Safety Effectiveness of Highway Design Features

Volume II:

ALIGNMENT

ication No. FHWA-RD-91-045
ember 1992

U.S. Department of Transportation
Federal Highway Administration

ALIGNMENT

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FOREWORD

In the early 1960's, the highway community became increasingly interested in the safety effects of geometric design. The first attempt to quantify the state of knowledge on this topic was undertaken by the Highway Users Federation for Safety and Mobility (HUFSAM) in 1963 and 1971.

Considerable research on geometrics and safety was then initiated, and in the late 1970's, the Federal Highway Administration (FHWA) provided a consolidated resource for the safety impacts of various geometric and traffic control alternatives. This document, the Synthesis of Safety Research Related to Traffic Control and Roadway Elements, Volumes I and II (FHWA Report Nos FHWA-TS-82-232 & 233), which updated the earlier HUFSAM reports, served a critical and useful purpose by providing valuable geometric/accident relationships.

This present compendium is the result of the FHWA implementing one of the 23 recommendations contained in TRB Special Report 214, "Designing Safer Roads - Practices for Resurfacing, Restoration and Rehabilitation." This report specifically responds to the recommendation, calling for the FHWA to "...develop, distribute, and periodically update a compendium that reports the most probable safety effects of improvements to key highway design features..."

As an initial task, all available United States literature potentially relating a geometric feature with traffic accidents was identified. Resources included the Transportation Research Information Service, libraries at the University of North Carolina and United States Department of Transportation, authors, and the personal documents of the project team. In addition, accident/geometric data bases were identified as possible sources of data which could be used to develop needed relationships.

This identification effort revealed a lack of many new (post-1973) documents for several geometric topic areas. Accordingly, some major pre-1973 reports were included for critical review.

Critical reviews of these reports involved determination of the appropriateness of the study design, the adequacy of the sample size, the application of proper statistical tests and correct interpretation of results. Only information meeting all of these criteria is reported in each volume of this report. These documents are listed in the reference section at the end, and an additional bibliography section is included, covering related research of interest, but not used in this report.

INTRODUCTION

The design of highways primarily involves three geometric design elements: vertical alignment, horizontal alignment, and cross-section. Design speed controls the vertical and horizontal alignment of a highway, which is based partially on safe stopping sight distance. Therefore, vertical and horizontal alignment control sight distance and the safe operating speed of the highway. The correct combination of vertical and horizontal alignment promotes uniform speed for the motorist traveling the highway, and thus contributes to a safe design.

Safety research has focused on the combination of vertical and horizontal alignment features. This volume will discuss each of these highway alignment elements separately and in combination.

SUMMARY OF RESEARCH

Vertical Alignment

The vertical alignment of a highway is described by both vertical lines or grades, and vertical curves which include sags and crests. In general, three major factors which affect the design of vertical alignment of a highway are: safety, terrain, and construction costs. This section discusses the balance and interrelationship between safety and vertical alignment.

Studies have shown that the accident rate for downgrades is 63 percent higher than for upgrades, assuming that upgrades have as much vehicular traffic as downgrades. Table 1 shows that downgrade accidents are more frequent and result in higher percentages of injuries and fatalities than upgrade accidents. Also, injury and fatality rates on vertical curves are higher than on level or upgrade locations.[1]

A similar but more dated study by Mullins, et al, hypothesized that the general lack of sight distance contributes to the high accident rates at the peak of crests and uphill portion of sags.[2]

Studies were also conducted to compare and assess the safety of various truck combinations as related to vertical alignment. Results reveal that there were more truck accidents on urban roadways than on rural roadways. It was also found that trucks are more likely to have accidents on grades than on level terrain. In addition, double trailer combinations (tractor plus two trailers) appear to have more problems on downgrades than other truck and trailer configurations. Table 2 provides the distribution of accidents by truck type and grade measurement of the roadway at the accident site, and table 3 provides information on vertical slope by roadway type.[3]

Horizontal Alignment

Accident studies indicate that horizontal curves experience a higher accident rate than tangents, with rates ranging from one and a half to four times greater than tangent sections.[4,5,6] Past research has identified a number of traffic, roadway, and geometric features which are related to the safety of horizontal curves. These factors include:[4-13]

- Traffic volume on the curve and traffic mix (e.g., percent trucks).
- Curve features (degree of curve, length of curve, central angle, superelevation, presence of spiral or other transition curves).

