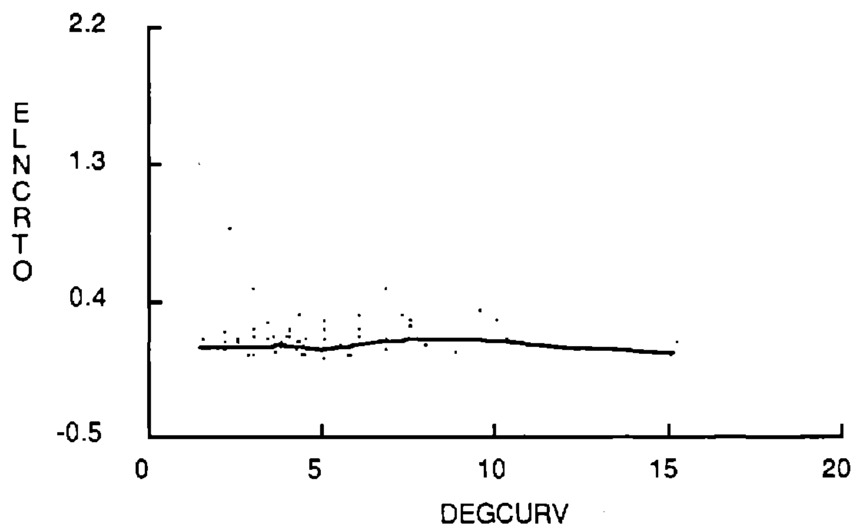

Figure 23. Edgeline encroachment rates from outside vs. degree of curve.

Table 55. Summary of results for univariable models of degree of curve effects on operational variables.

	Degree of Curve			
	Estimate	Std. Error	p-value	R^2
Centerline Encroachment: Outside Lane	6.01	0.58	<<0.01	0.37
Average Speed Reduction	0.40	0.08	<<0.01	0.30

It was hypothesized that a more definitive relationship could be determined between the operational variables and variables such as degree of curve if the curves were dichotomized into seemingly mild conditions vs. seemingly hazardous conditions. Thus, the data were categorized into two groups of curves based on certain ranges of the following three nonoperational variables:

- Superelevation deviation (termed superelevation error in the FHWA report.[4])
- Grade.
- Roadside Hazard Rating.

The two groups created from these three variables were classified as being 'favorable' or 'unfavorable.' The 'unfavorable' group consisted of curves meeting one or more of the following three criteria:

- Superelevation error greater than 0.05.
- Grade rating of 3 (i.e., very steep).
- Roadside hazard (outside or inside) rating of 6 (i.e., most hazardous).

Upon classification of all curves into one of the two groups, plots were again constructed within each group in the manner described earlier using degree of curve as the main nonoperational variable of interest (see figures 24 through 28 and figures 29 through 33 for 'favorable' and 'unfavorable' curve groups, respectively). Again, the data were extremely dispersed.

Residual analyses were conducted for the univariable models formulated in both the favorable and the unfavorable curve groups. These analyses attempted to determine whether certain regression assumptions were invalidated. Plots of

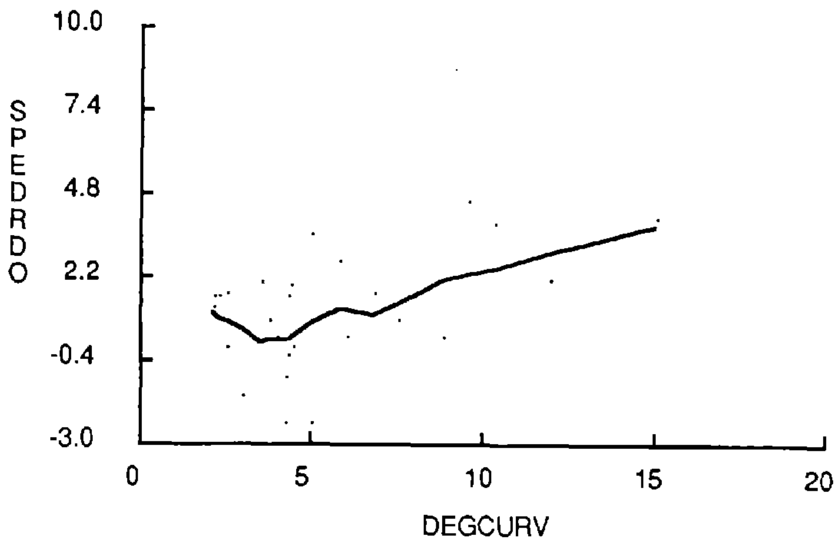

Figure 24. Speed reduction vs. degree of curve: "Favorable" curve group.

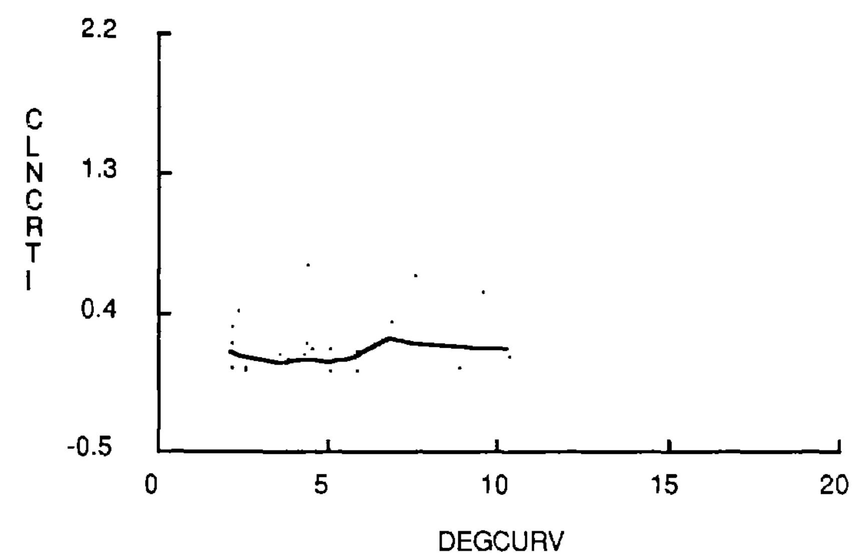

Figure 25. Centerline encroachment rates from inside vs. degree of curve: "Favorable" curve group.

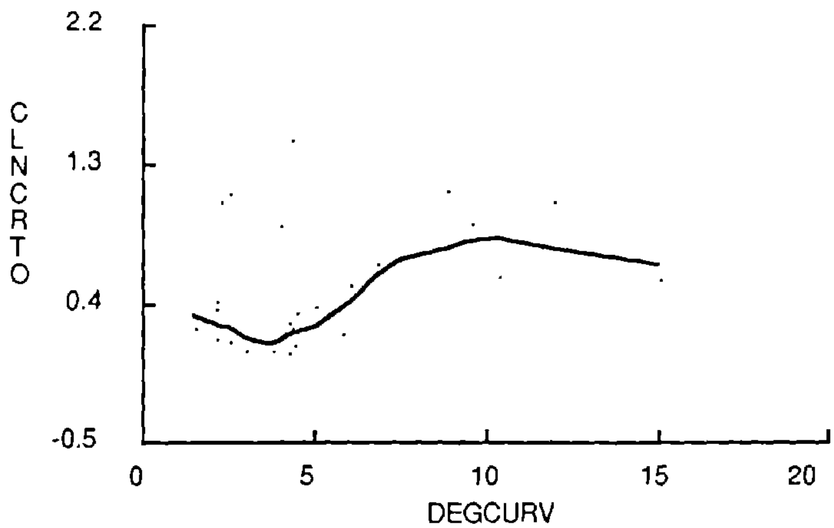

Figure 26. Centerline encroachment rates from outside vs. degree of curve: "Favorable" curve group.

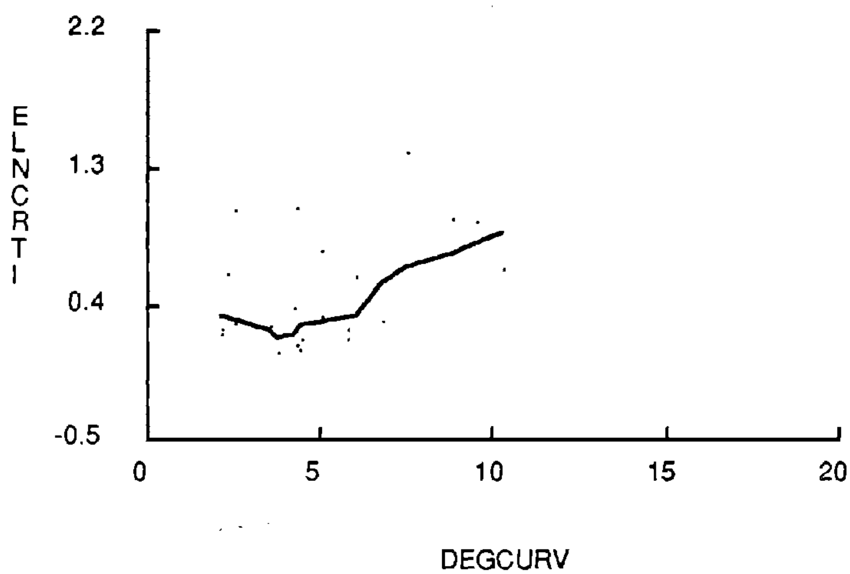

Figure 27. Edgeline encroachment rates from inside vs. degree of curve: "Favorable" curve group.

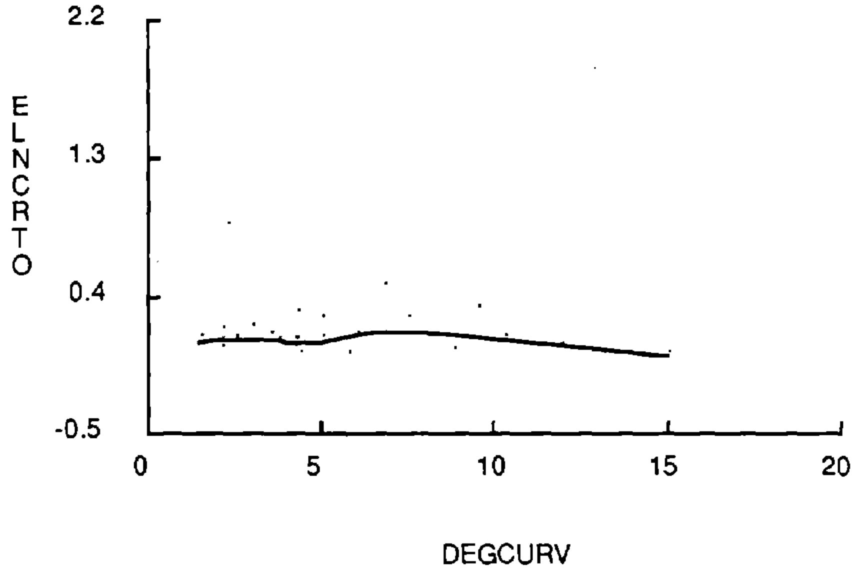

Figure 28. Edgeline encroachment rates from outside vs. degree of curve: "Favorable" curve group.

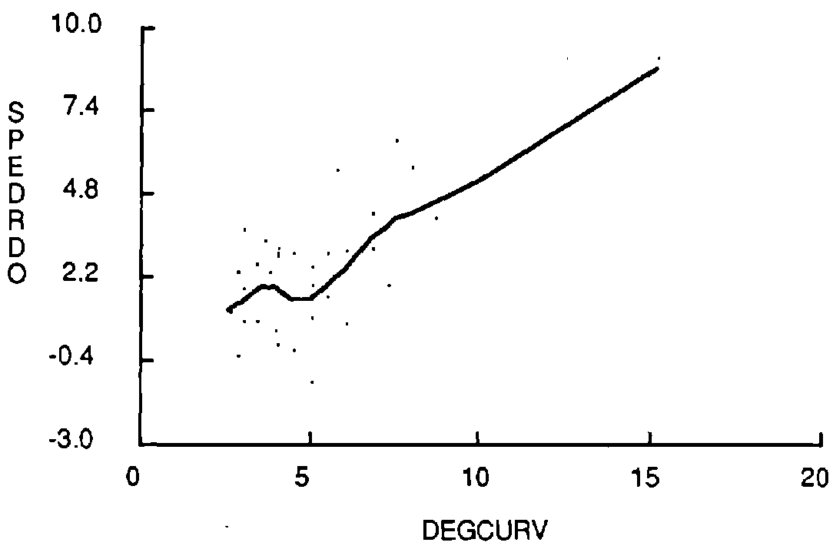

Figure 29. Speed reduction vs. degree of curve: "Unfavorable" curve group.

