INVESTIGATION OF CURRENT AND PROPOSED SUPERELEVATION DESIGN PRACTICES ON ROADWAY CURVES

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ABSTRACT

A common feature of curve design standards of the United States, Germany, and the United Kingdom is designers' freedom in applying above-minimum values for curve radii. On the basis of research findings suggesting a strong dependence of operating speed on degree of curve, it appears that, if consistency rules are not applied, this freedom may result in unrealistic assumptions for operating speed, with potential implications for safety. In addition, a comparison of the assumed values of the side friction coefficient (f) with empirical data for f-values "acceptable" by drivers confirms that, even for minimum-radius curves, actual operating speeds are underestimated for design speeds below 90 kph (56 mph). Innovative approaches to curve design suggest that, in addition to the incorporation of explicit consistency rules in design guidelines, the link between curvature and speed should be taken into account. A design procedure reflecting the association between curvature and speed, as well as enabling simplification of the superelevation - curvature relationship, is suggested in this paper and compared to existing design guidelines. It is suggested that the advantages and disadvantages of reconsidering design values for the f coefficient could be discussed at a future stage.

INTRODUCTION

The basic principle of horizontal curve design is derived from application of the kinematics equation, according to which the total lateral acceleration, applied through pavement superelevation and tire-pavement friction on a vehicle negotiating a circular curve, should be equal to the centrifugal acceleration (CA) due to vehicle movement:

$$CA = \frac{V^2}{R} = (e + f) * g \qquad (1)$$

where V is vehicle speed, R is curve radius, e is pavement superelevation rate, f is the tire-pavement side-friction factor, and g is acceleration of gravity. Application of the above equation to S.I. units leads to the following expression:

$$V_d^2 = 127 * R * (e + f) \qquad (2)$$

where:

V_d is the design speed in kilometers per hour (kph)
R is the curve radius in meters (m)
e is the pavement superelevation rate (m/m)
f is the tire-pavement side friction coefficient

In United States practice, the equivalent formula is:

$$V_d^2 = \frac{85660 * (e + f)}{DC} \qquad (3)$$

where:

DC is the degree of curve, in degrees per 100-ft (30.5-m) arc
V_d is the design speed in miles per hour (1 mph = 1.6 kph).

In determining the minimum radius (R_{min}) for a given design speed (V_d), the following values for e and f are used:

(a) the superelevation rate is equal to a pre-specified maximum value, e_{max};
(b) the side friction coefficient is, usually, a decreasing function of the design speed.

Designers are generally allowed the freedom of applying flatter, above-minimum radii (or smaller degrees of curve) for the same design speeds. From the above formulae it follows that the sum of e+f (which corresponds to the total centrifugal acceleration as a fraction of the acceleration of gravity, g) is proportionally reduced. To achieve that reduction, it is common to apply lower values for e and to assume lower values for f. A limiting value for the superelevation rate is the e_{min}, which is the rate applied (for the purpose of drainage) in tangent sections. It is also noted that, for curve radii above a threshold value, the cross-section is a normal crown section as in tangents, providing negative ("adverse") superelevation of $e = - e_{min}$ for vehicles moving on the outside of a curve.

The above is an outline of the basic principles of curve superelevation design. Diverse procedures are applied in different countries regarding:

(a) maximum superelevation rates
(b) values of f in relation to the design speed
(c) application of e and f values in curves of above-minimum radius

For the above features, the procedures specified in the design guidelines of the United States, Germany and the United Kingdom are reviewed and discussed - along with relevant empirical findings - in the following chapters. Next, a set of improvements to curve superelevation design are presented, based on suggestions from research and on a proposal developed by the authors for treating above-minimum curve design and simplifying the curvature - superelevation relationship. The paper concludes with a summary of the main points and identification of issues for further research.

REVIEW OF EXISTING CURVE SUPERELEVATION DESIGN PRACTICES

Maximum Superelevation

United States

In U.S. AASHTO guidelines (*1*), there are several possible e_{max} values, of which the most common for interurban links are .06, .08 and .10. This variability has been criticized on the grounds of not helping achieve nationwide consistency in the U.S. For example, it has been shown (*2, 3, 4*) that identical curves may have different inferred design speeds depending on whether the assumed maximum superelevation is .06, .08 or .10.

Germany

In German RAS-L-1 guidelines (*5*), the maximum superelevation value depends on the class of highway. For A-type roads (interurban links), e_{max} is normally equal to .07. Exceptionally, the rate of .08 may be applied in conjunction with below-minimum radii.

United Kingdom

The British Highway Link Design standards (*6*) specify a maximum superelevation value of .07. This rate is not exceeded even in the exceptional cases of below-minimum curve radii (known as "departures from standards").

Values of f in Relation to the Design Speed

United States

The design value for f is determined (*1*) on the basis of experiments identifying desirable values for driver comfort. The experiments on which this practice is based were mainly conducted several decades ago. The f is a decreasing function of the design speed. It changes linearly from .16 for 30 mph to .14 for 50 mph and then, linearly again but with a steeper slope, to .10 for 70 mph.

