Horizontal Curve Design: An Exercise in Comfort and Appearance

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AASHTO's 1990 *A Policy on Geometric Design of Highways and Streets* contains information on procedures for three superelevation designs: rural highways and high-speed urban streets, low-speed urban streets, and curvature of turning roadways and curvature at intersections. The history of the horizontal curve design procedures through the published policies (1940 to 1990) is reviewed, the findings from the literature on key issues are presented, and additional research needs on side friction factors and transition length determination are discussed. The side friction factors used in high-speed and low-speed design were determined by using vehicle occupant comfort as the selection criterion. This criterion assumes that drivers limit their speed on curves to ensure comfort and that discomfort is directly related to the unbalanced side friction. Several concerns or issues accompany these assumptions. For example, the speed at which discomfort (or side pitch) first becomes noticeable may be slower than necessary for comfort or safety, and the level of discomfort felt by a driver may not be solely related to side friction only. These assumptions also do not directly consider vehicle characteristics or constant safety factors over the range of design speeds. Transition length determination for high-speed and intersection design is based on appearance and comfort. The criterion was developed to avoid an appearance that results from too rapid a change in superelevation. For low-speed design, a change in acceleration over the change in time factor, known as *C*, is used to determine superelevation runoff. High-speed design includes factors that are to be used to determine runoff lengths for roads with more than two lanes. Low-speed design does not include similar factors that adjust for wider pavements; however, it does include a method for adjusting runoff length for radii larger than the minimum that the high-speed design procedure does not include. Three research areas were identified on the basis of the present findings: (a) selection of side friction factors, (b) determination of transition lengths, and (c) evaluation of the need for and basis of the three different design procedures (high speed, low speed, and curvature at intersections). Research is needed in these areas because current practice is largely based on limited empirical data and existing practice without supporting material. Efforts to address these issues would require substantial funds.

Highway geometric design and safety issues are a constant challenge. Many of the concerns facing the industry today also were a problem in the 1920s and 1930s. In the early part of the century the existing system needed to be reconstructed to accommodate the needs of motorized vehicles rather than horse-drawn traffic. The surfaces needed to be stronger and the alignment redesigned to accommodate higher operating speed. During these early road-building days, procedures for horizontal curve and superelevation design were developed. In the design of roadway curves, it is necessary to establish the proper relationship of speed and curvature with superelevation and side friction. Although these relations stem from the laws of mechanics, the actual values selected for the design depended on practical limits and factors determined more or less empirically over the range of variables involved.

AASHTO's 1990 *A Policy on Geometric Design of Highways and Streets* (*1*) (commonly called the Green Book) includes information on three superelevation design procedures:

- Rural highways and high-speed urban streets,
- Low-speed urban streets, and
- Curvature of turning roadways and curvature at intersections.

These procedures are referred to in this paper as high-speed, low-speed, or intersection design, respectively. The high-speed design is for use on all rural highways, on urban freeways, and on urban streets where speed is relatively high and relatively uniform. Low-speed design is used for through roads and streets in urban areas where the use of superelevation is impractical and where drivers have developed a higher threshold of discomfort. Intersection design is used for curvatures of turning roadways and curvatures at high-speed, at-grade intersections.

The objective of the study (*2*) that formed the basis of this paper was to identify the research needs in horizontal curve design by using information from a historical review and a literature search on horizontal curve design. The historical review identified how the current procedures were developed and how the procedures have evolved over the past 80 years. This review was conducted primarily by reviewing seven different design policies (*1,3–8*) and early textbooks. The literature review provided information on the issues examined and also assisted in identifying and clarifying the issues needing additional research.

OVERVIEW OF SUPERELEVATION

When a vehicle moves in a circular path, it is forced radially outward by centrifugal force. Superelevation is the rotating of the roadway cross section to offset the centrifugal force acting on a vehicle traversing a curved section. For each combination of curve radius and travel speed, there is a specific superelevation that will precisely balance the centrifugal force. When a vehicle travels at speeds greater than those at which the superelevation balances all of the centrifugal force, side friction is needed to keep the vehicle on the curved path.

