Curvilinear Alinement: An Important Issue for More Consistent and Safer Road Characteristic

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A highway alinement design process called *curvilinear alinement* is described. It is based on a process called *relation design*, which means that no more single design elements with minimum or maximum limiting values are put together more or less arbitrarily; rather, design element sequences are formed in which the design elements following one another are subject to specific relations or relation ranges. Quantitative criteria are given for evaluating the driving behaviors of motorists in the transitions between successive design elements as well as tuning the operating speed to the design speed for single design elements on two-lane rural roads. The curvilinear alinement can provide sounder, more consistent road alinements. The suggested procedure for modern highway design provides better quantifiable and more sophisticated criteria than those that already exist in western European design guidelines. It is recommended that curvilinear alinement design be evaluated for inclusion as a recommended design process in the AASHTO Green Book for two-lane rural roads.

Each year more than 500,000 people are killed in vehicle accidents—or about one life every 2.5 min—and more than 10 million people are injured worldwide. Of the millions who are injured, tens of thousands are maimed for life. The financial costs are many thousands of millions of dollars annually (*1*). Road accidents are now the main cause of death for young people in the 15- to 25-year-old age group (*2*).

It is estimated that more than 60 percent of the fatalities can be attributed to accidents that occur on two-lane rural highways, and at least half of them can be attributed to those that occur on curved roadway sections (*2*). Thus, it becomes understandable that curved sites and the corresponding transition sections represent the most critical locations when considering measures for reducing accident frequency and severity.

It is the purpose of this paper to describe a practical design procedure, expressed here by the term *curvilinear alinement*, to help alleviate the above-mentioned problems. This procedure is developed for the practical design and possible redesign of two-lane rural roads, because multilane highways are much safer.

BACKGROUNDS, INTERIM RELATIONS, AND GOALS

The background for the study was the call for papers by TRB for the conference session Cross Section and Alinement Design Issues (1993). According to this call the task should be to address the most recent AASHTO Geometric Design policy to discuss implications and consequences, to present findings or solutions, and to include recommendations or suggestions for consideration in future editions of the AASHTO Green Book (*3*) to incorporate current practice, experience, and research.

The authors selected the subject curvilinear alinement to illustrate the positive safety impacts that may be accomplished by establishing an appropriate design procedure for two-lane rural roads. An important goal was to present important findings for future editions of the AASHTO Green Book (*3*).

To achieve this important goal it was necessary to refer to theoretical and practical basic research, which was established since 1986 for the United States. In that year a paper, "Comparison of Different Procedures for Evaluating Speed Consistency" was presented by TRB (*4*); that paper included the methods of Leisch and Leisch (*5*), the Swiss (*6*), and the Germans (*7*). It was followed in 1988 by "Possible Design Procedure to Promote Design Consistency in Highway Geometric Design on Two-Lane Rural Roads" (*8*); this first attempt at a proposal on design was based on the actual driving behaviors and accident situations for 322 curved roadway sections in the state of New York. That paper (*8*) was based mainly on the safety criterion of achieving consistency in horizontal alinement.

Meanwhile, Safety Criterion I for evaluating good, fair, and poor design practices was further developed and completed. As shown in Figure 1 the classification is based on the following:

1. The experience of Criterion I, that the driving behaviors of motorists expressed by the absolute difference of the 85th percentile speeds between successive design elements (for example, tangent to curve or curve to curve) should fall into certain ranges when evaluating good, fair, and poor design practices; and
2. The experience of Safety Criterion II, that, considering single design elements alone (for example, tangents or curves), the absolute difference between the observed 85th percentile speed and the design speed should also correspond to certain ranges.

For proposed Safety Criteria I and II, the analytical background was developed on the basis of multiple regression analysis to be able to describe the relationships between design parameters on the one hand and operating speed and accident risk (rate) on the other hand under real-world conditions (*9–12*). In doing this, recommendations regarding consistency in horizontal alinement or achieving a more consistent road characteristic could be given according to the criteria of Figure 1. Also see the section Suggested Procedure for Modern Highway Design later in this paper.

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SAFETY CRITERION	GOOD	FAIR	POOR
	DESIGN PRACTICES		
I	$\lvert V85_i - V85_{i+1} \rvert \leq 10$ km/h	10 km/h $< \lvert V85_i - V85_{i+1} \rvert \leq 20$ km/h	20 km/h $< \lvert V85_i - V85_{i+1} \rvert$
II	$\lvert V85 - V_d \rvert \leq 10$ km/h	10 km/h $< \lvert V85 - V_d \rvert \leq 20$ km/h	20 km/h $< \lvert V85 - V_d \rvert$

V85 = 85th Percentile Speed ; V_d = Design Speed

FIGURE 1 Ranges of safety criteria for good, fair, and poor design practices.

