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Highway Alignment and Superelevation: Some Design-Speed Misconceptions

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Horizontal alignment and superelevation of curves have an impact on the traffic safety performance of highway sections. Research that relates traffic safety to roadway horizontal alignment has consistently shown that traffic accidents increase with increasingly sharper curves. Sharp curves in segments that otherwise have good alignment tend to surprise drivers and create even more hazardous situations. Consistency in design speeds along significant sections of highways has been advocated by some as a means of controlling the incidence of surprise curves in otherwise gentle alignments. However, design speeds for horizontal curves are a function of the maximum superelevation policies adopted by a design agency. Therefore, a single curve design may be regarded as having different design speeds by agencies that have different maximum superelevation policies. For this reason, the use of design-speed criteria for identifying potentially hazardous horizontal alignments would not appear to be appropriate. This finding is discussed in relation to the resurfacing, restoration, and rehabilitation projects proposed by the American Association of State Highway and Transportation Officials.

In recent years the highway design community has focused its attention on the development of geometric standards for the rehabilitation of existing highways. One important element in the improvement of roadways is the elimination of horizontal curves that, because of their geometric design, have created hazardous situations for the motorist. This paper outlines some of the research that has related safety to horizontal alignment of roadways and examines differences in current design policies of the states. Emphasis is placed on nonfreeway locations so that the resultant material would be relevant to resurfacing, restoration, and rehabilitation (3R) improvements of two-lane rural roadways.

The literature relative to alignment and superelevation shows that the highway research community is in basic agreement that roadway alignment is a key factor in unsafe vehicular operation. Increasing degrees of curvature cause more accidents. Single sharp curves in a highway system, generally characterized by long tangents and flat curves, create hazardous situations. Horizontal curvature may have the highest correlation with accident rates of major geometric characteristics for two-lane rural roads.

An examination of design practices in various states indicated a substantial difference in the manner in which horizontal alignment and superelevation is provided for the driver. Some states employ transition or spiral curves normally in design, others do not. Treatment of superelevation runout or transition also varies from state to state.

Perhaps the most significant variation in state design practices, however, is the assumption employed by various states regarding the maximum allowable superelevation on curves. This assumption has a direct bearing on the meaning of the term design speed for a curve and hence could have significant impact on any national 3R program for highways.

The following pages support the contention that highway alignment is related to safety performance. The issue of design speeds and 3R improvements will be touched on and some problems pointed out with respect to current definitions of design speed for specific curves. A review of basic highway curve formulas will be given and an analysis of how design speed changes with respect to maximum superelevation will be presented. Finally, some conclusions will be offered that relate 3R improvements to some general misconceptions about what design speeds really mean and how they relate to the dynamics of vehicles on curves.

SAFETY RESEARCH AND HIGHWAY ALIGNMENT

Research into the relationship between accident rates and highway curvature has been consistent in the finding that increasing curvature causes increased accident rates. Several studies have been summarized by Leisch (1) in the chart reproduced as Figure 1. A recent National Cooperative Highway Research Program (NCHRP) report by Jorgensen (2), which used information developed by Coburn (3), arrives at identical conclusions for rural roads. An extensive study by Taragin (4) on driver performance on horizontal curves noted that the sharper the curve, the closer drivers will operate their vehicles at speeds that approach the safe speed. Therefore, the margin for error for sharper curves is less than for flat curves. These findings led to the adoption of American Association of State Highway Officials (AASHO) policies as early as 1954 that specify that (5, p. 79) "Every effort should be made to use as high a design speed as practicable to attain a desired degree of safety, mobility, and efficiency."

The research literature offers some evidence that the frequency of curves within a roadway section also affects

Figure 1. Accident rate related to horizontal curvature.