Point-Mass Equation

In the design of highway curves, a mathematical relationship exists among design speed, curvature, superelevation, and side friction. When a vehicle moves in a circular path, it is forced radially

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outward by centrifugal force. The centrifugal force is counterbalanced by the vehicle weight component related to the roadway superelevation or the side friction developed between the tires and the surface or by a combination of the two. By using the laws of mechanics, the basic point-mass (curve) formula derived to represent vehicle operation on a curve is:

$$e + f = \frac{V^2}{127R} \quad (1)$$

where:

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

The above equation is used to determine the minimum radius of a curve for a specific superelevation rate and side friction factor. On the basis of accumulated research and experience, the Green Book presents limiting values for superelevation and friction. These values vary in the different design categories included in the 1990 Green Book (high speed, low speed, and intersection design).

Rates

If a radius selected for a curve is greater than the minimum radius determined from Equation 1, then the designer uses a superelevation rate that is less than the maximum superelevation assumed. Tables, figures, or both, are included in the Green Book for this purpose. These tables and figures were developed on the basis of an assumed distribution of superelevation rates and side friction factors. Several methods are available for distributing superelevation and friction over a range of curves.

The Green Book lists five methods: Method 1, straight-line relation; Method 2, counteracting the centrifugal force with friction up to the maximum friction and then using a straight-line relation, increasing superelevation as the curvature increases up to maximum superelevation; Method 3, counteracting the centrifugal force with superelevation only until maximum superelevation is reached and then using a straight-line relation, increasing friction as the curvature increases up to maximum friction; Method 4, same as previous method, except that the method is based on average running speed instead of design speed; and Method 5, a curvilinear relation between superelevation and side friction.

The curvilinear relation (Method 5) is assumed for high-speed design. Low-speed design has the centrifugal force counteracted with friction until maximum friction is reached and then uses superelevation (Method 2). Method 2 was selected because "drivers [in urban areas] are more tolerant of discomfort, thus permitting employment of an increased amount of side friction for use in design of horizontal curves."

Side Friction

The side friction factor represents the friction present between the tires and the surface that is counteracting the unbalanced lateral force on a vehicle negotiating a curve. The upper limit of this factor is the point at which the tire is skidding or the point of impending skid. Because, as the Green Book states, "highway curves are designed to avoid skidding conditions with a margin of safety, the friction values should be substantially less than the coefficient of friction of impending skid." The Green Book also states "the portion of the side friction factors that can be used with comfort and safety by the vast majority of drivers should be the maximum allowable value for design." The values present in the 1990 Green Book for high-speed design are at "the point at which the centrifugal force is sufficient to cause the driver to experience a feeling of discomfort and cause him to react instinctively to avoid higher speed." Figure 1 compares the different friction factors for the three design methods.

Transition

Transition consists of superelevation runoff and tangent runout. The 1990 Green Book defines *superelevation runoff* as the general term denoting the length of highway needed to accomplish the change in cross slope from a section with adverse crown removed to a fully superelevated section, or vice versa. *Tangent runout* is the general term denoting the length of highway needed to accomplish the change in cross slope from a normal crown section to a section with the adverse crown removed, or vice versa. Table 1 compares the superelevation runoff lengths determined for each design procedure by assuming a 64.4-km/hr (40-mph) design speed.

DESIGN PROCEDURES

Each of the three design procedures included in the Green Book has a unique history. Procedures for high-speed and intersection design were included in AASHO policies published in the 1940s [the 1945 *Design Standards (Geometric) for Highways (Primary)* (*5*) for high-speed and the 1940 *A Policy on Intersections at Grade* (*3*) for intersection design]. The low-speed procedures were introduced in the 1984 AASHTO policy (*8*). The following are summaries of the superelevation rates, friction, and transition design histories for each of the three design procedures.

High-Speed Design

Superelevation Rates

Superelevation rates of as high as 0.08 m/m (ft/ft) were used during the 1920s. The 1941 AASHO policy (*4*) stated that the maximum rate is 0.12 m/m (ft/ft), but if snow and ice conditions prevail, the 0.08-m/m (ft/ft) rate should be used. These recommended rates in high-speed design are also present in the current policy. The method for distributing superelevation rates over radii larger than the minimum radii have not changed since they were first introduced in 1954.