Germany

The design value for f is calculated (*5*) as a fraction of the maximum side-friction coefficient ($f_{R,max}$). This fraction, n, is assumed to be .5 for A-type (interurban) roads, when minimum curve radius is applied. (As will be seen, the value of n is lower for above-minimum radii.) The maximum side-friction factor is .925 of the maximum tangential friction factor ($f_{T,max}$). The value of $f_{T,m}$ax is a decreasing (second-degree) function of design speed and is based on the 95th-percentile level distribution curve for wet pavements from pavement friction inventories.

United Kingdom

For any design speed, the design value for f (*6*) is taken equal to .09. Given that e_{max} = .07, the total lateral acceleration for the case of minimum radius is thus assumed equal to .16 * g.

Application of e and f Values in Curves of Above-Minimum Radius

United States

The procedure described in AASHTO guidelines (*1*) recognizes the possibility that curves with above-minimum radius will be overdriven (driven at speeds above the design speed) but makes no corrections to the design speed. Rather, it provides an increasing ratio of e over f for increasing curve radius, resulting in a parabolic relationship between e and degree of curve. The limiting value e_{min} is equal to .02. Figure 1 shows the AASHTO guidelines' curvature-superelevation graph for e_{max} = .08.

Germany

The German RAS-L-1 guidelines (*5*) feature a logarithmic graph between e and R to enable the calculation of superelevation for above-minimum curves. This is based on the assumption of a linear reduction of the n (by which $f_{R,max}$ is multiplied) proportional to the increase in R. It is important to note that the estimate of V_{85}, rather than the assumed design speed, is used for calculating the rate of e in above-minimum curves. The limiting value e_{min} is equal to .025. Figure 2 shows the RAS-L-1 guidelines' logarithmic radius-superelevation graph for A-class interurban roads.

The Highway Link Design standard (*6*) states that the 7:9 ratio between e and f should remain stable for the whole range of superelevation values between e_{max} (=.07) and e_{min} (=.025). This leads to both e and f being linear functions of the degree of curve. Thus, the superelevation rate is determined, for each design speed, from the value of the V^2 / R ratio, by applying the graph shown in Figure 3.

United Kingdom

Figure 4 features a comparison of the application of the above three design guidelines. For the U.S. guidelines, the graph is based on the AASHTO tables for V_d = 64 kph (40 mph) and two e_{max} values (.08 and .06); for the German guidelines, the operating speed is 60 kph (37 mph) and e_{max} is .07; and for the British guidelines, the design speed is 60 kph (37 mph) and e_{max} is .07.

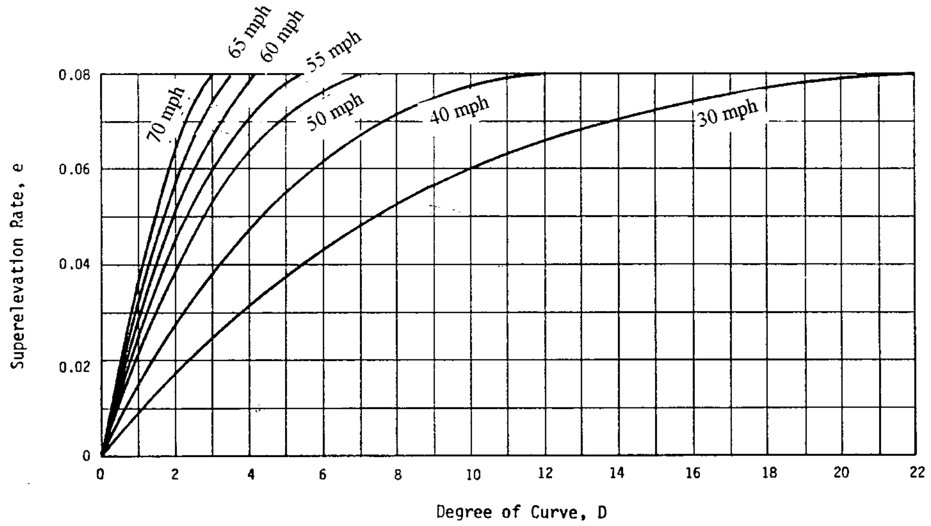

FIGURE 1 Curvature - Superelevation Relationship According to the U.S. AASHTO Guidelines for Maximum Superelevation of .08 (*1*)