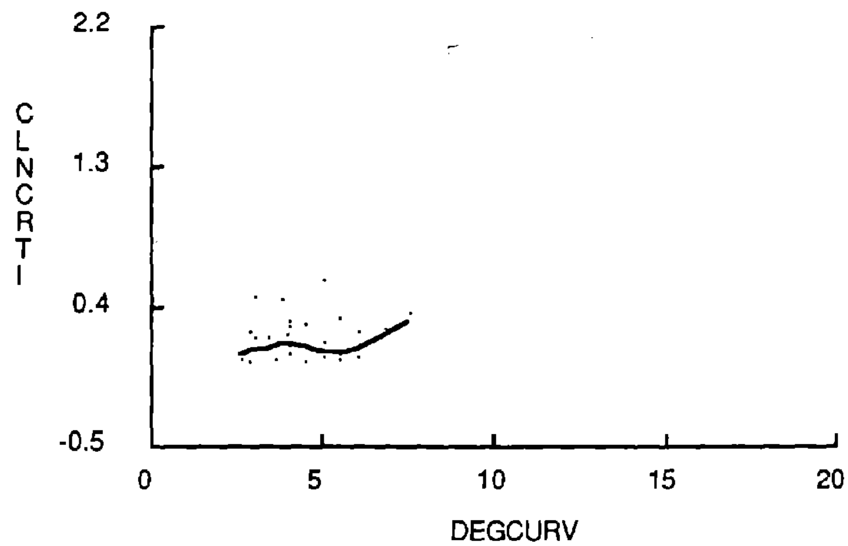

Figure 30. Centerline encroachment rates from inside vs. degree of curve: "Unfavorable" curve group.

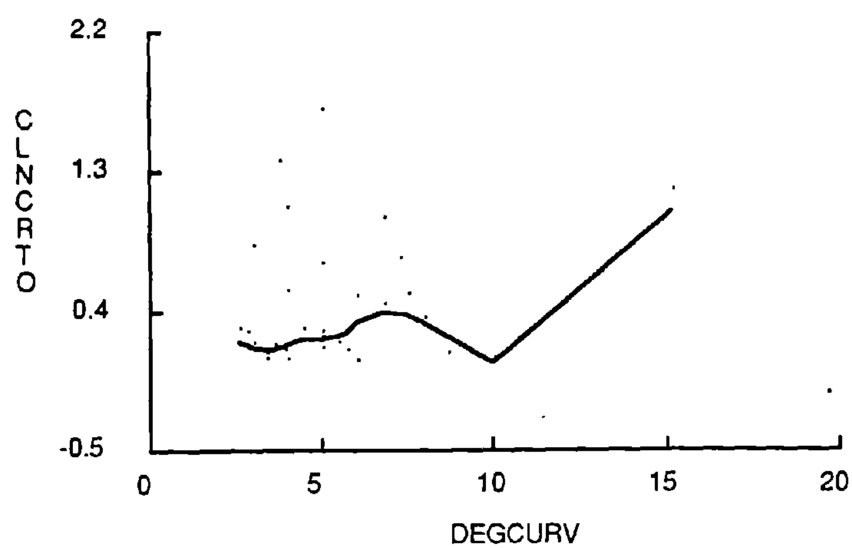

Figure 31. Centerline encroachment rates from outside vs. degree of curve: "Unfavorable" curve group.

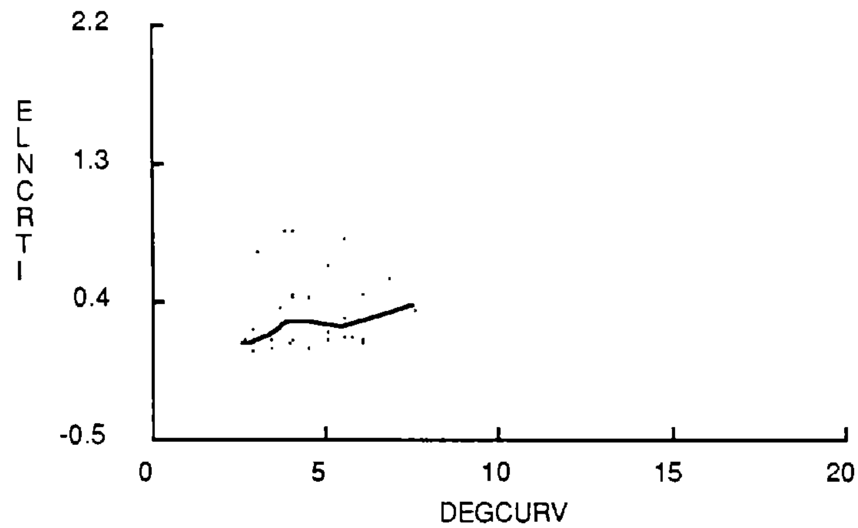

Figure 32. Edgeline encroachment rates from inside vs. degree of curve: "Unfavorable" curve group.

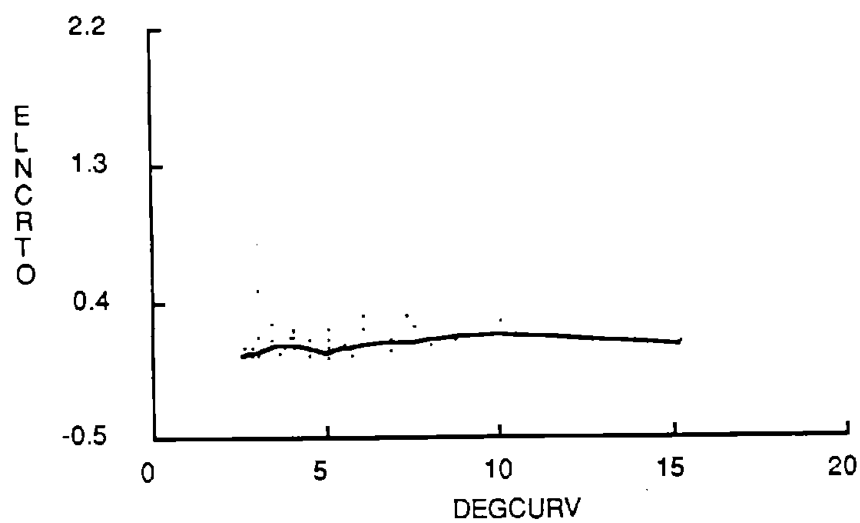

Figure 33. Edgeline encroachment rates from outside vs. degree of curve: "Unfavorable" curve group.

the residuals versus the observed values for all curves combined suggested that there is a violation of one of the regression assumptions due to the fact that the error variable increases with increasing values of degree of curve. This is indicated by the shape of the residual plot in figure 34 (see reference 31, chapter 16). This, in turn, suggested the use of a variance stabilizing transform; however, these transforms failed to improve on the univariable models previously constructed.

Upon completion of the residual analyses for the aforementioned models, it was decided to compare operational variable means within each of the two curve classifications to determine whether significant differences existed between them. Using the SAS PROC T-test, it was determined that there was a significant difference in speed reduction values between the two groups and a nearly significant difference between the two groups with respect to edgeline encroachment rates from the inside lane. The following hypothesis was tested:

> H_o: No difference between the two curve groups with respect to the operational variable of interest

This testing resulted in the following p-values for various operational measures:

Operational Variable	P-Value for Test of H_o
Average speed reduction	$\ll 0.01$
Edgeline encroachment from inside lane	0.10
Edgeline encroachment from outside lane	0.34
Centerline encroachment from inside lane	0.97
Centerline encroachment from outside lane	0.24

Due to problems presented by the extreme amount of dispersion in the data, locally weighted regression techniques were employed. This method of regression is a nonparametric approach and thus does not assume constant error

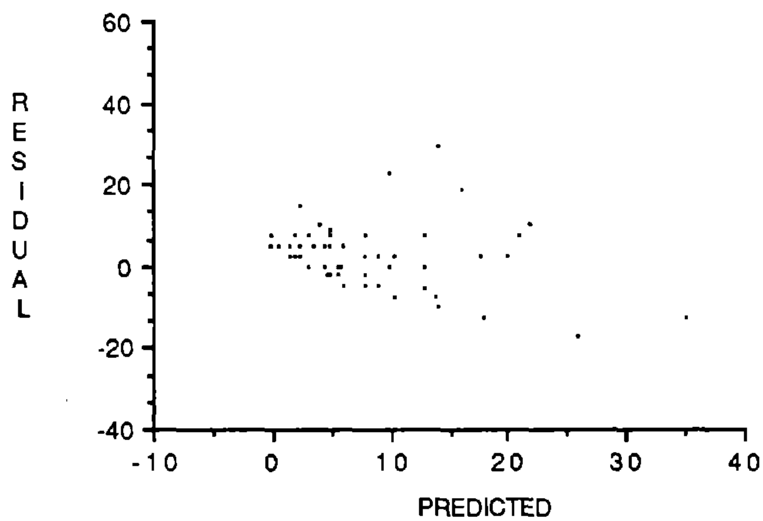

Figure 34. Predicted speed reduction vs. residual.

variance of the dependent variable as does the method of least squares regression explored earlier.

The locally weighted regression technique (LOWESS) fits a line within certain groups of points and then joins the lines for each group to form a curve. This technique gives only the shape of the curve. It does not give parameter estimates. LOWESS plots of the five operational variables versus degree of curve for the favorable and unfavorable groups of curves can be seen in figures 24 through 28 and figures 29 through 33, respectively. Plots for the ungrouped curves (i.e., combining favorable and unfavorable geometric combinations) are depicted in figures 19 through 23.

In view of the LOWESS plots, an unclear relationship exists between the values of the five operational variables and degree of curve values below five degrees. However, a number of the graphs depict a linear relationship when considering curves of five degrees and higher, particularly speed reduction and edgeline encroachment rates for inside lanes.

Keeping in mind that the amount of dispersion in the data presented problems when considering regression models, further examination using descriptive analyses was warranted. After the values of the four encroachment operational variables were normalized by traffic volume (number of vehicles per hour passing through the curve in either the inside or outside lane yielding encroachment rates), they along with speed reduction were dichotomized across each variable. The lower values (values below and including the median value of each variable) comprised one group while the other group contained the higher values (values above the median). Each of the two categories for each variable appears in the column headings in table 56 which also provides means and standard errors for each of the seven nonoperational variables for each of the operational variables. This breakdown allowed for visual comparison of the means of the nonoperational variables between high and low categories for each operational variable.

As is evident from table 56, the degree of curve mean (i.e., 6.42) in the high speed reduction category (at least 1.7 mi/h (2.7 km/h)) is markedly different and higher than the degree of curve mean (i.e., 4.22) in the low

Table 56. Means and standard errors of nonoperational variables dichotomized by operational variables.

Roadway Feature	Average Speed Reduction: Outside of Curve (mi/h)		Centerline Encroachment Rates (No/Hr/ADT)				Edgeline Encroachment Rates (No/Hr/ADT)			
			Inside		Outside		Inside		Outside	
	<1.7 (31)*	1.7+ (31)	<0.13 (27)	0.13+ (26)	<0.24 (31)	0.24+ (31)	<0.24 (32)	0.24+ (27)	<0.11 (37)	0.11+ (26)
Degree of Curve	4.22** 0.29+	6.42 0.60	4.69 0.35	4.68 0.36	4.35 0.32	6.13 0.60	4.09 0.23	5.29 0.42	5.38 0.52	5.09 0.45
Curve Length	764.7 63.52	714.9 52.28	788.1 57.86	758.5 69.76	875.0 56.67	639.0 58.38	844.4 59.99	700.0 64.72	719.0 46.15	806.5 81.24
Superelevation Error	0.04 0.004	0.05 0.003	0.04▾ 0.004	0.04▾ 0.004	0.04 0.004	0.04 0.003	0.05▾ 0.004	0.04▾ 0.003	0.04 0.003	0.04 0.004
Shoulder Width	7.74 0.29	8.48 0.31	8.56 0.25	7.85 0.36	8.39 0.23	7.88 0.36	8.41 0.29	8.00 0.34	8.11 0.24	8.15 0.39
Grade	1.39 0.11	1.65 0.14	1.26 0.11	1.62 0.15	1.35 0.12	1.66 0.13	1.19 0.11	1.69 0.14	1.38 0.11	1.69 0.15
Roadside Hazard Outside	3.81 0.29	3.45 0.33	3.26 0.34	3.80▾ 0.36	3.52 0.35	3.66 0.27	3.26 0.33	3.80 0.37	3.84 0.30	3.23 0.31
Roadside Hazard Inside	3.48 0.28	3.65 0.36	3.07 0.33	3.65 0.36	3.71 0.32	3.41 0.32	3.37 0.35	3.35 0.35	3.68 0.31	3.38 0.32

*number of curves in operational variable group

**mean +standard error ▾data not available for several sites

Note: 1 mi/h = 1.61 km/h

speed reduction category (less than 1.7 m/h (2.7 km/h)). A similar relationship appears when comparing the means of degree of curve among the high and low categories of centerline encroachments on the outside lane and the high and low categories of edgeline encroachments on the inside lane.

In conclusion, several relationships bear mentioning. Average speed reduction and edgeline encroachments from the inside lane are clearly linearly related to degree of curve for curves above five degrees. As curves become sharper, there is a proportionally greater increase in speed reduction and edgeline encroachments on the inside lane. Centerline encroachments on the outside lane also increase more drastically than centerline encroachments on the inside lane.

These results on operational measures may be compared to the results of the accident analyses presented earlier. For example, degree of curve is clearly the geometric feature which most affects accidents and vehicle operations on horizontal curves, where sharper curves result in significantly increased rates of accidents, as well as high rates of speed reductions and vehicle encroachments. The greater incidence of speed reduction and edgeline encroachments on the inside line combined with increased centerline encroachments on the outside lane supports the contention of driver overshoot; that is, drivers oversteering as they enter a curve. This can result in run-off-road crashes on the inside of the curve and/or head-on and opposite direction sideswipe accidents with oncoming motorists.