Table 1. Accident frequency and severity by vertical alignment.[1]

Vertical Alignment	Number of Accidents	Percent of Total Accidents	Percent Injured	Percent Killed
Level	2001	34.6	53.6	4.7
Upgrade	943	16.3	55.6	3.9
Downgrade	1533	26.5	58.4	5.1
Up on crest	373	6.5	59.5	6.0
Down on crest	461	8.0	62.6	5.9
Up on sag	258	4.5	57.8	6.3
Down on sag	211	3.7	61.7	6.8
Total Known	5780	100.0		
Unknown	2192			
Total	7972			

Table 2. Distribution of accidents by vertical grade measurement and truck type.[3]

		Vertical Slope Measurement							
Truck Type		Down 6-7%	Down 4-5%	Down 2-3%	Level	Up 2-3%	Up 4-5%	Up 6-7%	Total
Straight	N	3	8	30	234	30	7	5	317
	%	1	3	14	74	9	2	2	100
	(%)	(7	20	73)	-	(71	17	12)	-
Singles		27	19	152	851	151	44	20	1294
	%	2	4	12	66	12	3	2	100
	(%)	(12	21	67)	-	(70	20	9)	-
Doubles	N	20	23	16	163	19	11	10	262
	%	8	9	6	62	7	4	4	100
	(%)	(34	39	27)	-	(48	28	25)	-

Table 3. Distribution of truck accidents by vertical grade measurement and roadway type.[3]

		Vertical Slope Measurement						
Roadway Type		Down 6-7%	Down 4-5%	Down 2-3%	Level	Up 2-3%	Up 4-5%	Up 6-7%
Rural Freeway	N	43	62	93	388	95	33	38
	%	6	8	12	51	13	6	3
Rural Nonfreeway	N	11	14	13	111	12	8	6
	%	6	8	7	63	7	5	0
Urban Freeway	N	-	18	103	675	104	22	1
	%	-	2	11	73	11	2	0
Urban Nonfreeway	N	-	-	3	185	7	-	-
	%	-	-	2	95	4	-	-
Total	N	54	94	212	1359	218	68	43
	%	3	5	10	66	11	3	2

- Cross-sectional curve elements (lane width, shoulder width, shoulder type, shoulder slope).
- Roadside hazard on the curve (clear zone, sideslope, rigidity and types of obstacles).
- Stopping sight distance on curve (or on curve approach).
- Vertical alignment on horizontal curve.
- Distance to adjacent curves.
- Presence/distance from curve to the nearest intersection, driveway, bridge, etc.
- Pavement friction.
- Presence and type of traffic control devices (signs and delineation).
- Others.

In terms of accident characteristics on curves, a 1991 study by Zegeer, et al. for the Federal Highway Administration (FHWA) identified accident factors overrepresented on curves compared to tangents based on 3,427 curve/tangent pairs in Washington State.[6] Groups of accidents generally found to have higher percentages on curves compared to tangents included more severe (fatal and A-type injury) crashes, head-on and opposite direction sideswipe crashes, fixed-object and rollover crashes, crashes at night, and those involving drinking drivers. Based on a larger sample of 10,900 horizontal curves in Washington State, the distribution of curve crashes by severity and type were determined, as shown in table 4.[6]

Consideration of horizontal curve design should involve two steps. First of all, problem curve sites should be identified for which improvements may be needed. Then, specific geometric and other improvements should be considered to reduce the accident experience at the curve sites. The following is a discussion of these two issues in terms of what is found in the literature.

Identification of problem curve sites

A 1983 study by Glennon, et al. developed a discriminant model for use in identifying horizontal curve sites which are potentially high-accident based on geometric, traffic, and roadside conditions. The identification of such sites will allow for investigating and possibly correcting such sites before a more serious accident problem develops. The data base used for the discriminant model included 330 curve sections which were either high-accident or low-accident sites.

Table 4. Summary of accident statistics on Washington State curve sample.