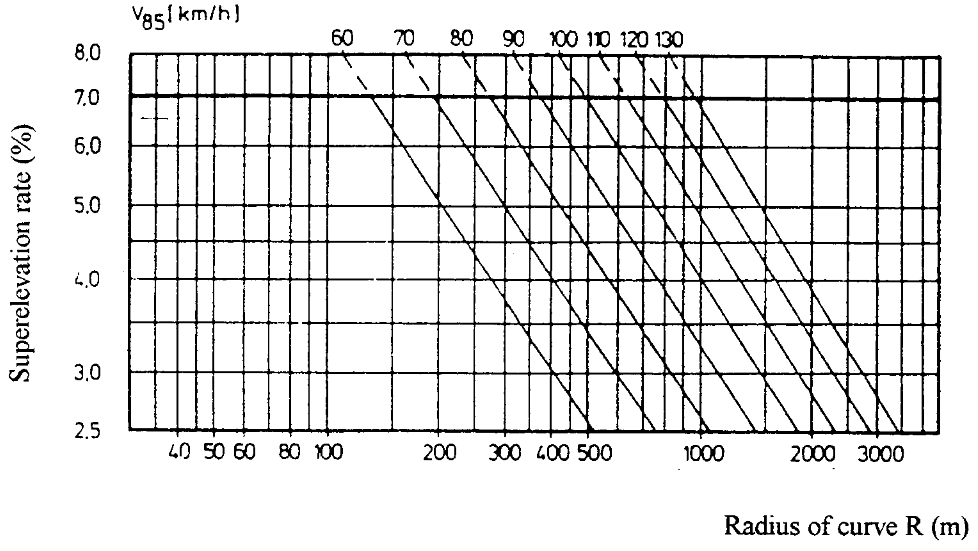

FIGURE 2 Curvature - Superelevation Relationship According to the German RAS-L-1 Guidelines for Interurban Highways (*5*)

DISCUSSION AND EMPIRICAL VALIDATION

Maximum Superelevation

There are practical limits to maximum applicable superelevation rates, arising from two main considerations:

(a) For very low speeds, drivers may be subject to negative side friction, having to steer in the opposite direction to that of the curve. For excessively high superelevation rates, a considerably large proportion of vehicles may operate with negative side friction.

(b) In the case of wet or icy pavement conditions, superelevation rates of .10 or above may be unsafe for slow-moving or still-standing vehicles (especially when tire quality is poor).

Values of f in Relation to the Design Speed

The main hazards from vehicle movement on a curve at an excessive speed are skidding and rollover. For the majority of vehicles, the critical f values for skidding / rollover exceed by far the design values assumed by highway design guidelines (*7*).

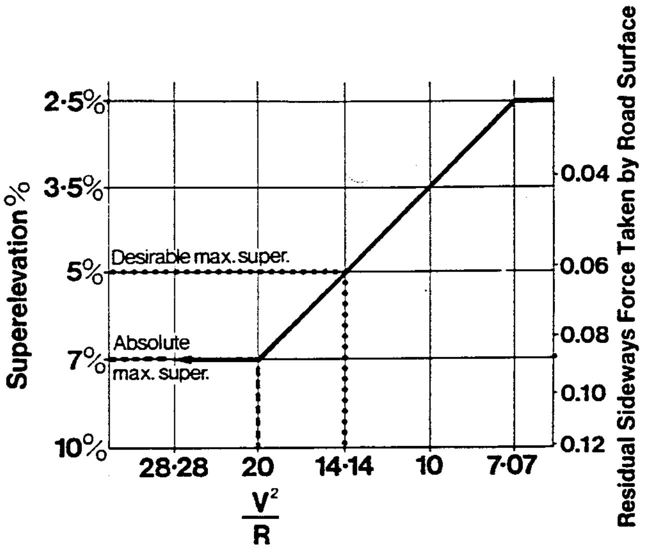

FIGURE 3 Curve Superelevation Design According to the British Highway Link Design Guidelines *(6)*

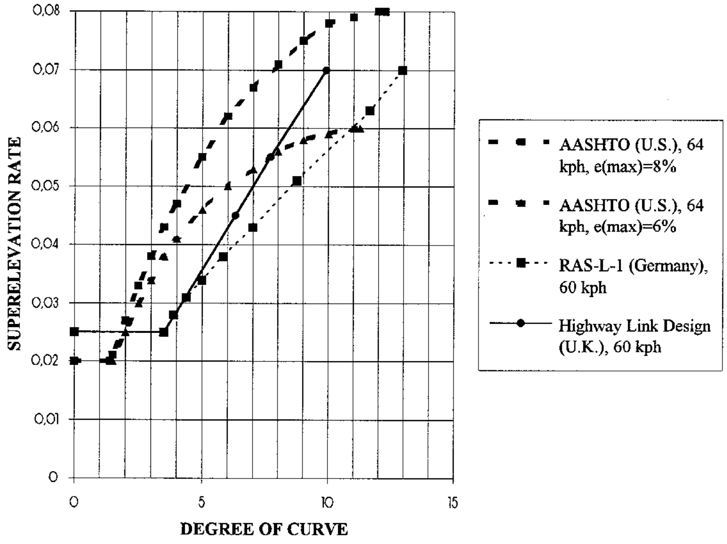

FIGURE 4 Comparative Graph of U.S., German and U.K. Superelevation Design Practices

The assumed f values in U.S. and German guidelines are a decreasing function of design speed. Empirical data reveal that also f values "acceptable" by drivers are:

(a) A decreasing function of operating speed (*4,8*). Analysis of data from 99 curves on two-lane interurban roads in Greece reveals a similar pattern. (The data were collected for the purposes of a research project (*9*) carried out by the National Technical University of Athens.)