Thus, the results of the operational analysis support and help to explain the predominance of single vehicle crashes (i.e., fixed-object and rollover) and opposing multi-vehicle crashes (i.e., head-on and opposite direction sideswipe) found in chapter 5 to be overrepresented on curves when compared to tangents. Finally, chapter 11 provides an economic analyses of various curve improvements, which considers accident and operational benefits along with project costs.

CHAPTER 11 - ECONOMIC ANALYSIS OF CURVE IMPROVEMENTS

The previous chapters of this report documented all data collection and analysis activities needed to determine the effects of various traffic and roadway features on curve crashes and vehicle operations on curves. These analyses resulted in estimates of expected accident reductions from various curve-related improvements. The purpose of the economic analysis in this chapter is to compute the benefits and costs associated with such curve improvements and to determine the traffic and geometric conditions for which various curve improvements are economically warranted.

The economic analyses stress two categories of costs and two categories of benefits. The costs included are construction costs and travel time costs associated with construction-related delay. The benefits included are crash reductions and travel time savings resulting from higher speed travel on flattened curves. A minor impact ignored in the analysis is the gain in pavement serviceability when curve flattening replaces a small section of existing pavement. This is a benefit to drivers, but it is unlikely to affect the resurfacing cycle for the roadway section. Also, although resurfacing costs would be higher if the curve is widened (i.e., more pavement to be resurfaced), we assume that these future costs are offset by the crash reduction benefits during the life of the resurfaced pavement. When volume drops on a section, this assumption is too generous; flattening will be slightly less cost effective than suggested here.

Assumptions and Constants Used in Benefit-Cost Computations

The cost and benefit computations require externally supplied values for six parameters, namely the discount rate, the traffic growth rate, the useful life of design improvements, crash costs, the value of travel time, and the costs of delaying traffic. Table 57 summarizes the values used and their sources.

The discount rate assumed is 5 percent, the rate recommended in reference 32 for evaluation of highway improvements with a useful life of at least 5 years.[32] The traffic growth rate used is 1.5 percent per year, which is the

Table 57. Values for constants in the economic analysis.

Constant	Value	Source
Discount rate	5%	Reference 32
Traffic growth rate	1.5%	Reference 33
Useful project life	20 years	Reference 10
Cost per crash	$59,000	Reference 36
Value of travel time	$11.85	Reference 35
Value of delay time	$15.45	Reference 35

average from 1982 through 1986 for all rural secondary roads in the U.S. A useful project life of 20 years is often utilized in evaluating design improvements, under the assumption that any benefit beyond that time period is offset by future maintenance costs. This choice is consistent with the project life used in TRB Special Report 214.(10)

Using the project's useful life, the discount rate, and the traffic growth rate, lifetime conversion factors were developed that can be multiplied times daily or annual project benefits to compute the present value of total benefits over the life of the project. The conversion factors are lifetime project benefits = 5,300 x benefits per day = 14.52 x annual benefits. Table 58 shows the proportional difference in lifetime conversion factors for various discount

Table 58. Rate adjusters for estimating lifetime benefits at discount rates and traffic growth rates different from the 5 percent discount rate and 1.5 percent traffic growth rate assumed herein.

Traffic Growth	Discount Rate (Percent)						
	2	3	4	5	6	8	10
-3.0%	0.868	0.802	0.743	0.691	0.644	0.566	0.503
-2.0%	0.948	0.872	0.806	0.747	0.695	0.607	0.537
-1.0%	1.037	0.951	0.876	0.809	0.751	0.652	0.574
-0.5%	1.086	0.994	0.914	0.844	0.781	0.677	0.594
0.0%	1.137	1.040	0.954	0.879	0.813	0.703	0.615
0.5%	1.192	1.088	0.997	0.917	0.847	0.730	0.637
1.0%	1.250	1.139	1.042	0.957	0.883	0.758	0.660
1.5%	1.312	1.193	1.090	1.000	0.921	0.789	0.685
2.0%	1.377	1.251	1.141	1.045	0.961	0.820	0.710
3.0%	1.521	1.377	1.252	1.143	1.048	0.890	0.766
4.0%	1.683	1.519	1.377	1.253	1.145	0.967	0.828
5.0%	1.866	1.679	1.518	1.377	1.254	1.053	0.896
6.0%	2.073	1.860	1.676	1.516	1.377	1.149	0.973

rates and traffic growth rates. Many tables in this chapter can be converted to other discount rates or traffic growth rates by multiplying times the appropriate factor from table 58.

The crash costs used were from a Federal Highway Administration Technical Advisory, (June 30, 1988).(36) The costs were inflated from 1986 dollars to 1988 dollars using the Consumer Price Index for all items. Table 59 lists the crash costs used by crash severity.

Table 59. Costs per crash and percentage distribution of crashes on curved sections of rural, two-lane roads by severity (in 1988 dollars).

Crash Severity	Cost	Percent of Crashes
Fatal	$1,825,000	2.55
Non-fatal A-Injury	50,000	11.00
Nonfatal B-Injury	20,000	20.50
Nonfatal C-Injury	9,000	13.30
Prop. Damage Only	3,000	52.65
Average	$ 59,000	

Multiplying the crash costs times the percentage distribution of crashes by severity on curved sections of rural, two-lane roads in the Washington State data base (shown in the last column of table 59) and summing yields an average cost estimate of $59,000 per crash on a curved section of a rural, two-lane road. Note that the Washington percentages appear to be typical; the percentage of crashes by severity for the Washington State data on all rural, two-lane roads was roughly comparable to the percentage distribution for rural crashes in the National Highway Traffic Safety Administration's National Accident Sampling System data.

The values of travel time savings resulting from faster speeds on flattened curves and of travel time lost to construction delay are based on a recent synthesis of the literature on the value of time. The synthesis was performed as part of the Federal Highway Administration's efforts to develop the Highway Economics Requirements System (HERS) for estimating highway needs.(35)

For the present purpose, the cost values of travel time HERS uses for rural trips by type of vehicle were weighted by the percentage of vehicle mi by vehicle type in 1985 on rural roads other than Interstates and arterials, yielding an average value of $11.85 per vehicle-hour of travel on rural roads.(35,33) Both because people dislike waiting and because delay results in unplanned late arrival, the costs of delay time for non-work travel are higher than the predictable time costs associated with this travel. Delay time costs are valued at $15.45 per vehicle-hour.

Computation of Costs

Construction costs were estimated for curve flattening, lane widening on curves, and shoulder widening on curves. The cost of delay resulting from construction of these improvements also was estimated. Most of the cost estimates were based on TRB Special Report 214; the remainder were developed for this study.(10) In addition to explaining the new cost estimates, this section provides formulas for all costs. Figure 35 defines the symbols used in the formulas in this chapter. The lower case symbols are used in conjunction with the upper case symbols. For example, S_a is the speed (S) on a curve after (a) flattening.

Symbol	Definition
ADT	Average daily traffic volume
ARF	Accident reduction factor (percent)
C	Cost
D	Degree of curvature
I	Central angle of the curve
L	Curve length in mi (1.61 km) = I/(52.8 x D)
S	Speed
a	After flattening
b	Before flattening
l	Lane widening
p	Paved shoulder widening
u	Unpaved shoulder widening

Figure 35. Definitions for symbols used in formulas in this chapter.

Curve flattening costs were computed using the formula given in Appendix I of TRB Special Report 214.[10] Table 60 shows the costs of curve flattening (in 1988 dollars) as a function of the central angle, initial degree of curvature, and final degree of curvature.

Table 60. Cost (C_f) of curve flattening (in 1988 dollars (in thousands)).

Degree of Curve Before	Degree of Curve After	Central Angle 10	20	30	40	50	60	70	80	90
30	25	$42.8	71.0	95.1	116.7	136.7	155.4	173.1	190.0	206.2
30	20	52.1	87.1	117.2	144.4	169.6	193.3	215.8	237.4	258.0
30	15	64.3	108.6	147.1	182.1	214.7	245.5	274.9	303.0	330.1
30	12	73.7	125.6	170.9	212.4	251.3	288.0	323.1	356.9	389.5
30	10	81.4	139.5	190.8	237.8	282.0	323.9	364.0	402.6	440.0
30	8	90.7	156.8	215.5	269.6	320.6	369.2	415.9	460.9	504.5
30	5	110.3	194.1	269.6	340.1	407.0	471.2	533.1	593.2	651.7
25	20	47.3	79.1	106.5	131.2	154.1	175.6	196.0	215.6	234.3
25	15	59.3	100.3	135.8	168.1	198.2	226.7	253.8	279.7	304.8
25	12	68.8	117.2	159.5	198.2	234.5	268.8	301.5	333.0	363.4
25	10	76.5	131.2	179.4	223.6	265.2	304.6	342.3	378.6	413.8
25	8	86.0	148.7	204.3	255.7	304.0	350.1	394.3	437.0	478.4
25	5	106.0	186.6	259.2	327.0	391.4	453.1	512.6	570.4	626.6
20	15	53.8	90.9	123.1	152.5	179.8	205.6	230.1	253.7	276.4
20	12	63.2	107.7	146.6	182.2	215.4	247.0	277.1	306.0	333.9
20	10	71.0	121.7	166.4	207.4	245.9	282.5	317.5	351.2	383.8
20	8	80.6	139.3	191.4	239.6	284.9	328.0	369.5	409.5	448.2
20	5	101.1	177.9	247.1	311.7	373.0	431.8	488.6	543.6	597.2
15	12	56.7	96.5	131.4	163.3	193.2	221.4	248.4	274.4	299.4
15	10	64.4	110.5	151.0	188.3	223.2	256.4	288.2	318.8	348.3
15	8	74.1	128.1	176.0	220.3	261.9	301.6	339.7	376.5	412.2
15	5	95.0	167.2	232.3	293.0	350.6	405.9	459.3	511.0	561.4
10	8	65.8	113.8	156.4	195.7	232.7	268.0	301.9	334.5	366.2
10	5	87.1	153.2	212.9	268.5	321.4	372.0	420.9	468.3	514.5
8	5	83.0	146.1	202.9	255.9	306.3	354.6	401.2	446.4	490.4
8	3	108.0	193.8	272.3	346.5	417.5	486.1	552.8	617.7	681.2
5	3	100.5	180.2	253.3	322.2	388.3	452.1	514.0	574.5	633.5

Formula: $C_f = \$18395\ (I)^{.902}\ (D_a)^x\ (D_a/D_b)^y$

where $x = -.0944 - .405\ (I)^{.1014}$
$y = -.0758\ (D_a)^{.648}$

Source: Updated from TRB Special Report 214, pp. 297-298.

In flattening a curve, a spiral could be added. The additional cost for the spiral in most cases will be small when compared to the total cost of the curve flattening project. In fact, the cost for design and construction of the new curve usually can be assumed to be approximately the same regardless of whether spiral transition curves are added. Although our cost analysis of curve flattening does not incorporate spirals, these improvements generally add effectiveness at minimal costs. Provided costs are minimal, we recommend spirals.

The costs of widening lanes and shoulders vary by type of terrain. In addition, unpaved shoulders cost less than paved shoulders. The costs used in this report are summarized in table 61 drawn from table 5-2 of TRB Special Report 214 and updated to 1988 dollars.(10)

Table 61. Cost per ft (.3048 m) to widen lanes and shoulders, by type of terrain (in 1988 dollars).

Terrain	Lanes	Paved Shoulders	Unpaved Shoulders
Flat	$42,150	$15,700	$ 5,150
Rolling	50,000	23,750	13,250
Mountainous	76,450	50,000	39,450

Source: TRB Special Report 214, p. 140, inflated to 1988 dollars using the GNP State and local government purchases inflator.

Travel delay is associated with both widening and flattening of curves. For rural, two-lane roads, 2 minutes (.033 hours) of delay are assumed for each vehicle travelling past the construction. Based on a discussion with personnel at the North Carolina Department of Transportation, the number of days of construction was estimated as a function of degree of curvature before flattening (D_b) using the function $14 + 42(D_b-10)/20$, with a minimum value of 14 days for curves of 10 degrees or less. The longest construction period was 8 weeks for flattening a 30 degree curve. Widening a curve or adding a spiral while flattening was assumed to require negligible additional construction time. Days of construction for various degrees of curve were estimated and presented in table 62 below.

Table 62. Estimated days of construction for curve flattening.

Degree of Curve	Days of Construction
30	56.0
25	45.5
20	35.0
15	24.5
10	14.0
8	14.0
5	14.0

The cost (CD) associated with construction delay can then be computed as

CD = (ADT) (no. days of construction) (avg. hrs. of delay/veh)
x (cost per hour of delay)

For example, flattening a 20 degree curve will result in an estimated 35 days of construction at 2 minutes (.033 hr) delay per vehicle and a cost of $15.45 per hour of delay. The cost of construction delay would then be

CD = (ADT) (35 days) (.033 hrs/veh) ($15.45/hr)
= (ADT) ($17.84)

Thus, on a curve with an ADT of 600, the construction delay cost would be $10,704. The average delay cost per vehicle is (.033 hrs/veh) ($15.45/hr) = $.51. The total cost for construction delay for curve flattening is therefore a function of ADT and degree of curve, and example values are given in table 63 below.