The practical fundamentals elaborated in this paper are extended in another paper by Lamm and Guenther, in this Record; that paper is based on a case study in which an old, unsafe alinement was transformed into a sound curvilinear one by introducing complex data processing systems. Although the superior goal of the considerations so far was traffic safety, other superior goals, such as esthetics, environment, function, traffic quality (capacity), and economy, are also of great importance.

Esthetics is discussed by Smith and Lamm in another paper in this Record, and environment is presented by Lamm and Guenther in another paper in this Record.

HISTORICAL DEVELOPMENT OF ALINEMENT DESIGN PROCEDURES

Alinement design procedures are influenced primarily by the experience and education of the highway design engineer. The development started with simple polygonal sections that described the horizontal alinements, which were then based on circular curves. Finally, alinements were developed by using the standard elements tangent (straight), transition curve (clothoid or spiral), and circular curve in the horizontal alinement and the elements tangent, circular curve, and quadratic or cubic parabola in the vertical alinement. Generally, early incorporation of the vertical alinement into highway geometric design and mutual tuning with the horizontal alinement are adopted today.

Figure 2 shows the development, over time, of alinement design:

1. Tangent and circular curve.
2. Tangent and circular curve with transition curve (circular curve with double radii of curve as transition curve).
3. Tangent and circular curve with transition curve (clothoid or spiral, cubic parabola, etc.).
4. Alinement as for item 3, but without any interim tangent.
5. Three-dimensional alinement with superimposed distortion points as in item 4, but including the vertical alinement. This could be called an *ideal curvilinear alinement* (*13,14*).

It follows that the exact evaluation of the road characteristic is one important step in designing consistent and understandable curvilinear roadway sections. In this connection two-lane rural road safety is an issue of pressing national concern in Europe and the United States. These roads have the highest accident rates of any class of highway, with fatalities and injuries per vehicle kilometer of exposure (accident rates) consistently four to seven times higher than those on rural interstate highways (*15*).

Although design speed has been used for several decades to determine allowable horizontal alinement, it is possible to design certain inconsistencies into highway alinement, especially on two-lane rural roads. At low and intermediate design speeds, the portions of relatively flat alinement interspersed between the controlling curvilinear portions may produce operating speed profiles that may exceed the design speed in the controlling sections by substantial amounts (*5,8–11,13*). This is true for transition sections between successive design elements (Safety Criterion I) and for the observed single design element (Safety Criterion II) (Figure 1).

To overcome this weakness in current practice, consideration of curvilinear alinement becomes of significant importance.

Multilane highways, on the other hand, are much safer. For example, the U.S. Interstate system, with 8.7 percent of the total number of fatalities, and the comparable German *Autobahn* system, with about 9 percent of the total number of fatalities, represent the safest road classes, even though 25 percent of the vehicle kilometers driven are normally done on these roads (*2*). Thus, multilane highways and freeways are normally designed very generously. That means that curvilinear aspects are more or less included in the design of those roads in the United States and western Europe. Therefore, the following procedure primarily concerns two-lane rural roads.

CURVILINEAR ALINEMENT

In connection with a consistent road characteristic, consideration of curvilinear alinement becomes of significant importance.

U.S. Practice

The term *curvilinear alinement* in the United States is usually considered to mean a long-curve, short-tangent type of alinement, as opposed to the more common long-tangent, short-curve type of alinement. Furthermore, curvilinear alinement and the coordination of horizontal and vertical alinement are recognized as techniques for achieving an esthetically pleasing three-dimensional highway alinement.

Thus curvilinear alinement in the United States has principally been seen as a tool for achieving highway esthetics rather than as a tool for specifically achieving increased highway safety.

The 1990 Green Book (*3*) recommends the following:

- All of the pertinent features of the highway should be related to the design speed to obtain a balanced design.
- Changes in design speed should be in increments of no greater than 16 km/hr (10 mph).
- The use of greater sight distances or flatter horizontal curves is encouraged.
- Winding alinement composed of short curves should be avoided because it usually is a cause of erratic operation.
- In an alinement predicated on a given design speed, use of maximum curvature for that speed should be avoided whenever possible. The designer should attempt to use generally flat curves, retaining the maximum for the most critical conditions.