(b) In excess of f values assumed in guidelines (*4, 8, 10*). This is particularly the case in lower design-speed highways (below 90 kph). A similar pattern appears the Greek curve data. It may be thus concluded that assumed f values are generally conservative in comparison to the f values acceptable by the 85th percentile driver (f_{85}). Table 1 presents (for the speed range of 60 kph to 100 kph) a comparison of assumed f values in U.S., German and British guidelines, together with the values of a best-fitting relationship between f_{85} and V_{85} calibrated from Greek curve data. Figure 5 illustrates the above comparisons, on the background of the Greek data scatterplot.

TABLE 1 Assumed Side-Friction Factors (*f*) in Design Guidelines of Three Countries, and Acceptable 85th-Percentile Side-Friction Factors (*f_{85}*) According to the Best-Fit Model for Greek Two-Lane Rural Roads

Speed	Assumed Side Friction Factors (f)			Acceptable Side Friction Factors (f_{85})
V_d or V_{85} (kph)	AASHTO (U.S.)	RAS-L-1 (Germany)	Highway Link Design (U.K.)	Interurban road curves (Greece)
60	.153	.142	.090	.328
70	.146	.126	.090	.232
80	.140	.111	.090	.154
90	.128	.098	.090	.091
100	.116	.087	.090	.039

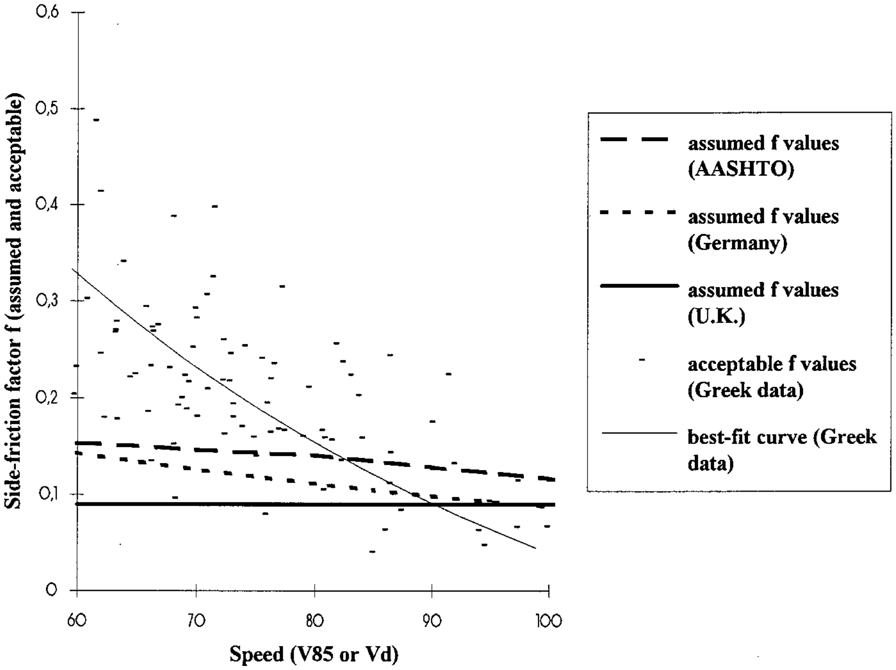

FIGURE 5 Assumed (f) and Acceptable (f_{85}) Side-Friction Coefficients

Application of e and f Values in Curves of Above-Minimum Radius

Effect of Curvature and Superelevation on Speed

There is ample and consistent empirical evidence linking operating speed to degree of curve. Relationships have been developed (*10, 11, 12, 13*) showing that degree of curve (or the inverse of curve radius, 1/R) can be a good predictor of speed. From the Greek curve data, the following best-fit regression equation has been calibrated:

$$V_{85} = 535.9 * (1.205 * DC^{-0.025} - 1) \qquad (4)$$

$(R^2 = 0.81)$

(valid for $2 < DC < 40$)

In contrast, superelevation rate is generally not significant in predicting operating speeds, as is also empirically corroborated (*8, 14*). Greek curve data reinforce this finding: the correlation coefficient between speed and superelevation rate was found to be R = -.33.

In current U.S. design practice regarding curves with above-minimum radii, it is usually assumed that the design speed is unchanged, that is unaffected by changes in curvature. Thus, curves of an above-minimum radius only serve to reduce the total centrifugal acceleration requirement (e + f), which is directly proportional to degree of curve (or inversely proportional to curve radius). However, this consideration does not take into account the fact that operating speed is affected by the horizontal alignment. In certain cases, this omission may lead to a serious underestimation of operating speed.