Variable	Freq	Pct
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
Opp. 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

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

The best derived discriminant function was as follows:

$$D = 0.071257(DC) + 2.9609(LC) + 0.10737(RR) - 0.035161(PR) - 0.14504(SW) - 1.54544$$

where

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

Thus, curves with sharper curvature, greater length, more hazardous roadsides, lower skid resistance, and/or more narrow shoulders have higher discriminant scores. A higher discriminant score (D) indicates a higher likelihood that a curve site will be a high-accident location. In fact, the equation correctly classifies 75.9 percent of the high-accident sites, 60.2 percent of low-accident sites, and 69.1 percent of all sites.

The probability of a site being high-accident is shown in figure 1 for various discriminant scores. For example, a curve section with a discriminant score of +2 will have about a 90 percent chance of being a high-accident site. The roadside hazard rating is the probability of an injury accident given a roadside encroachment. The roadside hazard rating depends on side slope, coverage factor, and lateral clear

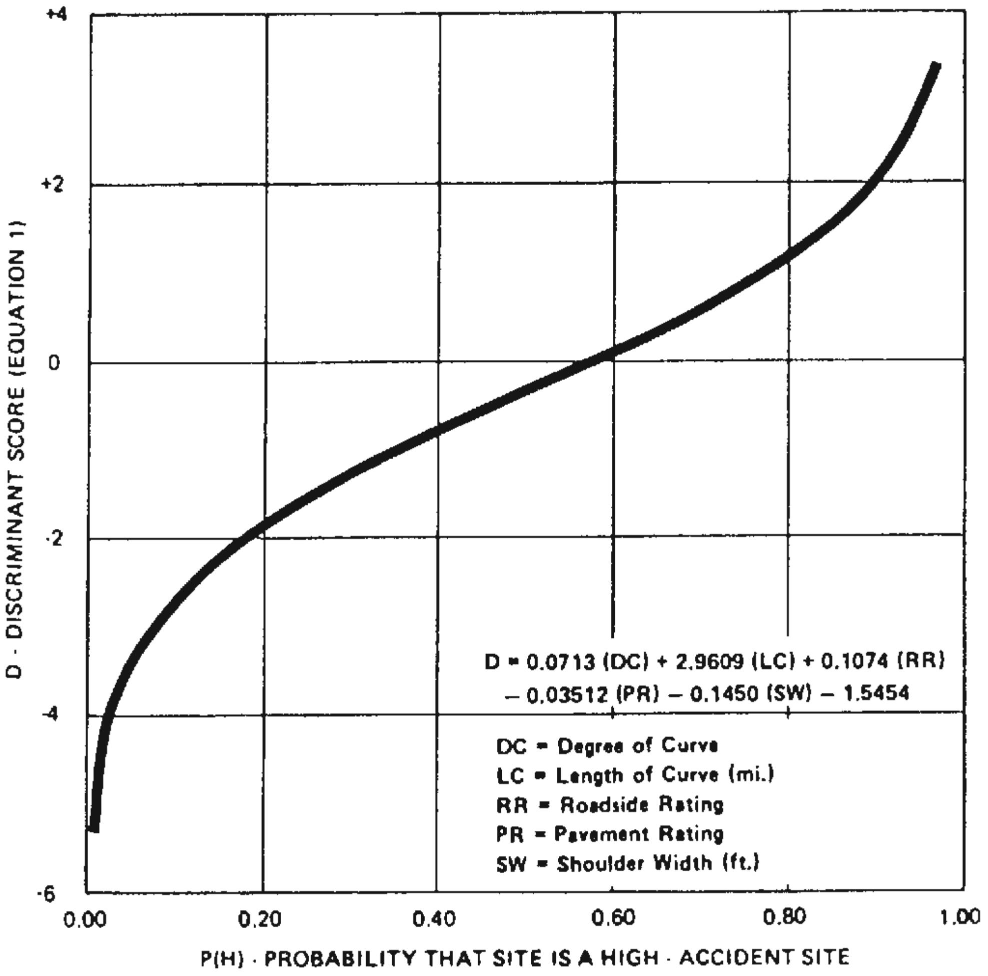

Figure 1. Relationship between discriminant score and the probability that a site is a high-accident site.[5]

width from the road to roadside objects. Values of roadside hazard between 24 and 53 percent can be selected from table 5. The study found that hazardous roadside designs represents the largest contributor to high-accident experience at highway curves.