Friction

The side friction factors present in the 1990 Green Book were determined from an assumed straight-line relation of data points from several studies conducted in the 1930s and 1940s. One of

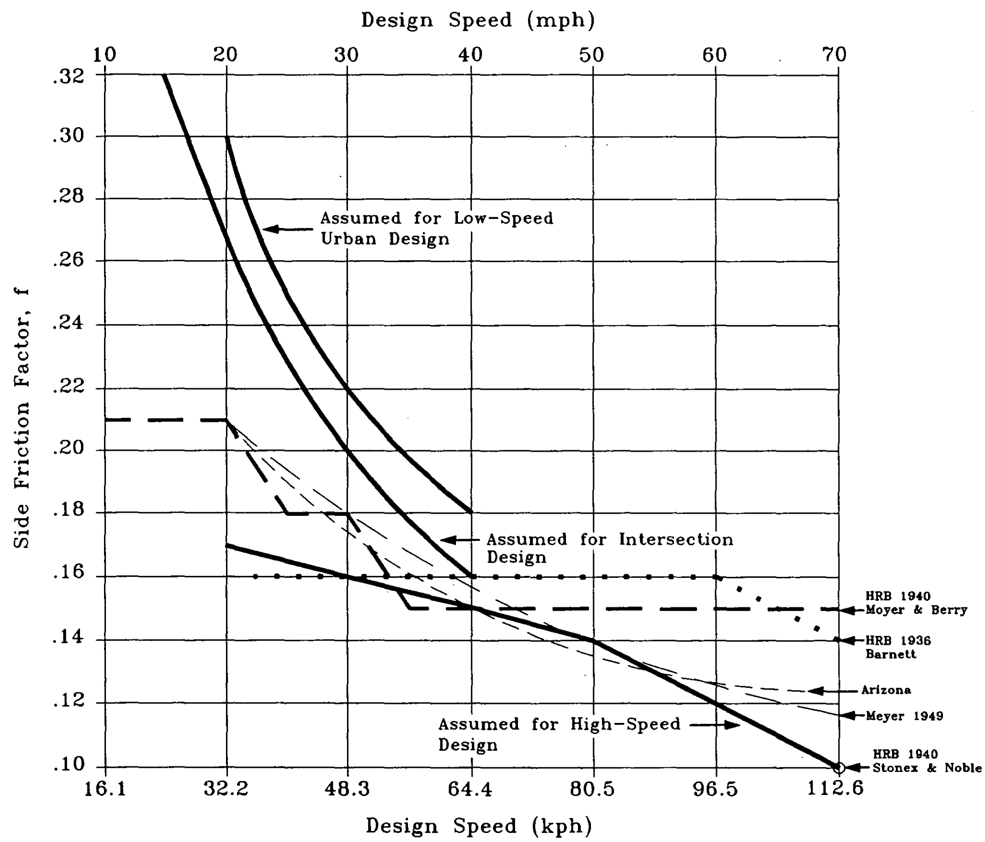

FIGURE 1 Comparison of friction factors.

TABLE 1 Comparison of Transition Designs

General assumptions: 64.4 kph (40 mph) design speed and 2-lane roadway with 3.7-m (12-ft) lanes		
High Speed Design	**Low Speed Design**	**Intersection Design**
Assumption Superelevation rate = 0.06	Assumption • Superelevation rate = 0.06	
Calculated/Determined • Friction factor = 0.15 (1990 Green Book Table III-6) • Minimum radius = 155.3 m (509 ft) (1990 Green Book Table III-6) • **Runoff length = 38.1 m (125 ft)** (1990 Green Book Table III-15)	Calculated/Determined • Friction factor = 0.178 (1990 Green Book Table III-6) • Minimum radius = 137.3 m (450 ft) (1990 Green Book Table III-6) • **Runoff length = 35.1 m (115 ft)** (1990 Green Book Table III-6)	Calculated/Determined • Friction factor = 0.16 (1990 Green Book Table III-17) • Minimum superelevation = 0.09 (1990 Green Book Table III-17) • Minimum radius = 131.1 m (430 ft) (1990 Green Book Table III-17) • Suggested **minimum length of spiral** (argued as what should be used as the transition length in previous editions of AASHTO Policies) = **48.8 m (160 ft)** (1990 Green Book Table III-18) • Maximum rate of change = 0.58 (1990 Green Book Table IX-13) calculation: **Runoff length** = 0.58 * 100 * 7.32 m * 0.06 = **25.5 m (84 ft)** • Note: the runoff length calculation is similar to the method used in high speed design except no discussion is included on a minimum runoff length.
Potential Changes • If the pavement is wider than two lanes, then use a 1.2, 1.5, or 2.0 conversion factor for a three-lane pavement, a four-lane undivided pavement, or a six-lane undivided pavement, respectively, to calculate the runoff length (1990 Green Book pages 178-179).	Potential Changes • If the radius used in the design is larger than the minimum radius of 137.3 m (450 ft), then the runoff length can be adjusted using information provided in the 1990 Green Book Figure III-20.	

those studies asked observers to report when they felt a "side pitch outward" when traversing a curve; another used a ball bank indicator and assumed that the 10-degree reading was the "value at which the driver of a car senses some discomfort and where the hazard of skidding off the curve becomes apparent." The factors based on those studies, which were not very different from the values included in the 1945 AASHO policy, were included in the 1954 AASHO policy. Only slight modifications of the friction values have occurred since then.