Table 63. Examples of construction delay costs for curve flattening projects.[1]

Initial Degree of Curve	ADT			
	100	500	1,000	2,000
30	$2,860	$14,280	$28,550	$57,100
25	$2,320	$11,600	$23,200	$46,400
20	$1,780	$ 8,920	$17,840	$35,690
15	$1,250	$ 6,250	$12,490	$24,980
≤ 10	$ 710	$ 3,570	$ 7,140	$14,280

[1]Note: Costs are based on 1988 costs of $15.45 per vehicle hour of delay and an average of 2 minutes of delay per vehicle.

Widening a curve without flattening has an average construction delay of 14 days. Therefore, the cost for construction delay would be similar to the cost of flattening a curve of 10 degrees (i.e., the bottom row of table 63).

Computation of Benefits

Travel time benefits for curve flattening were computed as the difference in traverse time between the endpoints of the flattened curve. After flattening, the curve would be of length $I/(52.8 \times D_a)$. Before flattening, the length of the curved section is computed by the same formula, but a tangent section of length [2.17 x Tangent (I/2)] must also be traversed. The speed on the tangent section is assumed to be 55 mi/h (89 km/h). Typical operating speeds on curves of varying sharpness, shown in figure 36, were taken from Winfrey.(37)

The dollar value of the travel time savings (TTS) was computed by multiplying the time saved per vehicle times the daily-to-lifetime conversion factor for the project of 5,300 times the value of travel time. For selected central angles and degrees of curvature before and after improvement, table 64 summarizes the savings over the lifetime of the improvement per vehicle of current ADT.

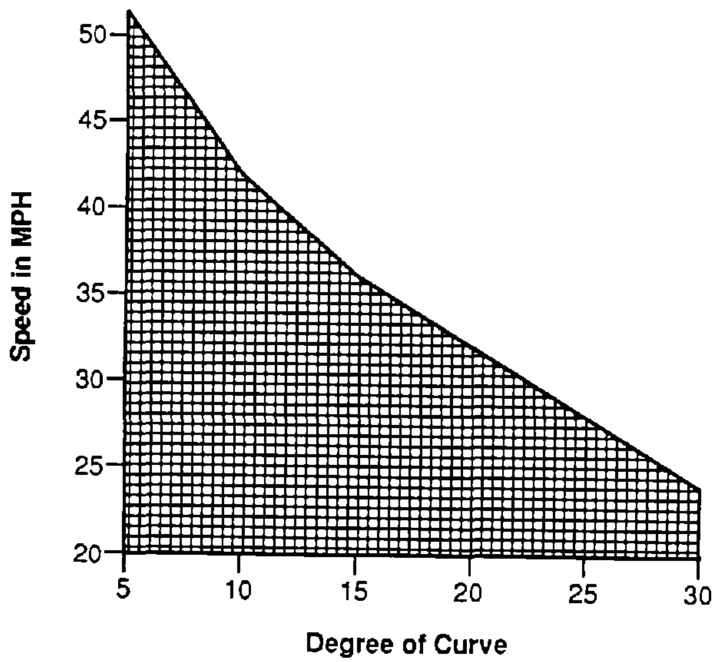

Figure 36. Typical operating speed on curves, by degree of curvature.(37)

The safety benefits attributable to a safety improvement equal the annual number of crashes prior to the improvement times the percentage crash reduction (AR factor) attributable to the improvement times the $59,000 cost per crash times the annual-to-lifetime conversion factor of 14.52.

Safety benefits are reported in two different ways in this report to aid the reader. For some analyses, they are reported as a function of the average number of before crashes on the curve per year. For others, they are computed as a function of ADT using the average crash rate that the predictive model (in chapter 6) indicates for the curve geometry.

Chapter 8 indicates the percentage crash reductions (AR factors) achievable through curve flattening, lanes widening, and/or shoulder widening. The calculations of benefits assume that no spiral is added. If a spiral is added, an additional crash reduction of 5 percent may be assumed.

Table 64. Dollar benefits of travel time saved through curve flattening over the lifetime of the improvement per vehicle of ADT (in 1988 dollars).

Degree of Curve Before	Degree of Curve After	Central Angle 10	20	30	40	50	60	70	80	90
30	25	$1.00	2.00	3.00	4.10	5.30	6.70	8.20	10.00	12.20
30	20	1.50	3.10	4.90	6.70	8.90	11.40	14.40	18.10	22.60
30	15	1.70	3.50	5.60	8.00	10.90	14.60	19.20	25.10	32.90
30	12	1.90	4.00	6.50	9.50	13.20	18.10	24.40	32.70	43.60
30	10	2.60	5.50	8.80	12.90	18.00	24.50	32.90	44.00	58.70
30	8	3.30	7.00	11.30	16.50	23.20	31.90	43.20	58.20	78.10
30	5	6.00	12.50	20.20	29.70	41.80	57.40	78.00	105.10	141.30
25	20	0.60	1.20	1.90	2.60	3.60	4.70	6.20	8.00	10.40
25	15	0.70	1.60	2.60	3.90	5.60	7.90	11.00	15.10	20.70
25	12	1.00	2.10	3.50	5.40	7.90	11.40	16.20	22.60	31.40
25	10	1.70	3.50	5.80	8.80	12.60	17.80	24.70	34.00	46.50
25	8	2.40	5.00	8.30	12.40	17.90	25.20	35.00	48.10	65.90
25	5	5.00	10.60	17.20	25.60	36.50	50.80	69.70	95.00	129.00
20	15	0.20	0.40	0.70	1.30	2.00	3.20	4.80	7.10	10.30
20	12	0.40	0.90	1.60	2.70	4.30	6.70	10.00	14.60	21.00
20	10	1.10	2.40	4.00	6.10	9.10	13.10	18.50	26.00	36.10
20	8	1.80	3.80	6.40	9.80	14.30	20.50	28.80	40.10	55.50
20	5	4.40	9.40	15.30	22.90	32.90	46.00	63.60	87.00	118.60
15	12	0.20	0.50	0.90	1.50	2.30	3.50	5.20	7.50	10.80
15	10	0.90	2.00	3.20	4.90	7.00	9.90	13.70	18.90	25.80
15	8	1.60	3.40	5.70	8.50	12.30	17.30	24.00	33.00	45.20
15	5	4.30	9.00	14.60	21.70	30.80	42.90	58.80	79.90	108.40
10	8	0.70	1.50	2.40	3.70	5.30	7.40	10.30	14.20	19.40
10	5	3.30	7.00	11.40	16.80	23.80	33.00	45.00	61.10	82.50
8	5	2.60	5.50	8.90	13.20	18.60	25.60	34.70	46.90	63.10
8	3	6.10	12.90	21.10	31.60	45.30	63.50	87.80	120.30	164.10
5	3	3.40	7.30	12.10	18.40	26.70	37.90	53.00	73.40	101.00

How to Compute Benefit-Cost Ratios

Dividing the sum of the benefits by the sum of the costs yields a benefit-cost ratio. For curve flattening, the benefit-cost ratio is given by the following:

$$BCR = (59000 \times 14.52 \times Ax \times ARF + ADT \times TTS) / (C_f + ADT \times CD) \quad (26)$$

where

Ax = accidents on the curved section

ARF = accident reduction factor for flattening for the particular curve geometry (see table 40 in chapter 8)

TTS = travel time savings from table 64

C_f = construction cost for flattening (in 1988 dollars) from table 60 or from local estimates

CD = construction delay cost from table 63

For curve widening, the formula is similar but a bit simpler, namely

$$BCR = (59000 \times 14.52 \times Ax \times ARF) / (2 \times L \times C_w + ADT \times 7.20) \qquad (27)$$

where

Ax = accidents on the curved section

ARF = accident reduction factor for curve widening for the particular curve geometry (see table 41 in chapter 8)

L = length of existing curved section

C_w = construction cost for widening (in 1988 dollars) from table 61 or from local estimates

Based on use of the models given above, the following indicates when to flatten and/or widen curves. **It should be mentioned that the results discussed below are based on average construction costs and other assumed values of accident costs (i.e., $59,000 per curve accident), interest rate, and other factors given earlier. If the actual cost for a given curve improvement is considerably higher or lower than these assumed costs, the values given would not apply. Instead, the user should refer to the corresponding Informational Guide entitled, "Safety Improvements on Horizontal Curves for Two-Lane Rural Roads." This guide has been developed to allow for computing expected benefits and project costs for curve flattening, roadway widening, providing spiral transitions to curves, improving superelevation, sideslope flattening, and other roadside improvements. The procedure allows for the user to input a variety of curve conditions and assumptions.**[38]

When to Flatten Curves

Table 65 shows the optimal (underlined) final degree of curvature after flattening for different curve geometrics given that the existing crash rate on the curve is high enough to justify flattening. Obviously, from a safety perspective, the flatter the curve, the better. In fact, a curvature of 15 degrees or less is always optimal. However, sometimes natural obstacles or a prohibitively costly right-of-way make the "optimal" amount of flattening impractical. Thus, table 65 also shows the minimum number of crashes needed to make lesser amounts of flattening cost-beneficial. Note that more crashes are needed to justify moderate flattening than to justify optimal flattening. Also note that the blank ranges in the table correspond to ranges where the incremental cost beyond more moderate flattening would exceed the incremental benefits.

Table 65 was prepared by computing benefit-cost ratios for a variety of geometric combinations and determining the number of crashes per year where the added benefit dropped below the added cost. That point provides the optimal final degree of curvature which varies with ADT. Because flattening becomes more costly as the central angle increases, the number of crashes needed to justify flattening generally rises with increasing central angle as well.

To illustrate the use of table 65, assume that you are considering flattening a 25 degree curve with a 40 degree central angle on a roadway with ADT = 1,000 and a 5-year accident experience of .70 crashes per year. Is flattening cost-beneficial in this case? Yes, since

$$.70 > .64 = \text{min. acc./yr. required for recommending flattening;}$$

In addition, the curve should be flattened to 10 degrees. However, suppose further that right-of-way costs would allow flattening to at most 15 degrees. Then since

$$.70 < .73 = \text{min. acc./yr. for } D_a = 15 \text{ degrees,}$$

it would not be cost-beneficial to flatten this curve because of the high right-of-way cost restriction.

Table 65. Minimum accidents per year on the curved section to justify flattening a curve.

ADT	Degree of Curve		Central Angle								
	Before	After	10	20	30	40	50	60	70	80	90
1,000	30	25	0.56	0.81	1.03	1.24	1.44	1.63	1.81	1.97	2.11
	30	20	0.31	0.47	0.61	0.74	0.86	0.98	1.09	1.19	1.28
	30	15	0.24	0.37	0.49	0.60	0.71	0.82	0.92	1.00	1.07
	30	12	0.22	0.34	0.46	0.58					
	30	10	0.21*	0.33							
	25	20	0.47	0.72	0.95	1.17	1.38	1.58	1.77	1.94	2.09
	25	15	0.28	0.43	0.59	0.73	0.88	1.02	1.14	1.26	1.35
	25	12	0.23	0.38	0.52	0.66	0.80	0.93	1.05	1.15	1.23
	25	10	0.22	0.36	0.50	0.64					
	25	8	0.21								
	20	15	0.40	0.65	0.89	1.13	1.37	1.60	1.81	2.00	2.15
	20	12	0.28	0.47	0.66	0.85	1.04	1.22	1.39	1.53	1.63
	20	10	0.24	0.42	0.59	0.77	0.95	1.12	1.28	1.41	1.49
	20	8	0.22	0.39	0.57						
	15	12	0.51	0.89	1.28	1.68	2.08	2.47	2.82	3.11	3.31
	15	10	0.34	0.61	0.89	1.18	1.48	1.76	2.01	2.20	2.32
	15	8	0.27	0.50	0.75	1.02	1.28	1.54	1.75	1.91	1.98
	15	5	0.23								
	10	8	0.61	1.21	1.90	2.64	3.38	4.05	4.59	4.94	5.07
	10	5	0.32	0.71	1.17	1.68	2.17	2.57	2.85	2.94	2.86
	8	5	0.46	1.05	1.76	2.53	3.26	3.83			
	8	3	0.38						3.79	3.60	3.17
	5	3	0.81	2.20	3.93	5.60	6.81	7.34	7.26	6.72	5.92
2,000	30	25	0.76	1.01	1.23	1.43	1.63	1.81	1.98	2.12	2.25
	30	20	0.41	0.56	0.70	0.83	0.95	1.06	1.16	1.24	1.30
	30	15	0.31	0.43	0.55	0.66	0.77	0.86	0.95	1.01	1.06
	30	12	0.27	0.40	0.51	0.62	0.73	0.83	0.91		1.00
	30	10	0.26	0.38							
	30	8	0.24	0.37							
	25	20	0.61	0.86	1.09	1.31	1.52	1.72	1.90	2.06	2.19
	25	15	0.35	0.51	0.66	0.80	0.94	1.08	1.19	1.29	1.36
	25	12	0.29	0.43	0.57	0.71	0.84	0.97	1.07	1.15	1.20
	25	10	0.26	0.40	0.54	0.68	0.81	0.93	1.03	1.10	1.12
	25	8	0.25	0.39							
	20	15	0.49	0.74	0.99	1.23	1.47	1.70	1.90	2.07	2.20
	20	12	0.34	0.53	0.72	0.91	1.09	1.27	1.42	1.54	1.62
	20	10	0.29	0.46	0.64	0.81	0.98	1.14	1.28	1.37	1.42
	20	8	0.26	0.42	0.60					1.31	1.32
	20	5	0.23								
	15	12	0.59	0.97	1.37	1.77	2.17	2.55	2.89	3.16	3.32
	15	10	0.38	0.65	0.93	1.22	1.51	1.77	2.00	2.16	2.24
	15	8	0.30	0.53	0.78	1.03	1.29	1.51	1.70	1.81	1.83
	15	5	0.25	0.47	0.73					1.60	1.47
	10	8	0.65	1.27	1.95	2.68	3.40	4.05	4.55	4.85	4.92
	10	5	0.33	0.71	1.15	1.62	2.06	2.40	2.59	2.59	2.41
	8	5	0.48	1.06	1.75	2.48	3.15	3.65	3.91	3.90	3.64
	8	3	0.39	0.97			2.96	3.24	3.18	2.82	2.22
	5	3	0.83	2.20	3.86	5.43	6.49	6.88	6.63	5.95	4.99

*Optimal flattening

Table 65. Minimum accidents per year on the curved section to justify flattening a curve (Continued).