Relationship Among Curvature, Superelevation And Acceptable Side Friction

It is interesting to note the large diversity of superelevation rates and the lack of a clear association between e and R (or e and DC). Figure 6 illustrates this diversity. A similar pattern emerges from a U.S. study (*4*).

On the other hand, the superelevation rate does not seem to affect the acceptable value of f. The correlation coefficient between e and f in the Greek data was found to be .229. On the whole, superelevation appears to have little influence on driving-behavior parameters (speed and side-friction factor).

As increasing speeds are associated with (a) decreasing degree of curvature and (b) decreasing acceptable side-friction factors, acceptable side-friction factor would be expected to be an increasing function of speed. Greek curve data reveal that the relationship between f_{85} (f value corresponding to the V_{85}) and degree of curve is a fairly strong one. The calibrated relationship is:

$$f_{85} = .2029 * DC^{0.3} - .205 \qquad (5)$$

$(R^2 = .77)$

(valid for $2 < DC < 40$)

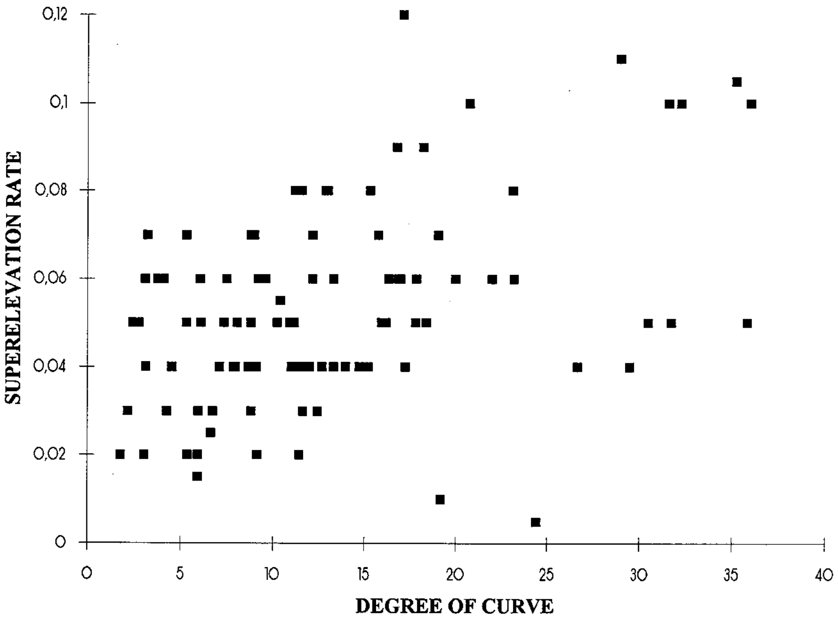

FIGURE 6 Superelevation Against Curvature for Greek Interurban Road Curves

PROPOSED IMPROVEMENTS TO CURVE SUPERELEVATION DESIGN

Current curve superelevation design procedures have been criticized on the grounds of being:

(a) Inadequate in their assumptions regarding vehicle operating speed: This problem is partly addressed by the German guidelines' (*5*) recommendation of using the V_{85} instead of the design speed in above-minimum curves; similarly, the parabolic form of the e vs. DC relationship in U.S. guidelines addresses the same issue by increasing the margin of safety (thus allowing the possibility of overdriving a curve without severe reduction in safety). However, by whichever method, the range of radii that are applicable for each assumed speed is fairly wide. The fact that operating speed is strongly influenced by curvature is not sufficiently accounted for. Curves of the same radius and different superelevation rates may have different design speeds, but it is doubtful if driver behavior will reflect that.

(b) Complex, leading to inconsistency: This problem is especially evident in the variety of e_{max} values applicable in United States practice. It has been argued (*3, 4, 15*) that agreement on a single nationwide e_{max} value for the United States would be beneficial and feasible. The rate of .08 can be seen as a reasonable compromise value for the maximum superelevation rate throughout the U.S.

Given the large potential disparity between design and operating speeds in above-minimum design practice, the approach towards design speed on rural road curves may have to be reconsidered. It may be unnecessarily restrictive to do away with above-minimum design. However, it would be wrong to ignore the risk-compensatory mechanisms leading to increases in the operating speed on flatter curves. In addition, due to conservative assumptions for the design f, design speed is even at minimum-radius curves an underestimation of operating speed. Therefore, it is important to assure that above-minimum design does not lead to potential safety problems.

Consistency

In the light of the above considerations, horizontal alignment consistency is an element that should be explicitly introduced in design guidelines. Research has shown that potential safety problems arise if, after a sequence of above-minimum curves, a curve of minimum or near-minimum radius is encountered. This amounts to a design inconsistency, leading to violation of driver expectancy. Large operating-speed differentials are known to be correlated to increased accident occurrence (*16*).