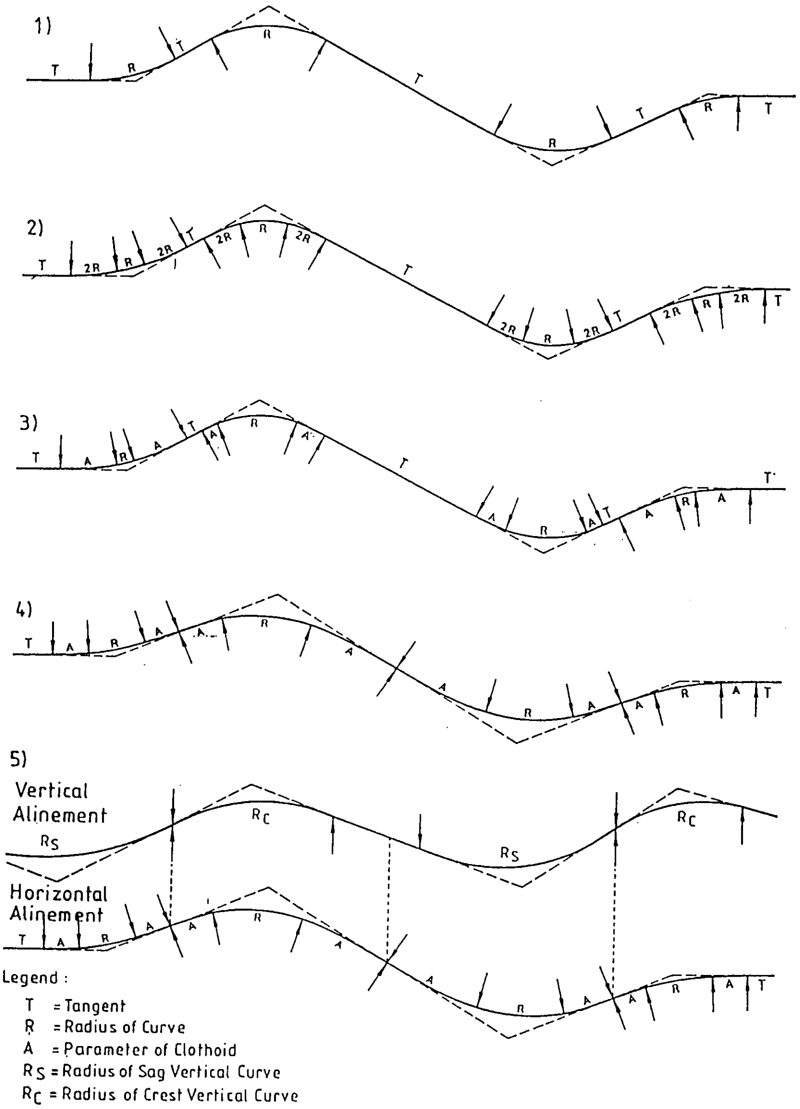


FIGURE 2 Development of alinement design (*13*).

- Consistent alinement should always be sought. Sharp curves should not be introduced at the ends of long tangents. Sudden changes from areas of flat curvature should be avoided.

With regard to human factors, H. Lunenfeld (*16*) made the following statements at the 1992 TRB meeting; these statements should be carefully considered in every highway geometric design guideline:

> Consistency is an often-violated aspect of geometric design. Driver expectancies are developed through experience and knowledge gained by driving a facility and is directly related to the geometric consistency of that facility. Consistency affects how drivers perceive and react to the information provided, by means of signing and pavement markings. Geometric consistency reinforces driver expectancies, which aids the driver in making quick and correct responses to decisions. (*16*)

In addition he warned, "Incompatibility in geometric and operational requirements may be caused by trying to fit together geometric components conveniently and economically rather than trying to satisfy operational requirements. Therefore, design consistency should be maintained," and one consequence would be a more curvilinear alinement, besides standardizing, additionally, "roadside features such as concrete barrier walls, aluminum guardrail, signing, pavement marking, traffic control devices and the like."

In conclusion, in the United States an acceptable design is one in which each design element, such as radius or degree of curve, superelevation rates, vertical curves, and sight distances, meets the Green Book (*3*) minimum or maximum requirements for the individual design element for the selected design speed(s). No specific guidelines are given in the Green Book for relationships among design elements that occur in sequence; that is, no mention is made of nor is guidance given on any design procedure comparable to curvilinear alinement design for achieving better consistency and safety on two-lane rural roads.

German Practice

Besides the Swiss (*6*) and the Swedish Guidelines (*17*), recommendations about consistency, and thereby curvilinear alinement, are found in the German Guidelines for the Design of Roads (*7,18*).

The German road system is classified on the basis of road network functions and traffic quality (capacity) requirements into different groups and categories, as shown in Tables 1 and 2. The following procedure for achieving a consistent road characteristic as a consequence of curvilinear alinement design is valid, first, for two-lane rural roads of Group A and, partially, for those of Group B. For multilane roads and two-lane roads with collector or even local functions, other assumptions become relevant.