Accident reductions from curve improvements

The accident effects of various geometric curve features were quantified in a 1991 study for FHWA by Zegeer, et al.[6] The primary data base developed for the accident analysis consisted of 10,900 horizontal curves in Washington State with corresponding traffic, accident, and geometric characteristics of each curve.

The following mathematical model was developed from that study for predicting accident occurrence on curves:[6]

$$A = [(1.552)(L)(V) + .014\,(D)(V) - (.012)(S)(V)](.978)^{W-30}$$

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).

Table 5. Roadside hazard ratings.[5]

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

Coverage Factor is the probability that a vehicle reaching the clear-zone width will impact a fixed object.

D = degree of curve.

S = presence of spiral, where S=zero if no spiral exists, and S=1 if there is a spiral.

W = width of the roadway (lane width plus shoulder width) on the curve in ft.

Note that curve accidents are related to both the degree and length of curve, a finding that is consistent with an earlier FHWA study.[5] Other factors related to curve accidents include total roadway width, the presence of a spiral, and total traffic volume. This model form is similar to that developed by Deacon in a 1986 study.[12]

Accident reduction factors were developed based on this predictive model regarding geometric improvements at horizontal curves on two-lane rural roads. These accident reduction factors, given in tables 6 through 10, correspond to expected percent reduction in total curve accidents.[6]

Curve flattening. Previous studies show clearly that sharper curves are associated with higher accident rates than milder ones.[5,6,9,12] Greater speed reductions for approaching vehicles are also associated with sharper curves.[5] Curve flattening refers to reconstructing a horizontal curve to make it less sharp (i.e., longer with a lower degree of curve). Expected accident reduction factors are given in table 6 associated with flattening curves for various degrees of curve before and after improvement and for central angles of 10 to 50 degrees. The table shows percent reductions separately for isolated curves and non-isolated curves, where an isolated curve is defined as one having tangents of 650 ft or more on both ends of the curve.

To illustrate the use of table 6, assume a 10-degree curve with a 30-degree central angle having approach tangents of 1,200 ft in one direction and 1,650 ft in the other direction. The curve is thus considered to be isolated (i.e., both approach tangents are greater than 650 ft). Consider a project that would flatten the curve from 10 degrees to 5 degrees with the central angle remaining at 30 degrees. From table 6, 48 percent of the total curve accidents would be expected to be reduced from the project. The authors of the study point out that due to high construction costs for curve flattening, such improvements are more practical when a sharp or poorly designed curve has an abnormally high accident experience.[6]

Roadway Widening on Curves. Wider lanes and shoulders on curves are also associated with a reduction in curve-related accidents. Percent reductions in total accidents are given in table 7 for improvements involving widening lanes and/or shoulders on horizontal curves.[6] From the left column of the table, the user should select the amount of lane or shoulder widening that is proposed for the project.

The columns in table 7 provide the expected percent reduction in total accidents for widening lanes, paved shoulders, and unpaved shoulders, respectively. For example, assume a 20-ft roadway (i.e., two 10-ft lanes with no shoulder) which is to be widened to 22 ft of paved surface with 8 ft gravel shoulders (i.e., 16 total ft of shoulder widening). From table 7, these improvements would reduce curve accidents

Table 6. Accident reduction factors for flattening horizontal curves.[6]

Degree of Curve		Percent Reduction in Related Accident Types for Central Angle in Degrees									
		10°		20°		30°		40°		50°	
Original	New	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

NOTE: The central angle refers to the angle which would be formed by extending the tangents on either end of the curve.