On the whole, the importance of consistency is well-documented (*4,17*). There have been proposals in research (*18*) for design standards to include consistency checks as a "feedback loop". The German guidelines (*5*) have made some steps in that direction, not only by estimating V_{85} for use (instead of the design speed) in above-minimum curve design (as well as other design features) as a function of "bendiness" (curvature change rate), but also by specifying ranges of acceptable horizontal-curve radius sequences.

Regarding the U.S. guidelines on curve design, the calibration of a nationwide speed-prediction model and the definition of "acceptable" differences between the operating speeds of two consecutive segments - research (*18, 19*) suggests that the maximum difference should be in the order of 10 to 20 kph - would be crucial to the development of consistency rules. For reasons of comprehensiveness, these rules should also cover the case of tangent sections, where different speed models may be applicable depending, among others, on tangent lengths and predicted acceleration / deceleration rates. (It is noted that German guidelines (*5*) also include a rule linking tangent length to the radius of the adjacent curve.)

Speed Standards

Going one step further, the existence of a consistency rule could be supplemented by a redefinition of the above-minimum design procedure. Since each curve radius value corresponds, approximately, to a value (estimated through suitable prediction models) for operating speed, it may be desirable to define **"speed standards"** for ranges of radius (or DC) values. For each speed standard, the minimum curve radius will be estimated by application of the basic kinematic equation (using the AASHTO (*1*) assumption for f). The speed standards may be estimated in convenient increments (corresponding, for example, to the increments used in the consistency rules, e.g. in the region of 10 to 20 kph).

The application of speed standards as defined here would not mean the abolition of the design speed concept. Indeed, for a given design speed, a minimum radius would be defined, corresponding to the minimum radius of a speed standard equal to the design speed. However, it will be possible to have a speed standard higher (but not lower) than the design speed. The higher speed standard will reflect the fact that, at these flatter curves, operating speed will exceed the design speed. The existence of consistency rules will guarantee that transition between segments of different speed standards will not lead to violations of driver expectancy. In addition, above-minimum design should not be practiced where factors other than horizontal curvature are critical (limiting) for the design speed.

The proposed redefinition of above-minimum design could then enable the simplification of horizontal curve superelevation design. Since each radius would correspond to one speed standard, the development of a unique relationship between superelevation rate and R (or DC) would be possible. It would have the advantage of leading to increased consistency (compared to the current large scatter of values). The fact that superelevation is a "background" feature (i.e. not found to directly affect driver behavior) and at the same time important for driving safety makes consistency (in the sense of predictability, compatibility to driver expectancies, and avoidance of confusion) an important factor. In addition, the proposed simplification would make curve design easier for engineers to understand and properly implement, provided that the meaning and merit of the concept of consistency are adequately appreciated.

Proposed Curve Superelevation Design Procedure

The idea of simplifying the curvature - superelevation relationship is not new. There have been arguments and actual proposals (*20*) for a change in that direction. The procedure proposed in the present paper begins with a presentation of a number of criteria that should be satisfied.

(1) For U.S. practice, the minimum superelevation rate of .02 currently employed should be adhered to. The maximum rate could be set at .08, as has already been argued.

(2) The concept of speed standards, as explained above, would be applied: for each design speed, curves should be designed on a speed standard greater than or equal to the design speed, and consistency rules would govern application of speed standards higher than the design speed. For determining maximum curvature (minimum radius) for each speed standard, the assumed f value should equal the AASHTO-specified maximum (*1*).

(3) For each speed standard, the portion of the total sideways force that is provided by superelevation (that is, the ratio of e over e+f) should be higher than a desirable minimum value. Craus and Livneh (*15*) point out that, the higher the above ratio, the "safer" curve design is considered; they suggest that the desirable minimum for that ratio is around .30. However, for design speeds of 100 kph or more, design f values are seldom exceeded, since curvature ceases to be the critical factor affecting driver behavior. Therefore, the requirement for the e / e+f ratio could be somewhat relaxed for these higher speed standards; a possible value would be .25.

(4) The hands-off speed (also known as the "comfort speed" (*15*) and defined, on a curve of known R and e, as the threshold speed between positive and negative side friction) is an important parameter regarding the safety and comfort of slower drivers. British guidelines (*6*) require that the hands-off speed should be approximately equal to the predicted 15th percentile free speed; the ratio of that speed to the design speed is estimated at around .60. To provide acceptable conditions for slow-moving vehicles, this ratio of .60 could be set as a maximum.