ADT	Degree of Curve Before	Degree of Curve After	Central Angle 10	20	30	40	50	60	70	80	90
3,000	30	25	0.96	1.21	1.42	1.63	1.81	1.99	2.14	2.28	2.39
	30	20	0.51	0.66	0.79	0.91	1.03	1.13	1.22	1.29	1.33
	30	15	0.37	0.50	0.61	0.72	0.82	0.90	0.98	1.02	1.04
	30	12	0.33	0.45	0.56	0.67	0.77	0.85	0.92	0.96	0.96
	30	10	0.31*	0.43	0.54	0.64	0.74			0.91	0.88
	30	8	0.29								
	25	20	0.75	1.00	1.23	1.45	1.66	1.85	2.02	2.17	2.28
	25	15	0.42	0.58	0.73	0.87	1.01	1.13	1.24	1.32	1.37
	25	12	0.34	0.49	0.63	0.76	0.89	1.00	1.10	1.16	1.17
	25	10	0.31	0.45	0.58	0.71	0.84	0.94	1.02	1.06	1.05
	25	8	0.29	0.42							0.96
	25	5	0.26								0.68
	20	15	0.58	0.84	1.09	1.33	1.57	1.79	1.99	2.15	2.25
	20	12	0.39	0.59	0.78	0.97	1.15	1.32	1.46	1.56	1.60
	20	10	0.33	0.50	0.68	0.85	1.01	1.16	1.28	1.34	1.35
	20	8	0.29	0.46	0.63	0.80	0.96	1.10	1.19	1.23	1.18
	20	5	0.25								0.83
	15	12	0.67	1.06	1.46	1.87	2.27	2.64	2.96	3.21	3.34
	15	10	0.43	0.70	0.98	1.26	1.54	1.79	1.99	2.12	2.16
	15	8	0.33	0.56	0.80	1.05	1.29	1.49	1.64	1.71	1.67
	15	5	0.27	0.48	0.72			1.34	1.39	1.31	1.07
	10	8	0.70	1.32	2.00	2.72	3.43	4.05	4.51	4.76	4.76
	10	5	0.35	0.71	1.13	1.56	1.95	2.23	2.33	2.24	1.95
	8	5	0.50	1.07	1.73	2.43	3.04	3.47	3.64	3.53	3.17
	8	3	0.39	0.94	1.60	2.22	2.66	2.79	2.57	2.04	1.27
	5	3	0.86	2.19	3.79	5.25	6.18	6.41	6.01	5.17	4.07

*Optimal flattening

When to Widen Curves

Here, there are basically two issues. First, are there sufficiently many accidents per year to justify widening the lanes and, if so, how many ft (.3048 m) per lane should be added, assuming a maximum final lane width of 12 ft (3.7 m)? Secondly, should either paved or unpaved shoulders be added, and, if so, how many feet of shoulder widening would be cost beneficial again assuming a maximum final shoulder width of 10 ft (3.0 m) (or a maximum shoulder width based on AASHTO Guidelines for new highways).[15] It is always assumed that if lane widening is cost beneficial, the lane should be widened. Also it is assumed that if it is cost beneficial to add paved shoulders, this will be done rather than adding unpaved shoulders. Only if it is not cost beneficial to add paved shoulders will adding unpaved shoulders be considered.

As an aid to the user, table 66 provides curve length, L, as a function of degree of curve, D, and central angle, I. Then, with the curve length and terrain known, the user can turn to table 67 to address the two basic curve widening questions.

Table 66. Curve length (L) in mi for selected curve geometries.

Degree of of Curve (D)	Central Angle (I)								
	10	20	30	40	50	60	70	80	90
30	0.006	0.012	0.018	0.025	0.031	0.038	0.044	0.050	0.056
25	0.007	0.015	0.022	0.030	0.037	0.045	0.053	0.060	0.068
20	0.009	0.018	0.028	0.037	0.047	0.056	0.066	0.075	0.085
15	0.012	0.025	0.037	0.050	0.063	0.075	0.088	0.101	0.113
12	0.015	0.031	0.047	0.063	0.078	0.094	0.110	0.126	0.142
10	0.018	0.037	0.056	0.075	0.094	0.113	0.132	0.151	0.170
8	0.023	0.047	0.071	0.094	0.118	0.142	0.165	0.189	0.213
5	0.037	0.075	0.113	0.151	0.189	0.227	0.265	0.303	0.340
3	0.063	0.126	0.189	0.252	0.315	0.378	0.441	0.505	0.568
2	0.095	0.189	0.284	0.378	0.473	0.568	0.662	0.757	0.852

Formula: $L = I / (52.8 \times D)$

The use of table 67 to answer the questions of widening lanes and/or widening paved or unpaved shoulders is perhaps best illustrated with a couple of examples. Each example addresses the two basic questions indicated at the outset of this section on "When to Widen Curves."

In the first example, assume that a curve of length .125 mi (.2 km) with an accident experience of .59 accidents per year is under consideration for treatment. This section now has 9-ft (2.7-m) lanes and 6-ft (1.8-m) paved shoulders and is located in rolling terrain. The first question asks whether it would be cost beneficial to widen the existing 9-ft (2.7-m) lanes? From table 67, one can see that

.59 = average acc./yr > .58 = minimum number of crashes needed to add 2 ft (.6 m) of lanes (in rolling terrain)

Thus, it would be cost beneficial to widen the lanes to 11 ft (3.4 m), i.e., by adding 2 ft (.6 m) to each lane.

Secondly, should the shoulders be widened? Since

.59 = average acc./yr = minimum number of crashes needed to add 3 ft (0.9 m) of paved shoulders

the paved shoulders should be extended an additional 3 ft (.9m). The improved curve section would then have 11-ft (3.4-m) lanes with 9-ft (2.7-m) paved shoulders.

Next, suppose that we are considering a .2-mi (.3-km) curve in flat terrain with a crash experience of .80 crashes per year. This curved section has 11-ft (3.3-m) lanes and 6 ft (1.8-m) paved shoulders. Should the lanes be widened? Since, from table 67,

.80 = average acc./yr > .70 = min. no. of crashes needed to add 3 ft (.9 m) of lane width (in flat terrain)

the highway engineer should consider widening the lanes by 3 ft (0.9 m). However, that would create 14-ft (4.3-m) lanes which are beyond the recommended maximum lane width. Hence, in this case, 1 ft (.3 m) of lane width should be added resulting in 12-ft (3.7-m) lanes.

Secondly, should the shoulders be widened? Since

.80 = average acc./yr < .87 = minimum number of crashes needed to justify adding only 1 ft (.3048 m) of paved shoulder

no additional paved shoulders should be constructed. However, might it still be cost-beneficial to clear some additional shoulder area? Since

.80 = average acc./yr > .77 = minimum number of crashes needed to add 3 ft (.9 m) of unpaved shoulders

clearing an additional 3 ft (.9 m) of unpaved shoulder would be cost beneficial and recommended, provided local policy allows adding unpaved shoulders to already paved shoulders.

It should be noted that curves can be widened less expensively during flattening than at other times because the additional construction delay is minimal. Furthermore, curve widening can yield a percentage decrease in the crashes that would otherwide remain on a curve that is being flattened.

Table 67. Minimum crashes per year to make widening cost beneficial, by curve length and terrain.

Curve Length (in mi)	Ft Added (per side)	Lanes			Paved Shoulders			Unpaved Shoulders		
		Mount	Roll	Flat	Mount	Roll	Flat	Mount	Roll	Flat
.025	1	0.38	0.35	0.34	0.50	0.47	0.45	0.57	0.53	0.51
	2	0.39	0.37	0.36	0.53	0.49	0.48	0.60	0.55	0.54
	3	0.41	0.38	0.37	0.55	0.51	0.49	0.62	0.57	0.56
	4				0.58	0.53	0.52	0.65	0.60	0.59
	5				0.60	0.55	0.54	0.68	0.63	0.61
	6				0.63	0.58	0.56	0.71	0.65	0.64
	7				0.67	0.61	0.60	0.75	0.69	0.67
	8				0.69	0.63	0.62	0.78	0.72	0.70
	9				0.72	0.66	0.65	0.82	0.75	0.73
	10				0.76	0.70	0.68	0.86	0.79	0.77
.05	1	0.46	0.40	0.38	0.58	0.50	0.48	0.64	0.55	0.52
	2	0.48	0.42	0.40	0.61	0.52	0.50	0.67	0.58	0.55
	3	0.50	0.44	0.42	0.63	0.54	0.52	0.70	0.60	0.57
	4				0.66	0.57	0.55	0.73	0.63	0.60
	5				0.69	0.60	0.57	0.76	0.65	0.62
	6				0.72	0.62	0.59	0.80	0.68	0.65
	7				0.76	0.66	0.63	0.84	0.72	0.69
	8				0.79	0.68	0.65	0.87	0.75	0.71
	9				0.83	0.71	0.68	0.91	0.78	0.74
	10				0.87	0.75	0.72	0.96	0.82	0.78

Table 67. Minimum crashes per year to make widening cost-beneficial, by curve length and terrain (Continued).

Curve Length (mi)	Feet Added (per side)	Lanes			Paved Shoulders			Unpaved Shoulders		
		Mount	Roll	Flat	Mount	Roll	Flat	Mount	Roll	Flat
.075	1	0.53	0.45	0.43	0.65	0.54	0.50	0.71	0.57	0.53
	2	0.56	0.47	0.45	0.69	0.56	0.52	0.74	0.60	0.56
	3	0.58	0.49	0.47	0.71	0.58	0.54	0.77	0.62	0.58
	4				0.75	0.61	0.57	0.81	0.66	0.61
	5				0.78	0.64	0.60	0.85	0.68	0.63
	6				0.81	0.67	0.62	0.88	0.71	0.66
	7				0.86	0.71	0.66	0.94	0.75	0.70
	8				0.89	0.73	0.68	0.96	0.78	0.72
	9				0.93	0.76	0.71	1.01	0.82	0.76
	10				0.98	0.80	0.75	1.06	0.86	0.79
.1	1	0.61	0.50	0.47	0.73	0.57	0.52	0.78	0.60	0.54
	2	0.64	0.53	0.49	0.76	0.60	0.55	0.82	0.62	0.56
	3	0.67	0.55	0.51	0.79	0.62	0.57	0.85	0.65	0.59
	4				0.83	0.65	0.60	0.89	0.68	0.62
	5				0.87	0.68	0.62	0.93	0.71	0.64
	6				0.90	0.71	0.65	0.97	0.74	0.67
	7				0.96	0.75	0.69	1.03	0.78	0.71
	8				0.99	0.78	0.71	1.06	0.81	0.73
	9				1.04	0.82	0.75	1.11	0.85	0.77
	10				1.09	0.86	0.79	1.17	0.89	0.81
.125	1	0.69	0.56	0.52	0.80	0.61	0.55	0.85	0.62	0.55
	2	0.73	0.58	0.54	0.84	0.64	0.57	0.89	0.65	0.57
	3	0.75	0.60	0.56	0.87	0.66	0.59	0.92	0.67	0.60
	4				0.92	0.69	0.63	0.97	0.71	0.63
	5				0.96	0.72	0.65	1.01	0.74	0.65
	6				1.00	0.75	0.68	1.05	0.77	0.68
	7				1.06	0.80	0.72	1.12	0.82	0.72
	8				1.09	0.83	0.74	1.15	0.84	0.74
	9				1.14	0.87	0.78	1.21	0.88	0.78
	10				1.20	0.91	0.82	1.27	0.93	0.82
.15	1	0.77	0.61	0.56	0.88	0.65	0.65	0.92	0.64	0.56
	2	0.81	0.64	0.59	0.92	0.68	0.68	0.96	0.67	0.58
	3	0.84	0.66	0.61	0.95	0.71	0.71	1.00	0.70	0.61
	4				1.00	0.74	0.74	1.05	0.73	0.64
	5				1.05	0.77	0.77	1.09	0.76	0.66
	6				1.09	0.81	0.81	1.14	0.80	0.69
	7				1.16	0.86	0.86	1.21	0.85	0.73
	8				1.19	0.88	0.88	1.25	0.87	0.76
	9				1.25	0.93	0.93	1.31	0.92	0.79
	10				1.32	0.97	0.97	1.37	0.96	0.84

Table 67. Minimum crashes per year to make widening cost-beneficial, by curve length and terrain (Continued).