The following provides for the first time in a TRB publication a brief overview of the important steps of the German design procedure for two-lane rural roads of Group A and partially for roads of Group B. The reason for this is to compare the German assumptions with the more sophisticated procedure for modern highway design suggested by the authors in the next section.

1. Fundamentally, the design speed V_d shall remain constant for longer roadway sections. Thus, the road characteristic should be well balanced for a driver along the course of the road section. This is a basic assumption for achieving curvilinear alinement. If, along the course of a longer road section, a change in the road characteristic and a corresponding change in the design speed are necessary, for example, by definite changes in the topography, then in the transition section the design elements should be carefully tuned to each other so that they change only gradually. (Nowhere in the German guidelines is the term *longer road section* defined.)

2. Besides the design speed, the operating speed, expressed by the 85th percentile speed (V_{85}), should also be consistent along the selected road section. First, this is achieved by using the required sequences of curves shown in Figure 3. This figure is based solely on experience. It defines the ranges in which the radii of two successive circular curves in either the same or the opposite direction for roads of Group A and Category BII would need to fall to reach a well-balanced relationship for safety reasons; this is also desirable for roads of Category BIII and, if possible, Category BIV (Table 2).

As an example for Figure 3, when a curve with a radius of 500 m (1,640 ft) is combined with curves with the following radii (R), one obtains the indicated range classifications:

R = 200 m (600 ft) falls into the avoidable range,

R = 300 m (1,000 ft) falls into the fair range,

R = 350 m (1,200 ft) falls into the good range, and

R = 400 m (1,300 ft) falls into the very good range.

For roads of Categories AI and AII (major connector function), the sequences of the radii or curves fall into the very good or good range. For roads of Categories AIII, AIV, and BII (minor connector function), the fair range is sufficient. A sequence of radii falling into the fair range is also desirable for roads of Categories BIII and BIV.

Such a tuning of radii of curve sequences is called *relation design*, the design method to strive for today. Relation design means that no more single design elements with minimum or maximum limiting values are put together more or less arbitrarily. Design element sequences will be formed, and the design elements following one another in these sequences must be subject to certain relations corresponding to Figure 3. In this way the evaluation of alinements becomes possible and comparisons between design speed (Table 2, column 7) and operating speeds (V_{85}) can be made according to Figure 4.

All curves in Figure 3 are extrapolated down to a curve with a radius of 50 m (164 ft), since this value may still exist on some state and federal roads in Germany.

Besides these assessments for circular curve sequences according to Figure 3, for the sequence tangent-transition curve-circular curve, the following minimum radii shall be applied, depending on the length *L* (in meters) of the tangent, if the design speed V_d does not require a curve with a larger radius (*7*).

Road Category	*Length (m) of Tangent*	*Minimum* R*(m) of Circular Curve*
AI, AII	≥600	>600
	<600	>*L*
AIII, AIV, BII (BIII, BIV)	≥500	>500
	<500	>*L*

In addition, the minimum length of a circular curve should be so long that driving through the curve at the design speed will require at least 2 sec.

Finally, the German guidelines suggest that the continuance of the same road group and category over longer road sections is very important for a consistent curvilinear alinement. This is especially true for two-lane rural roads of Group A and Category BII, and sometimes even for roads of Category BIII (Table 2).

TABLE 1 Classification of Roads by Groups

LOCATION	CONCENTRATION OF BUILDINGS	IMPORTANT FUNCTION	GROUP
Rural Areas	Low (or Zero)	Connector	A
Urban Areas	Low (or Zero)	Connector	B
	High	Connector	C
		Collector	D
		Local	E

TABLE 2 Classification of Roads by Groups and Categories

ROAD FUNCTION		DESIGN AND OPERATIONAL CHARACTERISTICS				
Category Group	Road Category	Kind of Traffic	Permissible Speed Limit (km/hr)	Cross Section	Intersection Access	Design Speed V_e(km/hr)
1	2	3	4	5	6	7
A: - Low Concentration of Buildings - Rural Areas - Important Connector Functions	AI Statewide or Interstate Functions	Vehicles Vehicles	None ≤100 (120)	Multiple Lane 2 Lane	Controlled (Controlled) Free	120 100 100 90 (80)
	AII Regional Functions	Vehicles All*	None (100) ≤100	Multiple Lane 2 Lane	Controlled (Free) Free	100 90 (80) 90 80 (70)
	AIII Functions Between Municipalities	Vehicles All	≤100 ≤100	Multiple Lane 2 Lane	(Controlled) Free Free	(90) 80 70 80 70 60
	AIV Large Area Accessibility Functions	All	≤100	2 Lane	Free	70 60 (50)
	AV Subordinate Functions	All	≤100	2 Lane	Free	(50) None
B: - Low Concentration of Buildings - Urban or Suburban Areas - Important Connector Functions	BII Primary Arterial	Vehicles	≤80	Multiple Lane	Controlled (Free)	80 70 (60)
	BIII Secondary Arterial	All All	≤70 ≤70	Multiple Lane 2 Lane	Free	70 60 (50) 70 60 (50)
	BIV Main Collector	All	≤60	2 Lane	Free	60 50