(5) Finally, the predicted V_{85} value (by application of a tested and reliable model) should not exceed the speed standard by more than a certain difference. This maximum differential could be, following the suggestion in German guidelines (*5*), in the order of 20 kph. This criterion is particularly meaningful for roads of lower speed standards (below 90 kph), which are the ones most frequently overdriven. For the purposes of this paper, V_{85} was estimated by using the Ottesen-Krammes model (*13*), predicting speed as a function of degree of curve according to the following relationship: For tangents and curves of $DC<3: v_{85} = 97.8$ (kph) For curves of DC equal to or above 3: $V_{85} = 103.6 - 1.947*DC$ (kph)

The above criteria were applied for speed standards between 60 kph and 110 kph (in increments of 10 kph). For reasons of simpleness and correspondence to practically-usable values, superelevation rates used in this application had an accuracy of .005 and degree of curve had an accuracy of .25. The following stepwise procedure was followed:

Step 1: For each superelevation rate between .02 and .08 [Criterion 1], estimation was made of the maximum degree of curve for which the assumed f did not exceed its AASHTO-specified maximum value [Criterion 2]. This resulted in a set of pairs of e - DC values.

Step 2: For each of the pairs in the set, it was checked whether the remaining three criteria [Criteria 3, 4 and 5], pertaining to the e / e+f ratio, the hands-off speed, and the V_{85}, were satisfied. If for a pair of e - DC values at least one of the criteria was not satisfied, the pair was omitted from the set.

The diagram of Figure 7 shows, for speed standards between 60 kph and 110 kph, the final sets of pairs of e - DC values which satisfy all five criteria.

The next step is to specify a simple relationship between superelevation and curvature. The simplest solution would be a single straight line passing from the acceptable ranges of all speed standards *and* assuring that $e = e_{min} = .02$ for tangents. However, from Figure 7 it follows that this solution is not possible. Therefore, the next-best option of a series of intersecting straight lines is followed.

One of the several possible relationships of that type is illustrated in Figure 8. According to this relationship, the minimum superelevation of .02 is applied for curvature up to DC=1 (i.e. for radii above 1750 m); for 1<DC<4 (or 1750>R>440), superelevation changes linearly from .02 to .06; for 4<DC<12 (440>R>150), e changes from .06 to .08; and for curves sharper than DC=12 (i.e. for R<150), the maximum superelevation of .08 is applied.

Table 2 summarizes the application of the above relationship, featuring the following elements and criteria values for each of the speed standards considered: maximum DC (minimum radius); corresponding superelevation rates; the e / e+f ratio; hands-off speed; and the V_{85} as estimated by using the Ottesen-Krammes model (*13*).

Comparison to Current Guidelines

As has already been explained, the proposed speed-standard concept can help achieve better harmonization between assumed and actual vehicle speeds in above-minimum curve design. Next, the suggested procedure will be compared to the current guidelines of the U.S. (*1*), Germany (*2*) and the U.K. (*3*), on the basis of the criteria of the e / e+f ratio and hands-off speed.

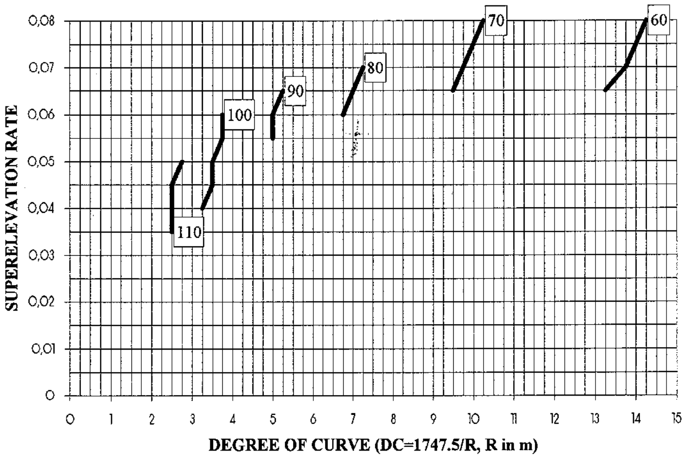

FIGURE 7 Application of Criteria for Proposed Curvature - Superelevation Relationship: Ranges of Possible Pairs of Superelevation - Degree of Curve Values for Speed Standards of 60 to 110 kph

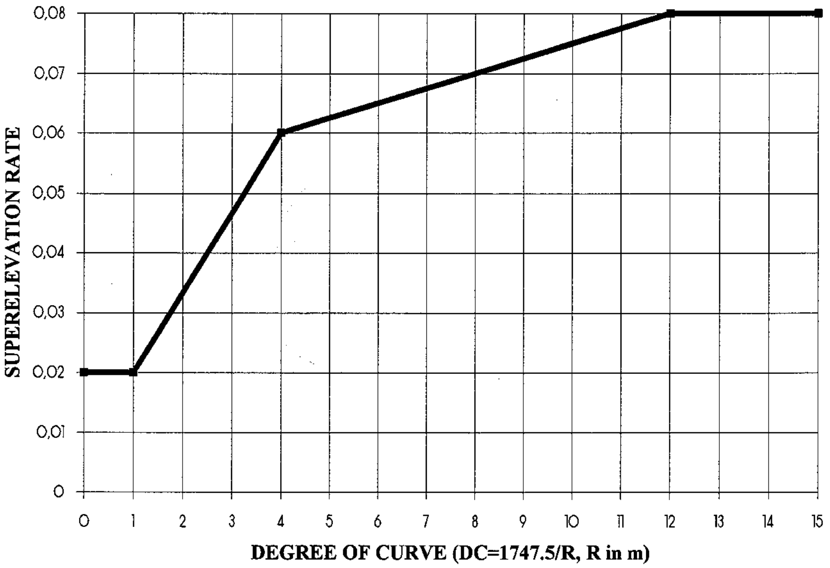

FIGURE 8 Proposed Curvature - Superelevation Relationship

TABLE 2 Design Values for Elements of Curves Using the Proposed Design Procedure, and Corresponding Values for the Relevant Criteria