Table 7. Percent reduction in accidents due to lane and shoulder widening.[6]

Total Amount of Lane or Shoulder Widening (ft)		Percent Accident Reduction		
Total	Per Side	Lane Widening	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

by 5 percent (due to lane widening) and 24 percent due to widening unpaved shoulders by 8 ft. Note that the 5-percent and 24-percent accident reduction values cannot merely be added numerically. The proper procedure for combining two or more accident reduction factors is discussed elsewhere.[14]

Spiral transitions. A 1983 FHWA study by Glennon, et al. found a measurable operational benefit of spirals. Drivers were found to position themselves in advance of the curve to effect a spiral transition.[5] Based on computer simulation, the authors concluded that adding spiral transitions to highway curves dramatically reduces the friction demands of the critical vehicle traversals.[5]

These findings were supported by the 1991 FHWA study, which represents the first successful documentation of safety effectiveness for spiral transitions on high-speed horizontal alignment. The model for curve accidents revealed that spiral transitions reduced curve accidents by 2 to 9 percent, depending on degree of curve and central angle.[6] The researchers determined that an accident reduction of 5 percent of total accidents was most representative of the effect of adding spiral transitions on both ends of a curve on two-lane rural highways.

Providing a spiral transition curve to an existing curve may be accomplished in conjunction with a routine 3R (resurfacing restoration, and rehabilitation) project, particularly where a curve flattening and/or curve widening improvement is proposed.

Superelevation improvements. Superelevation is the amount of "banking" of the curve, or more specifically, the ratio of the difference in elevation on the outside of the curve compared to the inside of the curve divided by the road width. It is measured in ft per ft, since it represents ft of elevation difference per ft of roadway width.

A number of studies have attempted to link superelevation to accident causation. One study by Zador noted deficiencies in available superelevation at fatal accident sites, compared with nearby control sites.[13]

In the 1991 FHWA study, a small but significant accident effect of too little superelevation was noted.[6] The authors concluded that curve sites with a superelevation "deficiency" had significantly worse accident experience than curves with a proper amount of superelevation. The superelevation deficiency, e_D, was defined as the difference between the recommended superelevation according to the American Association of State, Highway and Transportation Officials (AASHTO) Greenbook, e_R, and actual superelevation e_A; or $e_D = e_R - e_A$. The percent reduction in total curve accidents due to improving superelevation is shown in table 8. For example, assume the actual superelevation (e_A) on a curve is 0.04 and the AASHTO recommended superelevation (e_R) for a particular curve design is 0.06. This corresponds to a superelevation deficiency (e_D) of 0.02. According to table 8, a 10-percent reduction in total curve accidents could be obtained if proper superelevation is provided to the horizontal curve. Such improvements to superelevation should be made to curves whenever the roadway section is resurfaced, according to the study.

Table 8. Accident reduction factors for upgrading superelevation on existing horizontal curves.[6]

e_D[a]	Percent Reduction in Total Accidents Due to Upgrading Superelevation
.01 to .019	5
$\geq$ .02	10

[a] e_D = recommended - actual superelevation

It should be noted that the 1991 study also investigated the safety effect of too much superelevation. No adverse effects were found based on available data. Current design policy is implemented with an assumed upper limit on superelevation for areas with snow and ice. The presumption is that excess superelevation produces sliding down the curve under low-speed conditions, and hence increases accident potential. While this condition could theoretically occur at low-speed curve locations with sharp curvature and a high rate of superelevation, no evidence was found of any such significant adverse safety effects.

Roadside Improvements on Curves. The 1991 FHWA study model did not reveal a sensitivity of curve accidents to roadside condition, primarily because of the lack of variation in roadside condition of the sample (i.e., most curves had a relatively similar level of roadside hazard). The authors derived expected accident reductions due to roadside improvements based on such reductions found in an earlier study on two-lane rural roads and adjusting those values to correspond to total curve accidents.[6,15]

Accident reduction factors given in table 9 correspond to increasing the clear roadside recovery distance on a horizontal curve. Such roadside improvements include removing trees, relocating utility poles, providing traversable drainage structures, flattening roadside slopes, and relocating utility poles or other obstacles further from the roadway. Thus, an increase in recovery distance of 5 ft (e.g., increasing roadside clear distance from 7 to 12 ft) would be expected to reduce total curve accidents by 9 percent. Providing 20 ft of additional roadside recovery distance should reduce total curve accidents by 29 percent.

The percent reduction in total curve accidents due to flattening sideslopes on curves is given in table 10. The sideslope in the before condition is found in the left

Table 9. Accident reduction factors for increasing roadside clear recovery distance on curves.[6]

Amount of Increased Roadside Recovery Distance (ft)	Percent Reduction in Total Curve Accidents
5	9
8	14
10	17
12	19
15	23
20	29

column and the proposed sideslope is given across the top of the table. The number in the table corresponding to these two values yields the expected reduction in total curve accidents. For example, flattening a roadside slope from 2:1 to 6:1 on a horizontal curve would be expected to reduce total curve crashes by approximately 12 percent.