Transition Design

The 1-in-200 rate of cross slope change that is currently used to calculate superelevation runoff length [at the 80.4-km/hr (50 mph) design speed] was included in the 1941 AASHO policy. This rate is based on appearance; it determines a runoff length that is sufficient to avoid distorted appearance as the driver approaches a curve. Although the 1941 AASHO policy used the 1-in-200 rate for all design speeds, the 1954 AASHO policy used it for the 80.4-km/hr (50 mph) design speed and varied the rate for other design speeds. The 1954 AASHO policy also introduced a minimum runoff length that approximated the distance traveled in 2 sec at the design speed and factors for use in determining superelevation runoff lengths for roads with more than two lanes. The 1984 AASHTO policy included a discussion on determining the tangent runout.

Intersection Design

Superelevation Rates

The maximum superelevation rates listed in the AASHTO policies have not changed significantly in the past 50 or more years. In 1940, 0.10 m/m (ft/ft) was recommended for turning speeds of 64.4 and 80.4 km/hr (40 and 50 mph), and 0.05 m/m (ft/ft) "appears to be reasonable" for a turning speed of 48.3 km/hr (30 mph). The 1954, 1965, 1984, and 1990 policies contain similar material; the general range of maximum superelevation rates for curves is 0.06 to 0.12. The 1954 to 1990 policies include tables that list suggested superelevation rates in relation to design speed and radius of curve. These rates were "derived in much the same manner as for open highway curves."

Friction

The 1940 AASHO policy listed safety factors [1.3 at 32.2 km/hr (20 mph) to 1.6 at 80.4 km/hr (50 mph)] and coefficients of friction at impending skid. These values were multiplied to arrive at the design side friction factor used to determine minimum safe radii. The 1954 policy contained different friction factors than the 1940 policy and did not include a safety factor. The side friction factors were based on studies conducted to determine the distribution of speeds on intersection curves. A curve that "gives an average or representative curve" of the data and that used high-speed factors for one boundary and 0.5 for the other was drawn. Good (*9*), in his review of superelevation, commented that the plotted points represented averages of large vehicle samples, the scatter in the original data "would produce a diagram which defied the drawing of any trend line," and the apparent downward trend in the data depends rather critically on one or two data points. He also recommended [along with Harwood and Mason (*10*)] that a minimum radius is the result of a maximum assumed side friction factor and a maximum rather than a minimum superelevation rate. No changes to the information in the 1954 policy were made in 1965, 1984, or 1990 except for the addition of information on a 16.1-km/hr (10-mph) design speed in the 1984 and 1990 policies.

Transition Design

In the 1990 and 1984 AASHTO policies, superelevation runoff was calculated by using a "change in relative rate between the edge of a two-lane pavement and the centerline (in percent)." Earlier policies either used an equation commonly used to calculate a spiral (1940, 1954, and 1965 AASHO policies) or used a rate of cross slope change per 30.5 m (100 ft) of length (1954 and 1965 AASHO policies).

Low-Speed Urban Street Design

Procedures for low-speed urban street design were first introduced in the 1984 AASHTO policy. The reasons for the introduction of this new procedure in superelevation design were not included in the 1984 Green Book.

Superelevation Rates

The maximum superelevation rate listed in the 1984 and 1990 AASHTO policies is 0.04 or 0.06. The distribution of superelevation with curvature follows the assumption that the centrifugal force is counteracted in direct proportion by side friction up to the maximum assumed friction; then, superelevation is used in direct proportion until it reaches maximum superelevation.

Friction

The assumed friction curve (Figure 1) for low-speed urban design is "based on a tolerable degree of discomfort and provides a reasonable margin of safety against skidding under normal driving conditions in the urban environment." Explanations as to why different friction factors for low-speed versus high-speed or intersection design for a particular design speed exist, other than the above statement, are not provided [e.g., at 64.4 km/hr (40 mph), high-speed side friction is 0.15, intersection side friction is 0.16, and low-speed side friction is 0.178].