Curve Length (mi)	Feet Added (per side)	Lanes			Paved Shoulders			Unpaved Shoulders		
		Mount	Roll	Flat	Mount	Roll	Flat	Mount	Roll	Flat
.175	1	0.85	0.66	0.60	0.95	0.76	0.76	0.98	0.66	0.57
	2	0.89	0.69	0.63	1.00	0.79	0.79	1.03	0.70	0.59
	3	0.92	0.72	0.65	1.04	0.82	0.82	1.07	0.72	0.62
	4				1.09	0.87	0.87	1.13	0.76	0.65
	5				1.13	0.90	0.90	1.17	0.79	0.67
	6				1.18	0.94	0.94	1.22	0.83	0.70
	7				1.25	1.00	1.00	1.30	0.88	0.75
	8				1.29	1.03	1.03	1.34	0.90	0.77
	9				1.36	1.08	1.08	1.40	0.95	0.81
	10				1.43	1.14	1.14	1.48	1.00	0.85
.2	1	0.93	0.71	0.65	1.03	0.87	0.87	1.05	0.69	0.57
	2	0.97	0.74	0.68	1.08	0.91	0.91	1.10	0.72	0.60
	3	1.01	0.77	0.70	1.12	0.94	0.94	1.15	0.75	0.63
	4				1.17	0.99	0.99	1.21	0.79	0.66
	5				1.22	1.03	1.03	1.26	0.82	0.69
	6				1.28	1.08	1.08	1.31	0.85	0.71
	7				1.35	1.14	1.14	1.39	0.91	0.76
	8				1.40	1.18	1.18	1.43	0.94	0.78
	9				1.46	1.24	1.24	1.50	0.98	0.82
	10				1.54	1.30	1.30	1.58	1.03	0.86
.225	1	1.01	0.76	0.69	1.10	0.97	0.97	1.12	0.71	0.58
	2	1.06	0.80	0.72	1.15	1.02	1.02	1.18	0.75	0.61
	3	1.10	0.83	0.75	1.20	1.06	1.06	1.22	0.77	0.63
	4				1.26	1.12	1.12	1.28	0.81	0.67
	5				1.31	1.16	1.16	1.34	0.85	0.70
	6				1.37	1.21	1.21	1.39	0.88	0.73
	7				1.45	1.28	1.28	1.48	0.94	0.77
	8				1.50	1.32	1.32	1.53	0.97	0.79
	9				1.57	1.39	1.39	1.60	1.01	0.83
	10				1.65	1.46	1.46	1.68	1.07	0.88
.25	1	1.09	0.81	0.73	1.18	1.08	1.08	1.19	0.73	0.59
	2	1.14	0.85	0.77	1.23	1.13	1.13	1.25	0.77	0.62
	3	1.18	0.88	0.80	1.28	1.18	1.18	1.30	0.80	0.64
	4				1.35	1.24	1.24	1.36	0.84	0.68
	5				1.40	1.29	1.29	1.42	0.87	0.71
	6				1.46	1.35	1.35	1.48	0.91	0.74
	7				1.55	1.43	1.43	1.57	0.97	0.78
	8				1.60	1.47	1.47	1.62	1.00	0.81
	9				1.68	1.54	1.54	1.70	1.05	0.85
	10				1.76	1.62	1.62	1.79	1.10	0.89

Table 67. Minimum crashes per year to make widening cost-beneficial, by curve length and terrain (Continued).

Curve Length (mi)	Feet Added (per side)	Lanes			Paved Shoulders			Unpaved Shoulders		
		Mount	Roll	Flat	Mount	Roll	Flat	Mount	Roll	Flat
.275	1	1.17	0.87	0.78	1.25	1.19	1.19	1.26	0.76	0.60
	2	1.22	0.91	0.81	1.31	1.25	1.25	1.32	0.79	0.63
	3	1.27	0.94	0.84	1.36	1.29	1.29	1.37	0.82	0.65
	4				1.43	1.36	1.36	1.44	0.87	0.69
	5				1.49	1.42	1.42	1.50	0.90	0.72
	6				1.55	1.48	1.48	1.57	0.94	0.75
	7				1.65	1.57	1.57	1.66	1.00	0.79
	8				1.70	1.62	1.62	1.71	1.03	0.82
	9				1.78	1.70	1.70	1.80	1.08	0.86
	10				1.87	1.79	1.79	1.89	1.14	0.90
.3	1	1.24	0.92	0.82	1.32	1.30	1.30	1.33	0.78	0.61
	2	1.30	0.96	0.86	1.39	1.36	1.36	1.39	0.82	0.64
	3	1.35	1.00	0.89	1.44	1.41	1.41	1.45	0.85	0.66
	4				1.52	1.49	1.49	1.52	0.89	0.70
	5				1.58	1.55	1.55	1.58	0.93	0.73
	6				1.65	1.61	1.61	1.65	0.97	0.76
	7				1.75	1.71	1.71	1.75	1.03	0.81
	8				1.80	1.77	1.77	1.81	1.06	0.83
	9				1.89	1.85	1.85	1.90	1.11	0.87
	10				1.99	1.95	1.95	1.99	1.17	0.92
.35	1	1.40	1.02	0.91	1.52	1.52	1.52	1.47	0.83	0.63
	2	1.47	1.07	0.95	1.59	1.59	1.59	1.54	0.87	0.66
	3	1.53	1.11	0.99	1.65	1.65	1.65	1.59	0.90	0.68
	4				1.73	1.73	1.73	1.68	0.95	0.72
	5				1.81	1.81	1.81	1.75	0.99	0.75
	6				1.88	1.88	1.88	1.82	1.03	0.78
	7				2.00	2.00	2.00	1.93	1.09	0.83
	8				2.06	2.06	2.06	1.99	1.12	0.85
	9				2.16	2.16	2.16	2.09	1.18	0.90
	10				2.27	2.27	2.27	2.20	1.24	0.94
.4	1	1.56	1.12	0.99	1.73	1.73	1.73	1.60	0.87	0.65
	2	1.64	1.18	1.04	1.82	1.82	1.82	1.68	0.91	0.68
	3	1.70	1.22	1.08	1.88	1.88	1.88	1.74	0.95	0.70
	4				1.98	1.98	1.98	1.84	1.00	0.74
	5				2.06	2.06	2.06	1.91	1.04	0.77
	6				2.15	2.15	2.15	1.99	1.08	0.80
	7				2.28	2.28	2.28	2.11	1.15	0.85
	8				2.35	2.35	2.35	2.18	1.19	0.88
	9				2.47	2.47	2.47	2.29	1.24	0.92
	10				2.60	2.60	2.60	2.41	1.31	0.97

Table 67. Minimum crashes per year to make widening cost-beneficial, by curve length and terrain (Continued).

Curve Length (mi)	Feet Added (per side)	Lanes			Paved Shoulders			Unpaved Shoulders		
		Mount	Roll	Flat	Mount	Roll	Flat	Mount	Roll	Flat
.5	1	1.88	1.33	1.17	2.16	2.16	2.16	1.88	0.97	0.68
	2	1.97	1.39	1.22	2.27	2.27	2.27	1.97	1.01	0.72
	3	2.04	1.45	1.27	2.35	2.35	2.35	2.04	1.05	0.74
	4				2.48	2.48	2.48	2.15	1.10	0.78
	5				2.58	2.58	2.58	2.24	1.15	0.81
	6				2.69	2.69	2.69	2.34	1.20	0.85
	7				2.85	2.85	2.85	2.48	1.27	0.90
	8				2.94	2.94	2.94	2.55	1.31	0.93
	9				3.09	3.09	3.09	2.68	1.38	0.97
	10				3.25	3.25	3.25	2.82	1.45	1.02
.6	1	2.19	1.54	1.34	2.60	2.60	2.60	2.15	1.06	0.72
	2	2.30	1.61	1.41	2.72	2.72	2.72	2.26	1.11	0.75
	3	2.38	1.67	1.46	2.83	2.83	2.83	2.34	1.15	0.78
	4				2.97	2.97	2.97	2.47	1.21	0.82
	5				3.10	3.10	3.10	2.57	1.26	0.86
	6				3.23	3.23	3.23	2.68	1.31	0.89
	7				3.42	3.42	3.42	2.84	1.39	0.95
	8				3.53	3.53	3.53	2.93	1.44	0.98
	9				3.71	3.71	3.71	3.07	1.51	1.02
	10				3.90	3.90	3.90	3.23	1.59	1.08
.75	1	2.66	1.85	1.60	3.25	3.25	3.25	2.57	1.20	0.77
	2	2.79	1.93	1.68	3.40	3.40	3.40	2.69	1.25	0.81
	3	2.90	2.01	1.74	3.53	3.53	3.53	2.79	1.30	0.84
	4				3.72	3.72	3.72	2.94	1.37	0.88
	5				3.87	3.87	3.87	3.06	1.43	0.92
	6				4.04	4.04	4.04	3.19	1.49	0.96
	7				4.28	4.28	4.28	3.38	1.58	1.02
	8				4.41	4.41	4.41	3.49	1.63	1.05
	9				4.63	4.63	4.63	3.66	1.71	1.10
	10				4.87	4.87	4.87	3.85	1.79	1.16
1	1	3.45	2.36	2.04	4.33	4.33	4.33	3.26	1.43	0.86
	2	3.62	2.48	2.14	4.54	4.54	4.54	3.41	1.50	0.90
	3	3.76	2.57	2.22	4.71	4.71	4.71	3.54	1.55	0.94
	4				4.96	4.96	4.96	3.73	1.63	0.99
	5				5.16	5.16	5.16	3.88	1.70	1.03
	6				5.38	5.38	5.38	4.05	1.77	1.07
	7				5.71	5.71	5.71	4.29	1.88	1.14
	8				5.89	5.89	5.89	4.43	1.94	1.17
	9				6.18	6.18	6.18	4.64	2.04	1.23
	10				6.49	6.49	6.49	4.88	2.14	1.29

In summary, table 65 provides the user with guidelines based on cost-benefit considerations for optimal flattening of curves for several ADT ranges and existing curvature up to 30 degrees with central angles ranging from 10 to 90 degrees. Also provided are criteria for more moderate flattening when physical or right-of-way cost restrictions preclude optimal flattening. Not surprisingly, because flattening becomes more costly as the central angle increases (and hence the length increases for a given degree of curve), the number of crashes needed to justify flattening generally rises as well.

Similarly, table 67 provides criteria for deciding when to widen lanes and by how much by length of curve (.025 mi (.040 km) to 1.0 mi (1.6 km)) and by type of terrain (mountainous, rolling or flat). Likewise it provides guidelines for deciding whether to add paved shoulders and, if so, how much to provide. If the decision is to not add paved shoulders, it answers similar questions with regard to adding unpaved shoulders.

Not surprisingly, the minimum number of crashes needed to justify widening is always highest in the mountainous terrain and lowest in the flat regions. Also, the longer the curve, the higher the minimum number of crashes required regardless of terrain.

CHAPTER 12 - SUMMARY AND CONCLUSIONS

This study was intended to determine the horizontal curve features which affect safety and traffic operations and to quantify the effects on accidents resulting from curve flattening, curve widening, adding a spiral, improving deficient superelevation, and clearing the roadside. The economic impact of such countermeasures was also of concern in terms of developing guidelines for curve conditions in which various countermeasures are cost effective. The study involved a review and critique of the literature and data bases on horizontal curves and the analysis of three Federal data bases to gain insights into superelevation effects, roadside obstacle effects, and curve factors affecting safety and vehicle operations on curves. A merged data base of variables from 10,900 Washington State curves was analyzed to determine the effects of various countermeasures on curve crashes. In addition, an economic analysis was conducted to determine optimal improvements under various curve conditions.

The following are the key study results:

1. Based on a detailed analysis of hard-copy accident reports of crashes on curves in North Carolina, high vehicle speed is a definite factor in the occurrence of and the severity of crashes on curves. There is a significant problem with the first maneuvers in the curve, which could be the result of "curve overshoot" phenomenon. Also, many curve crashes result from a maneuver problem at the end of the curve after apparently successfully navigating most of the curve.

2. A data base of 3,427 curve/tangent pairs from Washington State was analyzed which showed the following accident groups to be generally overrepresented on curves compared with tangents:

   - Head-on and opposite direction sideswipe accidents.
   - Fixed-object and rollover accidents.
   - Fatal and A-type injury accidents.
   - Dark light condition accidents.
   - Drinking driver accidents.

   Curve features associated with higher occurrences of one or more of these accident groups include roadside recovery distances of 10 ft (0.3 m) or less, sharper curves (greater than 2 degrees), central angles of 30 degrees or more, maximum grades of 2 percent or greater, long curves (greater than .10 mi (.16 km) and narrow curve widths (30 ft (9.1 m) or less of total paved surface).