	Design Values			Criteria Values		
Speed Standard (kph)	Degree of Curve (max)	Equivalent R (min) (m)	Super-Elevation (m/m)	e / e + f	Hands-off Speed (kph)	V_{85} (kph)
60	14.25	125	.08	.35	35	76
70	10	175	.075	.34	41	84
80	7.25	240	.068	.33	46	90
90	5.25	335	.063	.33	52	94
100	3.75	465	.057	.34	58	96
110	2.50	700	.04	.29	60	98

Ratio of e / e+f

For minimum-radius design, the ratio generally ranges between .30 and .50 in all three guidelines. For above-minimum design, values of the ratio are an increasing function of curve radius, often going above .50. The German values are lower than those in U.S. guidelines, reflecting the fact that the former are based on V_{85}, while the latter are based on design speed, which is generally an underestimation of V_{85} and thus necessitates an increase in the margin of safety. In U.K. guidelines, the ratio is constantly held at .44, for superelevation rates above the minimum of .025.

Compared to the procedure proposed in this paper, which assumes smaller values (in the order of .25 to .35) for the ratio, current practices may be seen as partly compensating for the underestimation of operating speeds in above-minimum design.

Hands-Off Speed

Due to the higher superelevation rates applied in the U.S., hands-off speed in current U.S. practice is an increasing percentage of the design speed (often far above the 60% criterion), whereas application of German and U.K. guidelines results in more stable values for the hands-off speed, generally not much above 60% of the design speed (or of V_{85}). Application of the proposed procedure could mean that the probability of vehicles developing negative side-friction on curves may be considerably reduced, especially in comparison with U.S. standards.

SUMMARY AND FURTHER ISSUES

Current curve superelevation design procedures could be improved in a number of ways, for the purpose of achieving greater harmonization between design speed and actual operating speeds. The introduction of consistency rules, the necessity of which has been repeatedly pointed out, could be a first-step measure. These consistency rules should preferably feature models for predicting operating speeds on both curved and tangent sections.

In the longer term, the process of above-minimum curve design could be redefined, by introducing the concept of "speed standards" as a complement to the existing procedure based on design speed. According to this concept, for a given design speed, horizontal curves may be designed for speed standards equal to or greater than the design speed. In this way, the relationship between curvature and superelevation rate could be simplified and made independent of the design speed; each speed standard would correspond to a range of values for radius / degree of curve (and the corresponding superelevation rates). A set of criteria for determining a unique curvature - superelevation relationship has been proposed by the authors of this paper, and its application has led to the development of such a relationship. At a future stage, the relationship may be integrated by treating issues related with very flat curves (determining the threshold for removing adverse superelevation) and tangents (extension of the speed standard concept in straight sections).

The need for harmonization between design speeds and operating speeds (the latter expressed by V_{85}) has often been stressed (*17*, *18*); U.S. guidelines propose that the design speed should correspond to a high percentile of the expected speed distribution (*1*), while German guidelines (*5*) include a provision that predicted V_{85} should not exceed the design speed by more than 20 kph.

By using the proposed design procedure, differences between V_{85} and the speed standard will be less than these between V_{85} and the design speed using current above-minimum design guidelines. Still, harmonization between design and operating speeds will be far from perfect, due to the fact that the f values acceptable by the 85th percentile driver tend to exceed the design values (especially for speed standards below 90 kph). Given that the application of higher superelevation rates (.10 or greater) is generally not recommended, it would appear that the only feasible way of achieving harmonization between design and operating speeds would be by raising the design values for f.

Considering that the vector of friction has a tangential and a lateral component, any increase in the allowable side friction value (lateral component) will mean a decrease in the available tangential friction coefficient. Therefore, for an increase of side friction factors, the consequences with respect to stopping (reduction of available tangential friction factor, increase in required stopping sight distance) should be taken into account and weighted against whatever benefits would arise from harmonizing design speed and operating speed.

Moreover, it must be noted that tire-pavement friction inventories may reveal a large disparity among different pavement and tire types / qualities. Since engineering design should seek to cover the vast majority of cases, it may be inevitable that the guidelines' design values for f will be an underestimation of the f values that will be acceptable by drivers. In a longer-term perspective, improved quality and consistency in pavement and tire quality may make it possible to reduce or eliminate this underestimation.

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