Table 10. Accident reduction factors for flattening sideslopes on curves.[6]

Percent Reduction in Total Curve Accidents				
Sideslope in Before Condition on Curve	Sideslope in After Condition			
	4:1	5:1	6:1	7:1 or Flatter
2:1	6	9	12	15
3:1	5	8	11	15
4:1	-	3	7	11
5:1	-	-	3	8
6:1	-	-	-	5

General Alignment

Although each element may be designed separately, the effect that vertical and horizontal alignment have on each other in combination should be carefully considered in highway design. It is desirable that they increase safety and encourage uniform speed along a highway section. Poorly designed vertical and horizontal alignment combinations can detract from the desirable features and aggravate the deficiencies of each. Instead, vertical and horizontal components should complement each other.

The simplest and most widely used common denominator between vertical and horizontal alignment is the design speed of the roadway. Design speed is considered when determining the general location of a highway facility, but normally it assumes greater importance as designs proceed to more detailed alignment. The speed finally chosen acts to keep all elements of the design in balance.[16]

A study conducted by Zador, et al, evaluated the effects of vertical and horizontal alignment on safety by studying accident histories of several sites in New Mexico and Georgia.[17] The results of the study in both States indicated that sharp left hand curves and sharp downgrades are considerably more common at crash sites than at any of the other site types. In New Mexico, the 10th percentiles of curvature and grade at crash sites were 5 degrees and -4 percent, respectively. Sections that exceeded both of these values had fatal rollover crashes about 15 times as frequently per volume of travel as did average sections. This combination accounts for approximately 3.5 percent of all fatal rollover accidents in the State. In Georgia, the 10th percentile curve and grade were 6.4 degrees left and -3.3 percent, respectively. Sections that exceeded this combination accounted for 4.6 percent of all fatal rollover accidents in the State. In both States, these sites accounted for approximately 0.25 percent of all travel volume and less than 1 percent of all roadway miles, thus indicating a very high over-involvement of crashes at these sites.[17]

The study concluded by outlining a four step procedure that States can use to assess the importance of improving road sections with particularly undesirable combinations of vertical and horizontal alignment. The steps are: 1) collect a geometric inventory of short roadway sections that include potential candidates for improvement; 2) collect geometric data on crashes that have occurred, and estimate over-involvement; 3) define types of candidate sites in terms of the extent of estimated over-involvement rates; and 4) identify individual candidate sites for improvement. This could include sites that had crashes as well as sites with adverse geometry but no crashes.[17]

In another study, Dunlap et. al. researched and developed tentative guidelines for highway geometrics and pavement surface characteristics to ensure adequate vehicle control during maneuvers on highway sections with combined vertical and horizontal alignment.[18] Accident data files for the Ohio and Pennsylvania Turnpikes were established and analyzed to obtain a relationship between vertical and horizontal alignment and accident experience. In addition, field studies on the Ohio Turnpike and I-95 in Virginia were conducted to identify those characteristics having potential for producing accidents at these sites. It was determined that pavement width and cross slope are the primary factors affecting pavement surface drainage. The thickness of water film on long radius curves can be almost twice that on a crowned tangent section with the same cross slope.[18]

The essential conclusion from the combined accident analyses, simulation studies, surface drainage studies, and field investigations is that drainage of the pavement is a very important consideration that sometimes is overlooked in pavement cross section design. Water thickness on the pavement has a critical influence on the friction available at the tire-surface interface and thus the operation of the vehicle. The findings of the study do not indicate that the AASHTO design formula for horizontal curves should be modified for application to highway sections with combined horizontal curvature and vertical grade. However, increased emphasis should be placed on adequate pavement surface drainage, particularly on long-radius curves and other locations where drainage length is longer than one lane width. In addition, pavement surface skid resistance should be larger than the desired minimum for tangent sections on those sections of highway, such as downgrade curve sites, where operating conditions impose a greater demand force at the tire-surface interface.[18]

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