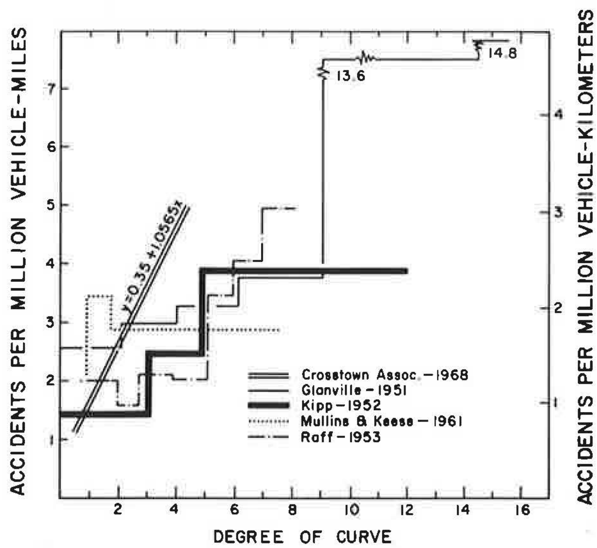
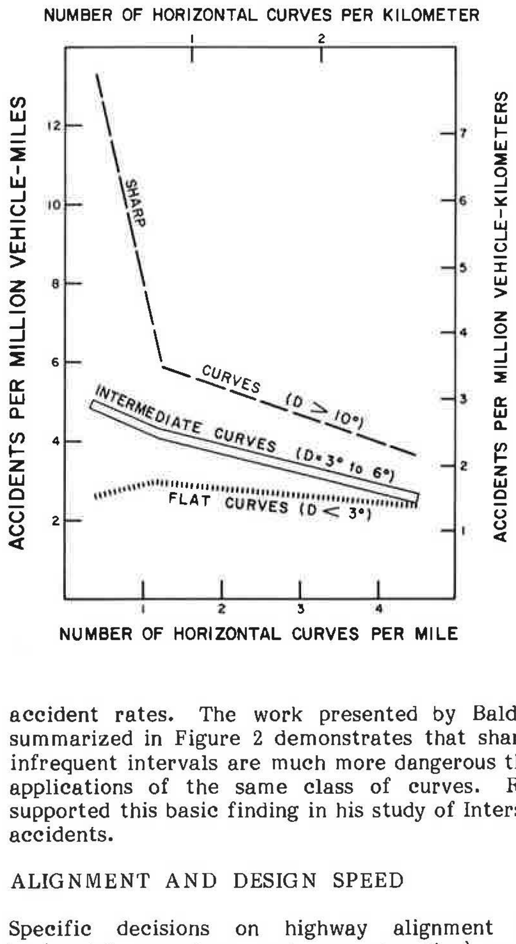


Figure 2. Accident rate related to curve frequency.



accident rates. The work presented by Baldwin (6) and summarized in Figure 2 demonstrates that sharp curves at infrequent intervals are much more dangerous than frequent applications of the same class of curves. Raff (7) has supported this basic finding in his study of Interstate system accidents.

ALIGNMENT AND DESIGN SPEED

Specific decisions on highway alignment (degree of horizontal curvature and superelevation) are based on assumptions about design speed. Therefore, it is useful to review the definition of design speed and its subsequent application to curve design.

AASHO defines design speed as follows (8, p. 283), "Design speed is the maximum safe speed that can be maintained over a specified section of highway when conditions are so favorable that the design features of the highway govern."

This definition differs from that offered in a 1940 AASHO publication (9, p. 8), which stated that

> The assumed design speed of a highway is considered to be the maximum approximately uniform speed which probably will be adopted by the faster group of drivers but not, necessarily, by the small percentage of reckless ones.

The proposed rules issued by the Federal Highway Administration (FHWA) on August 23, 1978, that govern 3R design standards offer some additional information on design speed with the following sentence (10): "The purpose of a design speed is to correlate those physical features of a highway that influence vehicle operation."

The choice of what design speed to use for a highway section is a function of the type of highway and the terrain. This basic assumption for the entire highway section is used in the design of most highway elements to achieve a balanced design. The alignment features of a roadway (i.e., horizontal curvature and superelevation) are directly related to (and change significantly with) the design speed.

Essentially, the design speed, when combined with a maximum allowable superelevation, fixes the maximum degree of curvature that may be employed in a highway section. The maximum degree of curvature employed in a highway section has a profound effect on section costs and, as noted in the research literature, a significant impact on operating safety. It seems obvious that any major rehabilitation program for a length of highway would be initiated by relating inconsistencies in design speed to traffic accidents in an attempt to provide a balanced design and improve safety.

3R IMPROVEMENTS AND HIGHWAY ALIGNMENT AND SUPERELEVATION

The American Association of State Highway and Transportation Officials (AASHTO) 3R guide (11) recognizes the need for improvements to highway alignment and superelevation. A primary objective listed in the guide is the improvement of superelevation on curves. This manual also classifies the improvement of an isolated curve as a 3R project that could result in considerable traffic operational improvement. The guide further states that (11) "Every attempt should be made to maintain a uniformly safe running speed for a significant segment of highway."