3. Based on a merged data base of 10,900 curves in Washington State, statistical modeling analyses revealed significantly higher curve accidents for sharper curves, narrower curve width, lack of spiral transitions, and increased superelevation deficiency. All else being equal, higher traffic volume and longer curves were also associated with significantly higher curve accidents.

   Of the numerous model forms tested, the accident prediction model selected for computing accident reduction factors is as follows:

$$A = [(1.55)(L)(V) + .014\,(D)(V) - (.012)(S)(V)]\,(.978)^{W-30}$$

   where,

   A = Number of total accidents on the curve in a 5-year period

   L = Length of the curve in mi (or fraction of a mi)

   V = Volume of vehicles in million vehicles in a 5-year period passing through the curve (both directions)

   D = Degree of curve

   S = Presence of spiral, where S = 0 if no spiral exists, and S = 1 if there is a spiral

   W = Width of the roadway on the curve in ft

   This model was chosen since it predicts accident frequencies quite well, and the interaction of traffic and roadway variables makes sense in terms of crash occurrence on curves. The "pseudo R^2" for this model form was .35, which was among the highest values of all the models tested.

   For isolated curves (i.e., curves with tangents of at least 650 ft (198 m) on each end of the curve), the FHWA four-State data base of 3,277 curves was used to develop accident relationships with curve features. The results of this model were used to estimate crash reductions due to curve flattening improvements on isolated curves.

4. Based on the predictive models, the effects of several curve improvements on accidents were determined as follows:

   - <u>Curve flattening</u> reduces crash frequency by as much as 80 percent, depending on the central angle and amount of flattening. For example, for a central angle of 40 degrees, flattening a 30-degree curve to 10 degrees will reduce total curve accidents by 66 percent for an isolated curve, and by 62 percent for a non-isolated curve. Flattening a 10 degree curve to 5 degrees for a 30 degree central angle will reduce accidents by 48 and

32 percent for isolated and non-isolated curves, respectively. A table of accident reduction factors was produced for a variety of curve flattening improvements.

- Roadway widening effect on curves was determined based on the predictive model and crashes further refined for widening lanes versus shoulders and for widening paved shoulders vs unpaved shoulders.

  Widening lanes on horizontal curves is expected to reduce accidents by up to 21 percent for 4 ft (1.2 m) of lane widening (i.e., 8 ft (2.4 m) of total widening). Widening paved shoulders can reduce accidents by as much as 33 percent for 10 ft (3.0 m) of widening (each direction). Unpaved shouldres are expected to reduce accidents by up to 29 percent for 10 ft (3.0 m) of widening.

- Adding a spiral to a new or existing curve will reduce total curve accidents by approximately 5 percent.

- Superelevation improvements can significantly reduce curve accidents where there is a superelevation deficiency (i.e., where the actual superelevation is less than the optimal superelevation as recommended by AASHTO). An improvement of .02 in superelevation (i.e., increasing superelevation from .03 to .05 to meet AASHTO design guidelines) would be expected to yield an accident reduction of 10 to 11 percent. Higher percent reductions could result from superelevation improvements where greater deficiencies exist. No specific accident increases were found for the small sample of curves with a superelevation greater than the AASHTO guidelines. Thus, no support can be given to the assumption of increased accident risk on curves with slightly higher superelevation than currently recommended by AASHTO.

5. To quantify the effects of specific roadside improvements, a separate analysis was conducted of the FHWA cross-section data base, which contains detailed roadside obstacle information in addition to traffic, geometric, and accident data for approximately 5,000 mi (8,050 km) of two-lane, rural roads in seven States. Accident models were developed and used to estimate the frequency of crashes involving trees, utility poles, culverts, mailboxes, sign posts, fences, and guardrails for various levels of ADT, lane width, obstacle offset from the road, and number of obstacles per mi (1.61 km) (or percent roadside coverage for longitudinal obstacles). Accident reductions were computed for relocating utility poles, clearing back trees, and relocating other obstacles, if feasible. For example, cutting back trees by 5

ft (e.g., from 8 ft (2.4 m) to 13 ft (4.0 m)) will reduce tree accidents by approximately 34 percent.

6. To investigate the effects of curve features on traffic operations, an analysis was conducted of the FHWA surrogate data base, which consists of 78 curves in New York State. Average speed reduction and edgeline encroachments from the inside lane are clearly linearly related to degree of curve for curves above 5 degrees. As curves become sharper, there is a proportionally greater speed reduction, and edgeline encroachments increase on the inside lane (i.e., inside of the curve). Centerline encroachments on the outside lane also increase more drastically than centerline encroachments on the inside lane.

7. An economic analysis of various curve-related improvements was conducted using accident benefits, travel time savings (due to curve flattening), project costs, and construction delay costs during improvements. The average cost per curve accident was $59,000 for the Washington State data base.

   A series of tables were developed to indicate the minimum number of crashes required to justify curve flattening and lane or shoulder widening.

   During routine roadway repaving, deficiencies in superelevation should always be improved. Spiral transitions were also recommended, particularly for curves with moderate and sharp curvature. Improvements of specific roadside obstacles should be strongly considered, and their feasibility should be determined for the specific curve situation based on expected accident reductions and project costs.

CHAPTER 13 - RECOMMENDATIONS FOR DESIGNING AND IMPROVING HORIZONTAL CURVES

This research report is the culmination of a concerted, extensive program sponsored by the Federal Highway Administration which addresses the safety and operational characteristics of horizontal curves on two-lane, rural highways. In recent years, several major research projects which, taken together, have produced a wealth of information on curves, such as the FHWA four-State study, TRB Special Report 214, the FHWA study documented in this report, and many others included in the list of references.[2,10] The research in many of these studies focused primarily on horizontal curves on two-lane rural highways. Such highways comprise the majority of U.S. highway mileage and represent a critical safety problem to highway users. The combination of high-speed operation, lack of access control, variability in cross-sectional design, and variability of alignment are all characteristic of such highways.

Each of the studies had unique objectives, research plans, budget constraints, and research teams. Not surprisingly, the findings and conclusions from each study differ in some respects. Nonetheless, when one examines closely the disparate studies, a consensus emerges that clearly describes what is known to date about accidents, operations, and design implications for horizontal curves. It is the purpose of this chapter to summarize this knowledge, in the hope that highway designers, traffic engineers, and safety engineers will be able to understand and thus improve their work regarding highway curves.

Unique Operational and Safety Characteristics of Curves

Highway curves are distinctly different from tangents. The geometry of a curve requires unique perceptions and responses from the driver/vehicle system. Centrifugal forces result in a different "feel" to curve tracking than is produced on tangent alignment. Curve tracking requires a continual steering response not needed on a tangent. The dynamics of vehicles in loss of control conditions are much different on curved vs. tangent alignment. These and other aspects of vehicular operation on curves induce a different pattern of accidents from that on tangents and may be described as follows:

Highway curves tend to experience significantly higher accident rates, and a greater proportion of severe (i.e., injury or fatality-producing) accidents than highway tangents.

Estimates of the difference between curve and tangent accident rates vary, with the suggestion by some researchers that typical, isolated curves produce up to four times the accident rates of tangents. Greater accident severity is a result of the higher proportion of run-off-road accidents (fixed object and overturn) and opposing direction accidents (head-on and opposite direction sideswipe) that occur on curves vs. tangents.

Research also shows that accident and operational problems are based on more than just the sharpness or degree of curve. Recent studies, including the research reported here, show that many geometric elements that comprise a horizontal curve play a role in curve safety and operations.

Relationship Between Basic Curve Geometrics, Accidents, and Operational Behavior

Horizontal highway curves are defined in terms of three basic elements -- the degree or radius of curve, central angle, and length of curve. To review, the following simple mathematical relationships describe horizontal curves:

$$D = \frac{100\ (I)}{L} \qquad R = \frac{5729.6}{D}$$

where,

D = Degree of Curve (arc definition)
R = Radius of Curve (ft)
I = Central angle (angle subtended by a 100 ft (30.4 m) length of arc)
L = Length of curve in ft (.3048 m)

Research in the previous 20 to 30 years has focused on the relationship of degree of curve or radius to accident rate. Various conclusions were reached regarding the sensitivity of accidents to curvature. While there is general agreement that "sharper" curves are more hazardous, some researchers have noted that degree of curve is only part of the problem.

The length of curve also plays a role in curve safety. Sharp curves tend to be short. Designing milder curves may require longer sections of highway that are curved. The interaction of degree and length of curve, then, requires one to focus on frequencies of accidents rather than on accident rates. It also leads to the following conclusion regarding curves and curve safety:

The number of accidents expected for a given curve is a function of the degree of curve and length of curve.

Length of curve was an element used in accident prediction models developed for this study. In the earlier FHWA four-State curve study, length of curve also played a role in defining "high accident" curves.[2]

The conclusions regarding length of curve are important, in that they help form the "picture" of curve geometrics and safety. It is not sufficient to relate accident potential to degree of curve; length of curve also must be considered. Furthermore, this finding relates well to what is known about curve operations.

Stated simply, the task of operating on a curve can be characterized in terms of two important subtasks: (1) the transition (both approach and departure) from tangent to curve; and (2) curve tracking itself. Both tasks are more difficult than tracking a tangent. For a given degree of curve, a longer curve thus presents a more difficult driving task than a shorter curve. Moreover, since curve encroachments on the roadside are more severe than on tangents, longer curves would be expected to produce measurably greater exposure to roadside accident problems than shorter curves.

Of course, curve safety and operations are influenced considerably by factors other than the curve's geometry. Indeed, this study confirms the necessity to consider the roadway and shoulder width, roadside character, superelevation transition, and grades. In addition, other factors such as approach conditions, sight distance, presence of intersections, bridges, driveways, and terrain all play a role in curve safety and operations.

Cross-Section Effects

The importance of adequate width for operations, and a forgiving roadside for inadvertent encroachments, is significantly heightened on curves. The results of the analysis in this FHWA study found a significant effect of roadway width and quantified the accident reductions due to lane and shoulder widening. Also, edgeline encroachments and speed change were found to increase greatly for curves sharper than 5 degrees. The FHWA four-State study noted the tendency of drivers to track curves with paths much different from the highway geometry.[2] In addition, the FHWA cross-section study found significant crash reductions due to wider lanes and shoulders on two-lane rural roads.[3] Thus, these studies and others demonstrate the value of full lane widths through sharper curves. In most cases, lane widths of 11 to 12 ft (3.4 to 3.7 m) (i.e., traveled widths of 22 to 24 ft (6.7 to 7.3m)) will suffice. In others, however, even greater lane widths through the curve itself may be necessary. On particularly sharp, isolated drives, curve widening may be appropriate. Centerline encroachments would be both frequent as well as in conflict with opposing traffic.

Of course, the above discussion does not consider additional width requirements associated with trucks. Trucks, particularly the longer tractor-semi-trailers, have both tracking and dynamic characteristics much more critical than passenger cars. Where frequent traffic of such vehicles is present, curve widening beyond 12-ft (3.4-m) lanes with paved shoulders may be essential.

The width of the entire roadway, lanes plus usable shoulders, is clearly critical in both safety and operations. Full shoulders provide for better recovery from encroachments, and thus enhance the quality of the roadside. As discussed in chapter 8, full width cross sections produce up to 36 percent fewer curve-related accidents than narrow designs on curves (e.g., comparing a 40 ft (12.2 m) width of lanes plus shoulders to a 20 ft (6.1 m) width).

Another important consideration in highway curve safety is the quality of the roadside outside the shoulders. In this study, 57 percent of the accidents on Washington State curves were single-vehicle, run-off-road in nature, a number comparable to findings of the four-State curve study.(2) That study discovered that roadside design quality was a major factor in identifying high-accident, isolated curve sites.(2) While roadside quality was not found to contribute significantly in the accident model building using the Washington curve data base, this is because roadside data variability was not great enough to demonstrate a sensitivity. Accordingly, a separate analysis of roadside safety based on the FHWA cross-section study found roadside hazard was one of the most important highway features associated with accident experience.(3) In fact, more than 60 percent of the single-vehicle and opposing direction accidents could be reduced due to roadside improvements on rural, two-lane highways. Further, up to 27 percent of single-vehicle crashes could be reduced due to flattening steep sideslopes. This analysis supports the view that the quality of the roadside -- clear recovery areas and flat sideslopes -- is an important safety factor on curves.

Curve Geometrics

The degree and length of curve, superelevation in the curve, superelevation transition, and pavement surface friction all play critical roles in curve safety and operations. The point-mass equation that forms the basis for curve operations and design is a useful starting point in illustrating curve geometric relationships.

$$R = V^2/[15\ (e + f)]$$

where,

R = Radius of curve/vehicle path (ft)
V = Speed of vehicle (mi/h)
e = Superelevation (ft/ft)
f = Side friction factor

The combination of superelevation and side friction counterbalances the centrifugal forces acting on the driver and vehicle. As long as the vehicle does not go too fast, sufficient pavement friction is available, and the vehicle tracks the curve as designed so loss of control is presumably avoided.

Operational studies of vehicles driving through curves show the following:

1. In terms of speed, many drivers tend to "overdrive" horizontal curves (relative to assumptions implied by current design policy). Actual speed reductions are nominal for drivers proceeding through mild to moderate curvature. Even on curves greater than 5 degrees, the reduction in speeds is not as great as might be expected, particularly for isolated curves.