(continued on next page)

TABLE 2 *(continued)*

C: - High Concentration of Buildings - Urban Areas - Important Connector Functions	CIII Secondary Arterial	All All	50 (≤70) 50 (≤60)	Multiple Lane 2 Lane	Free	(70) (60) 50 (40) (60) 50 (40)
	CIV Main Collector	All	≤50	2 Lane	Free	50 (40)
D: - High Concentration of Buildings - Urban Areas - Important Collector Functions	DIV Collector	All	≤50	2 Lane	Free	None
	DV Local	All	≤50	2 Lane	Free	None
E: - High Concentration of Buildings - Urban Areas - Important Local Functions	EV Local	All	≤30 Walking Speed	2 Lane	Free	None
	EVI Dwelling Functions	All	Walking Speed	2 Lane	Free	None

*Indicates All Types of Road User Groups Combined (...) *exception

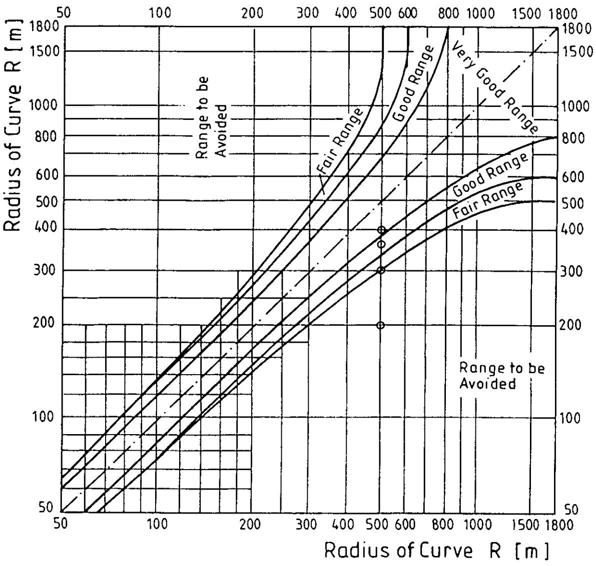
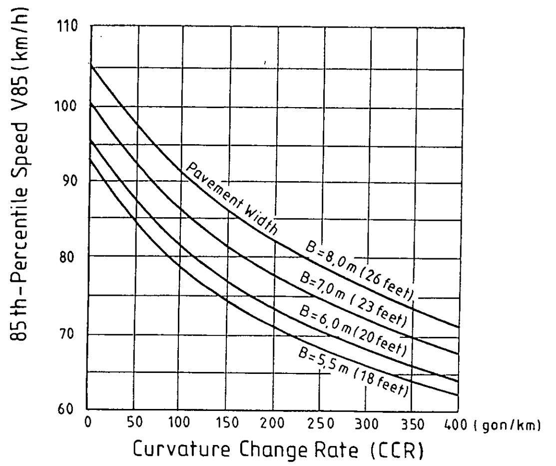


FIGURE 3 Tuning of radii of curve sequences for roads of Group A and Category BII for achieving curvilinear alinements in Germany (*7*).



Legend: $CCR = \frac{\sum_{i=1}^{n} |\gamma_i|}{L} \quad [\frac{gon}{km}]$

CCR [gon/km] = Curvature Change Rate
γ_i [gon] = Angular changes in curves
= $\tau_{1i} + \alpha_1 + \tau_{2i}$
τ_i [gon] = Angular change in transition curve
α_i [gon] = Angular change in circular curve
L [km] = Length of section
B [m] = Pavement width
[gon] = 0.9 degrees (exactly)

The conversion factor between DC (Degree of Curve) Imperial System and CCR (Metric System) is without regarding transition curves:

DC(°/100 ft.) · 36.5 ~ CCR (gon/km)

FIGURE 4 Nomogram for evaluating operating speeds (V_{85}) as related to curvature change rate (CCR) for individual pavement widths according to German design guidelines (*7*).

3. The V_{85} can be determined from Figure 4 with regard to the German design parameters curvature change rate (CCR), which is comparable to the U.S. design parameter *degree of curve* (see conversion factor in Figure 4) and lane width. For an observed design element (curve or tangent), the difference between V_{85} and design speed should not exceed

$$V_{85} - V_d \leq 20 \text{ km/hr.}$$

According to Safety Criterion II in Figure 1, this requirement would include good and fair design practices together; that means that a separate evaluation does not exist.