Rules proposed by FHWA echo the AASHTO guidelines on this point. In addition, FHWA-proposed rules suggest the collection of field data on average running speeds to determine how the existing or proposed design speed relates to actual operations. The rules note that (10) "Application of an ideal design speed that has no relationship to the speeds actually found on an existing highway would be arbitrary."

DESIGN-SPEED PROFILES

One way to identify problem alignments within a highway system would be to display the design speed of each component graphically and look for discontinuities in the design-speed curve.

On the surface, such a procedure would seem to be a quick way to spot problem areas in existing design by using readily available information (design drawings). For analysis of horizontal curvature, the analyst takes curve parameters (degree of curvature and superelevation) and solves for design speed by using standard curve design tables. The relation of the design speeds of individual highway elements to the entire system ought to give some indication as to where drivers are surprised and consequently have less of a safety margin.

This procedure is suggested in the proposed FHWA rules and some limiting values given as to the permissible disparities between specific highway components (curves) and the generally assumed design speed (10). If a difference

Table 1. Comparison of design speeds for identical curves under different e_{max} values.

Degree of Curvature	Actual Superelevation (m/m)	Design Speed (km/h)			
		e_{max} = 0.06	e_{max} = 0.08	e_{max} = 0.10	e_{max} = 0.12
3	0.05	89	79	72	69
8	0.05	56	47	45	43
10	0.05	50	43	42	40
3	0.06	113	89	80	77
8	0.06	72	55	48	47
10	0.06	64	48	45	43
3	0.08	NA	121	98	92
8	0.08	NA	79	63	56
10	0.08	NA	68	55	51

Note: 1 m = 3.28 ft; 1 km/h = 0.62 mph.

of less than 24 km/h (15 mph) exists between the calculated design speed for a curve and the designated design speed of adjacent sections, the curve ought to be signed and marked accordingly. If a difference of more than 24 km/h exists for horizontal curves, corrective work should be undertaken.

Problems with the Design-Speed Concept for Horizontal Curves

The design speed for a curve is perceived by most designers to represent the maximum speed of safe vehicular operation. This is probably true because most textbooks or geometric guidelines begin their discussion of horizontal alignment with a presentation of the basic formula that governs the dynamics of vehicles on curves:

$$e + f = V^2/127.5R \tag{1}$$

where

- e = rate of roadway superelevation (m/m),
- f = side-friction factor,
- V = vehicle speed (km/h), and
- R = radius of the curve (m).

From this basic formula and assumptions regarding safe side-friction factors and maximum superelevation rates, tables of acceptable curve geometrics have been developed and adopted for use in highway designs. For a given design speed and maximum allowable superelevation, the designer can easily determine the appropriate range of curve radius (or degree of curve) and the superelevation rate. One would normally assume that the geometrics of these curves are related in some consistent manner to the initial formula that governs the dynamics of vehicles on curves.

The problem is that they are not consistently related. Design speeds on curves are not representative of the maximum permissible safe speed as expressed by the formula. In fact, identical curves located in two different states can have different design speeds.

Put more precisely, a curve with a fixed degree of curvature and superelevation rate can be considered to have different design speeds, depending on the state criteria that have been used to design the curve.

Curve Design Speeds Differ by State

The theoretical design speed for a given curve geometry is also a function of the maximum superelevation rate permitted in that state. Each state chooses what maximum superelevation rate is appropriate to its particular terrain and condition. Generally, the maximum allowable superelevation is chosen after consideration of the climatic condition of the state. States that have a high incidence of snow and ice conditions typically adopt low maximum superelevation rates. States that have more temperate climates opt for higher rates. A range of current state practice is shown in the following table:

State	Maximum Superelevation Permitted (%)
California	8-12
Florida	10
Illinois	8
Indiana	8
Kentucky	10
New York	8
Ohio	8.3
Pennsylvania	8
Texas	8-12
Washington	10
Wisconsin	8

The maximum superelevation rate has an impact on the curve geometrics because of the manner in which superelevation and side-friction factors interact to keep the vehicle from leaving the curve. The maximum allowable degree of curvature for a specific design speed can be computed by using the maximum allowable superelevation and the maximum side-friction factor. The formula can be expressed as follows:

$$D = 222\,480(e + f)/V^2 \tag{2}$$

where

- D = the degree of curvature,
- e = superelevation (m/m),
- f = the side-friction factor, and
- V = the design speed (km/h).