Transition Design

Superelevation runoff length is calculated by using an equation that includes a rate of change of the side friction factor called *C*. The *C* values are similar to the values used in the spiral length calculations in other sections of the policy; however, the source of the formula was not discussed in the policy. Detailed guidance on adjusting the lengths of superelevation runoff for radii that are larger than the minimum is provided.

RECENT RESEARCH

Several research studies have examined key components or issues of horizontal curve design. Following are summaries of the findings from research on friction factors and the point-mass equation. Another area of concern is how existing design practices affect trucks. A summary of findings from two research efforts on trucks is also included below.

Friction

Emmerson (*11*) in 1969 used car speeds on curves to calculate side friction factors. Approximately 80 percent of the vehicles experienced a side friction factor of less than 0.15 on curves with radii of between 351 m (1,150 ft) and 196 m (642 ft). Sites with very small radii [101 m (330 ft) and 21 m (70 ft)] had mean factors of 0.22 and 0.27, respectively. Glennon (*12*) in 1969 commented that the use of friction demand design values that correspond to that point at which side forces cause driver discomfort has no objective factor of safety relationship to the side friction capability of the tire-pavement interface.

Glennon and Weaver (*13*) conducted a study that examined vehicle paths, lateral skid resistance, and the need for safety margins. They recorded free-flowing vehicles on five horizontal curves to relate actual vehicle paths to the highway curve radius. Their data indicated that most vehicles experience their critical path maneuver near the beginning or end of the curve. Bell's (*14*) United Kingdom study in 1980 found results similar to those of Glennon and Weaver (*13*).

McLean (*15*) in 1983 argued that the side friction factor is a result of driver behavior rather than an explanation for it. His two major objections were that (a) there is no empirical evidence that drivers respond to actual or subjectively predicted side friction in the selection of curve speed rather than to some other parameter, and (b) owing to the interrelationship among speed, curve geometry, and side friction, attempts to represent driver behavior as a side friction-speed relationship may cloud the more fundamental issue of driver speed behavior and road conditions.

Lamm et al. (*16*), using regression models, compared side friction demand (determined on the basis of the radius and the superelevation present at the site and the 85th percentile speed) and the available or assumed side friction (determined on the basis of the procedures presented in the Green Book) for a range of degree of curve, operating speed, and accident rate values. They found that side friction demand exceeded the side friction assumed in the following situations: degree of curves greater than 6.5 degrees, curves with operating speeds of less than 80.4 km/hr (50 mph), and curves with accident rates of greater than 9.7 to 11.3 accidents per 10^6 vehicle km (6 to 7 accidents per 10^6 vehicle mi).

Point-Mass Equation

A 1980s FHWA study (*17,18*) found that the minimum level of tire-road friction identified for maintaining the stability of passenger cars was found to be equal to the "point-mass" design value for the curve. The minimum level of friction necessary for maintaining the stability of the five-axle tractor-semitrailer, however, was approximately 10 percent higher than the point-mass design value. The authors also concluded that no substantive evidence regarding friction factor dispersion could be identified to conclude that current highway curve design practice, on the basis of a point-mass formulation, should be modified to accommodate the observed wheel-to-wheel variations.

Truck Concerns

Harwood and Mason (*10*) and Harwood et al. (*19*) determined the margin of safety against skidding or rollover for a passenger car or truck on a horizontal curve and the speed at which skidding or a rollover would occur. They concluded that on lower-design-speed horizontal curves designed by using the high-speed design criteria, the most unstable trucks can roll over when traveling at as little as 8.0 to 16.1 km/hr (5 to 10 mph) over the design speed. This is a particular concern, they noted, on freeway ramps, many of which have unrealistically low design speeds in comparison with the design speed of the mainline roadway. In their analysis of superelevation design at intersections, Harwood and Mason (*10*) found that for design speeds of 16.1 and 32.2 km/hr (10 and 20 mph), a truck could skid or roll over by exceeding the design speed of a minimum-radius curve by 8.0 km/hr (5 mph) or less.

SUMMARY

The side friction factors that are currently used in the high-speed and low-speed design procedures were determined by using vehicle occupant comfort as the selection criterion. This criterion assumes that drivers limit their speed on curves to ensure comfort for the occupants of the vehicles, and discomfort is directly related to the unbalanced side friction. Several concerns or issues accompany these assumptions. For example, the speed at which discomfort (or side pitch) first becomes noticeable may be slower than necessary for comfort or safety, and the level of discomfort felt by a driver may not be solely related to side friction only. The above assumptions also do not directly consider vehicle characteristics or constant safety factors over the range of design speeds. Side friction factors for intersection design were based on studies conducted in the 1950s that determined the distribution of speeds on intersection curves.