4. However, between two successive road sections (not design elements), the values for V_{85} that are determined should not differ by more than 10 km/hr (6 mph). This requirement would correspond to good design practices according to Safety Criterion I of Figure 1, but for the term *road section*, it is only stated that it should exhibit a similar road characteristic, a statement that is difficult to understand and a requirement that is difficult to achieve.

The discussions of Issues 3 and 4 above reveal that the assessments in Figure 1 appear to be more sophisticated than the German ones. Note also that the ranges for different design practices in Figure 3 are based on experience only and not on analytical derivations.

A detailed example application regarding Issues 1 to 4 discussed above is presented in a paper by Lammet al. in this Record.

The safety of traffic flow depends on numerous, partially unassessable influences. Besides traffic volume and composition, the design of the cross section of the road is also of significance.

In the German *Guidelines for the Design of Roads, Part: Cross Sections (RAS-Q)* (*18*), road characteristics and safety are discussed in the following way. Road cross section, alinement, and intersections are essential parts of the road characteristic and together influence traffic safety. Therefore, they must be tuned to each other. A cross section inconsistency may be the result of upgrading a highway cross section without upgrading the alinement. Because cross-section features can be more apparent than the alinement, there may be instances in which a wider cross section on an old alinement might convey a message to the driver that could lead to an inappropriate expectancy on the basis of visual aspects of the cross section. Therefore, cross-section features are very important for the road characteristic.

Furthermore, for a sound curvilinear alinement, the designer must be concerned not only with the horizontal alinement but also with the vertical alinement as well as their superimposition or coordination. The essentials of alinement coordination are reported by Smith and Lamm in a paper in this Record.

SUGGESTED PROCEDURE FOR MODERN HIGHWAY DESIGN

For achieving a good curvilinear alinement, Safety Criteria I and II (Figure 1) are of significant importance. They are based on research conducted in the United States and Germany to determine whether these criteria could be adopted for modern practice in new design, redesign, major reconstruction, and resurfacing, restoration, or rehabilitation (RRR) projects on both continents (*12*).

Research evaluated the impact of design parameters, degree of curve, curvature change rate, length of curve, superelevation rate, lane width, shoulder width, sight distance, gradient up to 6 percent, and traffic volume on a data base of 322 two-lane, curved highway sections in New York State (*8–11*) and one data base of 204 sections in Germany (*19,20*). The present data bases contain roadway sections with gradients of up to 6 percent and traffic volumes of between 500 and 10,000 vehicles per day. The research demonstrated that the most successful parameter in explaining much of the variability in operating speeds (V_{85}) and accident rates was degree of curve and curvature change rate. The relationship between operating speed and degree of curve was quantified by regression models and is schematically shown in Figure 5 for the United States.

With respect to degree of curve, V_{85} can be determined for every curve or independent tangent by using Figure 4. An *independent tangent* [for defining and classifying independent tangents (*21*)] is classified to be long enough to be regarded in the curve-tangent-curve design process as an independent design element, whereas a short tangent is called *nonindependent* and can be neglected. By knowing the V_{85} of every element, the absolute speed differences between successive design elements can be calculated. The observed road section, consisting of sequences tangent to curve or curve to curve, can then be classified as being of good, fair, or poor design (Figure 1). Operating speed backgrounds (like those in Figure 4 or 5) should be part of every modern geometric highway design guideline when striving for a good curvilinear alinement, as will be explained in the following section.

Safety Criterion I

For achieving sound transitions between successive design elements, the recommended ranges for good, fair, and poor design practices are given in Figure 1 on the basis of the absolute differences in the corresponding V_{85}s. They provide a quantifiable and sophisticated classification system and are largely based on mean accident rates (*10,11*).

- Good design practice means that, according to the ranges in Figure 1, consistency in horizontal alinement exists between successive design elements for these road sections and that the horizontal alinement does not create inconsistencies in vehicle operating speed. A curvilinear alinement can be expected.
- Fair design practice means that these road sections may contain at least minor inconsistencies in geometric design between successive design elements. Normally, they would warrant traffic warning devices but not redesigns.
- Poor design practice means that these road sections have strong inconsistencies in horizontal geometric design between successive design elements combined with those breaks in the speed profile that may lead to critical driving maneuvers. A noncurvilinear alinement must be expected. Normally, redesigns are recommended.