The maximum side-friction factor is assumed to vary with speed according to the following:

$$f = 0.19 - 0.000\,62V \tag{3}$$

where V is speed in km/h. Therefore, to solve for maximum D for a specific design speed (V), one uses the following expression:

$$D_{max} = 222\,480(e_{max} + 0.19 - 0.000\,62V)/V^2 \tag{4}$$

The problem of different design speeds for identical curves comes about because of the assumptions employed by AASHO about the relation of e and f for curves below the maximum degree of curvature for that speed for the geometric design of rural highways (12). The assumption is made that friction factors vary in curvilinear fashion with the degree of curve between the limits of e equal to zero and e_{max}. Therefore, for different e_{max} values, the curve takes on a different shape and hence affects the curve geometry.

Comparisons of Curve Design Speeds

Table 1 illustrates the magnitude of the difference in design speeds derived from constant curve geometry. The design-speed values are taken from the curves presented in the AASHO rural highway policy (12, pp. 163-166).

An examination of this table shows that differences between design speeds are substantial, depending on the maximum superelevation that is assumed. For differences in maximum superelevation of 0.06-0.12 m/m, the design speed varies by a maximum of 35 km/h (22 mph) (see 3° curve, e = 0.06).

As curves get flatter (D becomes smaller), the differences between design speeds become greater. Also, as the actual superelevation increases, the disparity between design speeds becomes greater.

CONCLUSIONS

The following statements serve to sum up this analysis of alignment and superelevation.

1. Highway alignment is definitely a causal factor in highway accidents: Curves surprise drivers. This leads to driver error and accidents. The sharper the curve, the higher the accident rate. Sharp curves in the middle of long segments that do not have speed-impeding environments are the worst curve-related safety problem.

For 3R programs to be effective, the locations that have alignment discontinuities associated with them should be identifiable. This identification might come from an analysis of highway plans, accident statistics, or over-the-road inventory techniques.

2. Design speed for a curve is not a limiting speed that is indicative of the maximum safe operating speed of the curve: The method used by most states to distribute the maximum superelevation throughout the range of intermediate curve radii has weakened the relationship between design speed and the limiting speeds suggested through the laws of physics. Because different states employ differing rates of maximum superelevation, the same curve can have different design-speed values in different states.

3. Tying 3R improvements to design speeds on curves can lead to inequities between states: Because the same curves can have different design speeds, depending on the maximum permitted superelevation, the adoption of a uniform policy for rehabilitation based on design speeds would be inconsistent. States that have lower e_{max} standards will show higher design speeds for a given curve than those states that have higher e_{max} standards.

Therefore, an analysis of the highway system that compares design speeds of curves to adjacent sections and a standard that attempts to improve situations with large disparities would penalize states that have high maximum permitted superelevation. Those states would show higher deviations from a uniform design-speed policy for an identical roadway section simply by virtue of their design policy.

4. Surprise curves and other geometric conditions that lead to improper average running-speed transitions need to be remedied; however, comparisons of design speeds are not the appropriate measures. The disparity between the maximum safe speeds as derived from the standard curve formula and that of the design speed is large. Therefore, comparisons of design speeds are not appropriate. However, some means of determining the impact of individual geometric elements on average vehicular speed performance must be developed and applied.

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Effect of Shoulder Width and Condition on Safety: A Critique of Current State of the Art

CHARLES V. ZEGEER AND DAVID D. PERKINS

A critical review was conducted of available studies on the effect of shoulder width and condition on safety. A set of criteria was established for use in evaluating the reliability of the conclusions reported in past studies on this subject. Most studies based conclusions on the analysis results of pre-1955 accident data and only two of them considered the effect of shoulder width on related accident types (run-off-the-road and head-on accidents). Several studies did not control for the effect of intersections and differing roadway alignment (tangent or curved sections) on rural highway accident rates. Wider shoulders were found to be associated with safer conditions in the studies that were judged most reliable. Shoulder stabilization was effective in reducing accident rates on two-lane roads, particularly on identified high-accident sections. Shoulder widening was found to be cost effective on high-accident sections that had shoulder widths less than 1.2 m (4 ft). In particular, sections of rural two-lane roads that had six or more run-off-the-road or head-on accidents per 1.6 kilometer per year were likely to result in benefit/cost ratios greater than one. Shoulder widening was not cost effective, however, for low-volume roads (less than 1000 vehicles/day) that had a low frequency of accidents. Shoulder paving or stabilization is generally desirable from a safety standpoint, although its cost-effectiveness is not well established. Rural winding highway sections and sharp horizontal curves were recommended as the best