2. Even where the curve is visible well in advance, drivers tend to adjust speeds only as they begin actual curve tracking, not well in advance of the curve. Through the initial 100 to 200 ft (30.5 to 61 m) of the curve, speeds are higher than in the middle of the curve.

3. Drivers do not track typical, unspiraled circular curves as they are designed. Instead, they produce what is termed as "path overshoot."(2) A typical driver entering an unspiraled curve gradually spirals or transitions the vehicle. At some point into the curve, the vehicle actually tracks a path sharper than the curve in order to avoid running off the road.

   Comparable observations of drivers tracking spiraled curves have not been made. However, modeling of driver behavior for HVOSM studies shows that spirals provide the means of accommodating typical driver behavior, thus mitigating path overshoot.

4. The frequency of centerline and edgeline encroachments increases as curvature increases, particularly for curves greater than 5 degrees. This observation is closely related to path overshoot, in that it confirms the difficulty drivers have in tracking a circular curve at high speed.

The above findings suggest that curve tracking involves two separate tasks, both of which are more difficult than the task of tracking a tangent. The first, and perhaps most important, is the transitioning of the vehicle from tangent to curve. The second is tracking of the curve itself. The design values for both superelevation and side friction, and the design methods for developing both features, are thus highly important.

Regarding superelevation, it may be concluded that the effects of superelevation are over-estimated relative to curvature in the formulation of current design policy. Superelevation presumably counteracts lateral acceleration on a one-for-one basis. However, speed and tracking behavior demonstrate that drivers typically generate lateral acceleration well in excess of that assumed by AASHTO.

To achieve the results intended by current design policy, then, more superelevation is necessary on many curves than currently exists. Note that the above finding is supported by accident studies conducted for this project as well as by others. In the current study, for example, accident reductions of 10 percent or greater were found due to adding superelevation to curves which had considerably less than AASHTO guidelines. Further, no adverse accident effects were found for curves with superelevation exceeding AASHTO guidelines.

In the FHWA four-State study, analysis of high- and low-accident curve sites for higher speed curves (1 to 3 degrees) showed a relationship between maximum superelevation and propensity to be a low-accident site.[(2)] Quantifiable safety benefits were estimated for curves with "deficient" (i.e., insufficient per current policy) superelevation.

All of the above research on safety and operations leads to another fundamental conclusion regarding design of horizontal curves:

More superelevation than is currently provided by current design criteria would enhance both the safety and operational quality of high-speed curves.

Current design policy for superelevation has remained unchanged for over 40 years. It was originally established based on an estimated upper limit on superelevation that would not create loss of control ("sliding down the curve") for low speed operations on icy pavements. A range of maximum superelevation values is used (e_{max} = .06, .08 or .10 in rural area), with the selection of a design policy generally based on local climate and terrain.

What is apparent from the research is the need to reformulate superelevation design policy. Consideration should be given to increasing maximum allowable superelevation, reducing maximum controlling curvature, or a combination of both. Such reformulation should be based on observed driver behavior rather than the classical point-mass relationship that is fundamental to current policy.

Regarding superelevation transition, there is evidence that insufficient superelevation at the point of curvature (P.C.) may produce problems. Developing superelevation too rapidly prior to the P.C. can also produce problems. The use of spiral transition curves were found in the current research to be associated with approximately 5 percent fewer crashes than for curves without spiral transitions. Further, curves with spiral transitions were found to have superelevation which was closer to the desired maximum value compared to curves without spiral transitions. This leads to a fourth fundamental conclusion of previous research on horizontal curvature:

> **Spiral transition curves, offering the only reasonable way to develop superelevation and accommodate driver/vehicle behavior on curves, are important to safer design of high-speed alignment.**

The value of spiral transitions has long been noted in the literature. Until recently, spirals were viewed as desirable features for high-speed highways, but not necessary to safe operation. This study, building on earlier work by others, firmly establishes the value that spiral curves have for safer design of modern, high-speed roadways. This study established for the first time that spirals produce small but measurable safety benefits. Spirals result in better operations in that severe "path overshoot" behavior is mitigated. Spirals also represent the only way to transition superelevation in a reasonable manner. Finally, the lone historical argument against spirals, that they are too complicated mathematically and too difficult to lay out in the field, is no longer an issue with the widespread application of computer aided design.

Pavement and Shoulder Surface

The condition of the traveled way and type of shoulder surface are also important factors in curve safety. Available pavement friction on the curve itself is directly related to the probability of loss of control. Earlier accident studies and others confirm the importance of maintaining adequate skid resistance, particularly on sharper highway curves where lateral acceleration and resulting friction demand is greatest.

Designers should also note that paved shoulders offer slightly greater safety on curves compared to unpaved shoulders. The FHWA cross-section study established an incremental effectiveness for paved vs. unpaved shoulders on two-lane highways.(3) Benefits of paved shoulders should be even greater for curves than tangents, given the higher frequency of run-off-road accidents on curves. The FHWA four-State curve study confirmed that shoulder type played a small but statistically significant role in differentiating high- and low-accident curve sites.(2)

Another safety problem involves the joint between lanes and shoulders. Pavement edge dropoffs were identified by TRB Special Report 214 as potentially accident-producing features on two-lane highways.(10) These typically occur where unpaved shoulders exist. Dropoffs along curves are particularly troublesome, given the propensity for edgeline encroachments, difficulties in curve tracking, and overall greater friction demands produced by cornering.

Confounding Geometry

Highway sections with multiple geometric features or conflict points present special problems to drivers. The confounding effect of intersections, steep grades, sight distance restrictions, narrow bridges, etc. with horizontal curves are well recognized. Indeed, many researchers have taken considerable effort to plan their data collection and evaluate accident data to minimize or control for these effects.

While not studied in detail in this research, it can be inferred that other problems to be avoided in design, or considered in countermeasure development, are combinations of proximate curvature. In particular, reverse curves on high-speed highways can pose severe problems.

The difficulties of driver/vehicle curve tracking would obviously be much greater for reversals at high speeds. Furthermore, where only short tangent alignment exists between reverse curves, there is insufficient distance to rotate the pavement. Little or no superelevation may be present at the P.C. of the second curve, producing the undesirable operations cited earlier.

General Guidelines for Curve Design and Upgrading

Designers and highway safety engineers are faced with two distinctly different types of problems regarding horizontal curves: (1) design of new highway sections, and (2) treatment or reconstruction of existing highway alignment. The guidelines in this chapter involve curve geometrics, safety, and operations relative to both of these situations.

Design Guidelines for New Highway Sections

Most highway design in the United States is governed by the procedures, criteria, and design values shown in the AASHTO Policies, such as contained in the AASHTO "Greenbook."[15] Research from recent studies on horizontal curves suggests that application of the following design guidelines would significantly improve the overall quality of horizontal curve design:

1. **Designers should provide for consistent roadway sections.**

   Over a given highway section, horizontal curves should be designed to minimize the element of surprise to a motorist. This suggests designing curves within a reasonable range of central angle and degree of curve, and the consistent use of adequate superelevation, roadway width and other design features.

   Designers should avoid sharp isolated curves and the use of one or more sharp curves after a series of mild curves.

2. **Designers should avoid large central angles wherever possible.**

   Large central angles force designers to choose between long curves or sharp curves, both of which present safety problems. In laying out and selecting new roadway alignments, designers should strive to avoid situations where large central angles are necessary. Central angles greater than 30 degrees may result in safety problems -- greater than 45 degree central angles should be avoided whenever possible.

3. **Designers should minimize the use of controlling curvature (i.e., maximum allowable curvature for a given design speed).**

   Many designers tend to view all curves as equally "safe" within a given design speed. This is not the case. Flatter curves will operate better and tend to have better accident histories, and thus are preferred. Where controlling curvature is used, designers should pay extra attention to the roadside design (in particular, on the outside of the curve).

4. **Designers should use spiral transition curves as a routine part of design, particularly for controlling curves and curves on highways with high design speeds (e.g., 60 mi/h (97 km/h) or greater.**

5. **Designers should routinely provide high quality roadside designs, particularly on sharper curves.**

   Wider shoulders, flatter slopes, and greater roadside clear zones in these areas are essential design features.

6. **Designers should use an adequate amount of superelevation on all curves.**

7. **Designers should avoid locating other potentially hazardous features at or near horizontal curves, in recognition of driver difficulty in tracking curvature.**

   Such features to avoid whenever possible include intersections, narrow bridges, major cross-section transitions, and driveways. Other potentially hazardous features include severe reverse curvature with curves in opposing directions separated only by a short tangent alignment.

8. **Designers should provide adequate pavement and shoulder condition, particularly on sharper curves where lateral acceleration and function demand are the greatest.**

   Increasing pavement skid resistance is often an essential curve improvement, particularly on curves having a problem with skidding accidents during wet pavement conditions. On highways designed with unpaved shoulders, consideration should be given to paving the shoulders at the sharper curves. Vertical curvature should be provided such that more than minimum stopping sight distance is available throughout the curve.

<u>Treatment of Existing Curves</u>

Addressing safety problems on existing horizonal curves is distinctly different from the design of horizontal curves on new highway sections. Each location is unique in terms of its constraints, physical conditions, and operational characteristics. There should be an opportunity for the engineer to assess existing conditions. Accident records should reveal whether the curve is a high-accident location, what types of accidents occur, and what are their severities. Speed, encroachment, and other operational studies can also provide guidance on curve accident countermeasures.

The importance of evaluating existing accident patterns and geometry cannot be overemphasized. Every sharp curve with a narrow roadway and/or poor roadsides is not necessarily a safety problem in need of safety improvements. Similarly, the presence of a high accident "hot spot" may not always suggest the need to apply a countermeasure. All research, even the most carefully conducted, has shown that there is much randomness in accident occurrences. It has been stated that less than 10 percent of curves on rural highways are candidates for treatment, with many of these carrying volumes too low to achieve cost effectiveness.[2]

Generally, countermeasures fall into three major categories: (1) complete reconstruction, (2) physical rehabilitation and/or partial reconstruction, and (3) low-cost spot improvements, such as signing, marking, and delineation. These groups of countermeasures are discussed below.

Curve Reconstruction: Curve reconstruction represents the most costly, but also potentially the most effective means of reducing severe curve accidents. Curve reconstruction may involve flattening of the curve; widening of lanes, shoulders, or both; new pavement; improved roadside; and the addition of a spiral where none previously existed.

Research results in the current study and others have found that curve flattening, although more expensive than other types of curve improvements, provides the greatest potential for reducing accidents on curves. What should be understood is that safety benefits may accrue not only because of the revised curve geometry, but also because a different cross section can be built, new higher friction pavement provided, and other features added. In assessing the cost effectiveness for curve reconstruction, application of the procedures in the Informational Guide "Safety Improvements on Horizontal Curves for Two-Lane Rural Roads" (which was developed in conjunction with this Final Report) will enable a reasonable estimate of safety effectiveness.

In any event, the feasibility or cost effectiveness of total curve flattening and reconstruction depends largely on site-specific conditions. The availability and cost of right-of-way, vertical alignment requirements, environmental impacts, and local access changes would all influence any decision to reconstruct a curve.

Besides curve flattening, other reconstruction measures applied to the existing curved alignment may be feasible in given locations. These may include widening the roadway and shoulder on the curve, reconstruction by adding spirals (involving minor relocation), or major roadside improvements, such as flattening roadside slopes and removing trees or other objects along the curve itself. Combinations of the above may also require acquisition of right-of-way, resolution of conflicts with local access, and accommodation of environmental concerns.

Rehabilitation and/or Partial Reconstruction: Less costly measures than curve flattening or roadway widening may be highly effective in treating existing curves. Foremost among these is removal of roadside hazards within the curve itself. Tree removal, utility pole relocation, sideslope flattening, and other such improvements may be cost effective at relatively low traffic volume levels. Resurfacing of the curve itself to improve skid resistance is also a low-cost solution. This resurfacing can also be used to improve the superelevation in the curve, adjust the superelevation transition, pave the shoulder through the curve, clear roadside obstacles, and eliminate pavement edge dropoff conditions. All of the above can be implemented within existing right-of-way, and with relative ease. The effectiveness of a "package" of curve rehabilitation countermeasures would, of course, depend on the particular site. TRB Special Report 214 provides useful information relative to 3R improvements.[10]

Signing, Marking, and Delineation: Advance warning signs, centerline and edgeline markings, and special delineation schemes have been tested at high accident locations. These types of countermeasures are intuitively appealing because of the low cost and ease of implementation.

Special attention to signing and markings is important along any highway, and particularly at critical locations such as sharp curves. It is clear, however, that the addition of signing, marking and delineation cannot be expected to solve a safety problem on a poorly designed curve. At the same time, proper signing, marking, and delineation in accordance with the Manual on Uniform Traffic Control Devices (MUTCD) is an essential ingredient to treating hazardous curves in conjunction with other improvements (e.g., clearing roadsides, widening the roadway, paving the shoulder, flattening the curve, and/or improving the superelevation).[39] Even if construction or reconstruction of a poorly designed curve is not possible, substandard signing, marking, and delineation should still be improved on hazardous curves.

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