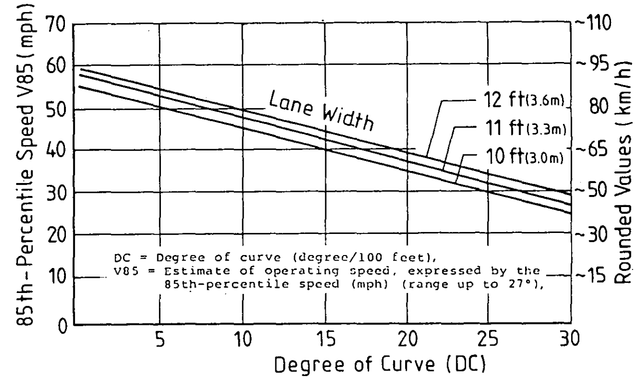


FIGURE 5 Nomogram for evaluating operating speeds (V85) as related to degree of curve for individual lane widths according to U.S. standards (*10,11*).

Safety Criterion II

For evaluating single design elements like curves and independent tangents, the recommended ranges for good, fair, and poor design practices are given in Figure 1 on the basis of the absolute difference between the observed V_{85} and the design speed.

V_{85} can be determined for the observed curved roadway section by using Figure 4 (Germany) or Figure 5 (United States). This time, however, the V_{85} of the circular curve itself or the independent tangent is of prime importance for new designs or examining old designs, for example, in cases of major reconstruction or RRR projects.

In Germany V_d is determined depending on the classification of roads in Table 2. In the United States the following design speeds (where 1 mph = 1.61 km/hr) are recommended in the Green Book (*3*):

Functional Type of Road	*Design Speed (mph)*
Local rural roads	30–50
Rural collectors	40–60
Rural arterial	40–70
Urban arterial	40–60
Urban freeways	50–60
Rural freeways	70

The variation in design speeds for a given road type generally depends on the type of terrain, driver expectancy, and in some cases, design hour volumes.

- Good design practice means that, according to the ranges in Figure 1, no adaptations or corrections between V_{85} and design speed are necessary. A curvilinear alinement can be expected.
- Fair design practice means that, for example, in the case of RRR projects, superelevation rates should be related to the V_{85} and not to the design speed to ensure that the assumed side friction will accommodate side friction demand. In cases of resurfacing projects, high skid resistance values should be required.
- Poor design practice means that redesigns are usually recommended. A noncurvilinear alinement must be expected.

TUNING OF RADII OF CURVE SEQUENCES

On the basis of the recommended changes in operating speeds (V_{85}) for the different design levels of Criterion I in Figure 1, the relationships in Figure 6 were developed. Contrary to the German relationships in Figure 3, which were gained more or less by experience, the boundaries for good, fair, and poor design in Figure 6 were precisely calculated for the assumed operating speed dif-

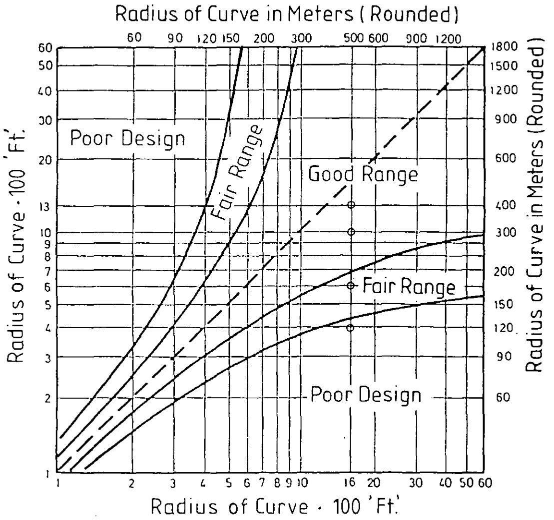


FIGURE 6 Tuning of radii of curve sequences for good and fair design as well as for detecting poor design practices on the basis of the U.S. operating speed background.

ferences in Figure 1 and the corresponding changes in degree of curve, as explained previously (*8*). The degree of curve values was then converted to radii of curve. For instance, Figure 6 shows the tuning of radii of curve sequences in the same or in the opposite direction for possible designs.

As an example for Figure 6, when a curve with a radius of about 500 m (1,600 ft) (see example for Figure 3) is combined with curves with the following radii (*R*), one obtains the indicated design classifications:

R = 120 m (400 ft) falls into the poor design,

R = 180 m (600 ft) falls into the fair design,

R = 300 m (1,000 ft) falls into the good design, and

R = 400 m (1,300 ft) also falls into the good design.