The transition distance from a normal crown section to the superelevated curve for high-speed and intersection design is based on appearance and comfort. The criterion was developed to avoid an appearance that results from too rapid a change in superelevation. For low-speed urban street design, a change in acceleration over the change in time factor, known as *C*, is used to determine superelevation runoff. This *C*-factor is similar to the factor used to determine spiral lengths. High-speed design includes factors that are to be used to determine runoff lengths for roads with more than two lanes. Low-speed design does not include similar factors that adjust for wider pavements; however, it does include a method for adjusting runoff length for radii larger than the minimum that the high-speed design procedure does not include.

PROPOSED RESEARCH

Three research areas were identified on the basis of the findings of the present study. These areas are the selection of side friction factors, determination of transition lengths, and evaluation of the need for and basis of the three different design procedures (high speed, low speed, and curvature at intersections). Research is needed in these areas because current practice is largely based on limited empirical data and existing practice without supporting material. Different design criteria could also provide additional flexibility to a designer attempting to meet existing driveways or culverts when redesigning a roadway. The reader should note that efforts to address the following issues would require substantial funds and efforts.

Side Friction Factors Used in Superelevation Design

Problem

The side friction factors that are currently used in the high-speed and low-speed design procedures were determined by using vehicle occupant comfort (in the 1930s and 1940s) as the selection criterion. This criterion assumes that drivers limit their speed on curves to ensure comfort for the occupants of the vehicles, and discomfort is directly related to the unbalanced side friction. Several concerns or issues accompany these assumptions. For example, the speed at which discomfort (or side pitch) first becomes noticeable may be slower than necessary for comfort or safety, and the level of discomfort felt by a driver may not be solely related to side friction only. The above assumptions also do not directly consider vehicle characteristics or constant safety factors over the range of design speeds. Other issues that need to be investigated include whether vehicles in different lanes of a multilane roadway experience significantly different side friction forces, whether constant margin of safety values are needed, and if so whether these values should be based on trucks or passenger cars. The likelihood that vehicles will slide down an iced superelevated section when driving slowly or stopped and the combination of stopping friction needs and available side friction on a maximum-degree curve are other concerns expressed by designers.

Proposed Research

Evaluate the appropriateness of using comfort for a passenger car occupant in the selection of side friction factors. Identify and evaluate other potential criteria that could be used in selecting the side friction factors.

Different Design Procedures for Horizontal Curve Design

Problem

Currently, the Green Book includes three methods that can be used to design the superelevation of a horizontal curve: rural highways and high-speed urban streets, low-speed urban streets, and curvature of turning roadways and curvature at intersections. Are three different procedures justifiable? What should form the basis of each design procedure?

Proposed Research

The research should critically evaluate the existing horizontal curve design procedures (e.g., high speed, low speed, and curves at intersections) as well as investigate other potential procedures for designing a horizontal curve. It should also critically evaluate the basis of each design procedure. The research should conclude with a recommendation on what design procedures should be included in the AASHTO Green Book.

Transition Design

Problem

The transition distance from a normal crown section to the superelevated curve for open highway or high-speed design and for curves at intersections is based on appearance and comfort. The criterion was developed to avoid an appearance that resulted from too rapid a change in superelevation. For low-speed urban street design, a change in acceleration over the change in time factor, known as *C*, is used to determine superelevation runoff. This *C*-factor is similar to the factor used to determine spiral lengths.

High-speed design includes factors that are used to determine runoff lengths for roads with more than two lanes. Low-speed design does not include similar factors that adjust for wider pavements; however, it does include a method for adjusting runoff length for radii larger than the minimum that the high-speed design procedure does not include.

The use of runoff lengths that are shorter than the lengths provided in the Green Book could assist engineers in designing horizontal curves in developed areas where meeting existing cross-road grades is vital or in areas where the cost to purchase rights-of-way are high. Identification of the consequences of providing superelevation runoffs that are less than the values indicated in the 1990 Green Book is critical in making or supporting these design decisions.

Proposed Research

The research should critically evaluate current transition design for all three design procedures (high speed, low speed, and curvature at intersections) and propose and justify new transition lengths (or procedures to determine transition length). When transition lengths should or can be adjusted and by how much should also to be investigated and reported.

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