Regarding a tangent-to-curve sequence, the boundaries of good designs correspond to curves with calculated radii of about 350 m ($\geq$1,200 ft). Thus curves with radii of $\geq$350 m ($\geq$1,200 ft) should follow an independent tangent (*21*) not to create inconsistencies in vehicular operating speeds. The boundaries of fair designs correspond to curves with calculated radii of 350 m (1,200 ft) > *R* > about 200 m (600 ft). Radii within this range should follow an independent tangent in the tangent-to-curve sequence for fair design practices. These values agree well with the minimum radii for design speeds of 97 km/hr (60 mph) (good design) and of about 72 km/hr (45 mph) (fair design) for a superelevation rate of 8 percent in Table III-6 of the Green Book (*3*).

Thus, in comparison with the example application of Figure 3, the example application of Figure 6 allows the use of a combination of a wider range of curve sequences for fair and good design practices. This may be because the relationships in Figure 6 correspond exactly to the assumptions of Criterion I in Figure 1 on the basis of the U.S. operating speed background in Figure 5. The German relationships are based on experience only. Furthermore the operating speeds (V_{85}) in Germany are higher than those in the United States. This leads automatically to higher V_{85} differences between successive design elements and results in a smaller range of permissible curve sequences for fair and good design practices in Germany (compare Figures 3 and 6).

These statements should clarify that operating speed backgrounds like those used for Figures 4 and 5 depend significantly on the driving behaviors of motorists in the specific country under study.

Consequently, the diagrams for tuning of radii of curve sequences for different design levels should be developed on the basis of operating speed backgrounds, as was demonstrated for the United States in this paper and previously (*8*). Therefore, those evaluation backgrounds for achieving a sound relation design like those in Figures 3 and 4 for Germany and Figures 5 and 6 for the United States are important assumptions for every country when establishing modern geometric design guidelines for highways.

For example, by applying Figure 6, the U.S. highway designer could immediately decide whether certain radii of succeeding curves fall into the range of good, fair, or poor design practices.

Thus, for achieving gentle curvilinear alinements in cases of new designs, major reconstruction, and RRR projects, the highway engineer should examine horizontal alinement by

- Safety Criterion I according to Figure 1,
- Safety Criterion II according to Figure 1, and
- The design ranges according to Figure 6.

If all three evaluation procedures fall into the good design range, it can be said definitely that a good and sound curvilinear alinement exists. Normally, the results of Safety Criterion I and for the design ranges in Figure 6 correspond to each other, since both evaluation procedures depend on similar assumptions. The results of Safety Criterion II, however, must be regarded as fully independent.

In the same way, existing two-lane rural roads can also be classified for detecting fair and poor design practices to evaluate endangered (fair) and dangerous (poor) road sections.

APPLICATIONS FOR THE GREEN BOOK

Curvilinear alinement design as described here will allow the designer to quantitatively determine if an alinement is consistent or the alinement change necessary for the required consistency meets driver expectancy to achieve safer operation. This quantification of consistency in terms of Safety Criteria I and II in Figure 1 as well as the proposed design ranges according to Figure 6 will allow the designer to evaluate the effects of fitting together geometric components conveniently and economically and to satisfy operational requirements. Curvilinear alinement design is applicable to new designs, the evaluation of existing designs, and RRR projects.

In new designs the curvilinear alinement design process should be of specific assistance in quantifying the effects of the following of the nine General Controls for Horizontal Alinement listed in the Green Book (*3*):

> 2. In alinement predicated on a given design speed, use of maximum curvature for that speed should be avoided wherever possible. The designer should attempt to use generally flatter curves, retaining the maximum for the most critical conditions.

3. Consistent alinement should always be sought. . . . Curvilinear Alinement design will enable the designer to quantify the consistency of alinements to effectively transition the alinement for "the most critical conditions" in a consistent fashion and to quantitatively determine how sharp a curve to satisfactorily use at the end of a long tangent.

6. Caution should be exercised in the use of compound curves, . . . compound curves with large differences in curvature introduce the same problems that arise at a tangent approach to a circular curve. . . .

7. An abrupt reversal in alinement should be avoided. . . . Curvilinear alinement design can assist in quantifying the level of consistency of various alinement designs in 6 and 7.

CONCLUSION

This paper presented curvilinear alinement design (relation design) as a useful, workable tool for achieving a more consistent road design and thereby avoiding potential safety errors than is generally attained by the individual element, maximum-minimum design approach. This is true for new alinements, upgraded highway alinements, or full-blown RRR projects of two-lane rural roads.

The proposed curvilinear alinement design process is based on quantifiable and sophisticated criteria for evaluating operating speed changes between successive design elements and for tuning operating speeds and design speeds of single design elements to each other.

It is recommended that curvilinear alinement design be evaluated for inclusion as a recommended design process in the Green Book (*3*).

The practical fundamentals described in this paper were extended in another paper by Lamm et al. in this Record. Both papers should be regarded as one unit.

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