Possible Design Procedure To Promote Design Consistency in Highway Geometric Design on Two-Lane Rural Roads

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European design guidelines explicitly address horizontal design consistency for two-lane, rural roads in an attempt to promote smooth operating speed profiles and, in turn, safe operation. U.S. practice qualitatively advocates consistent alignment but provides little objective guidance to assure that consistency is achieved. This paper presents a procedure for measuring the consistency of horizontal design as defined by operating speed and accidents expected. Operating speeds and accident rates can be predicted for various lane widths based on degree of curve and posted recommended speeds, as derived from measurement of 261 sites in New York state. Guidelines for changes in operating speeds and acceptable accident rates for good, fair, and poor designs are suggested, and various nomographs are developed to evaluate roadway sections based on design parameters. In addition, an example application is provided to illustrate the case of fair design practices. It is concluded that such a procedure could readily be adapted by the design community in prescribing improvements to existing facilities or in fine tuning new highway design.

Abrupt changes in operating speed because of horizontal alignment are a leading cause of accidents on two-lane, rural roads, according to many experts (*1–6*). State and Federal agencies spend approximately 2 billion dollars annually to resurface, restore, and rehabilitate these roadways, exclusive of major reconstruction required to refine roadway geometrics (*7*). It seems that in an improvement program of this magnitude a convenient method for locating alignment inconsistencies, which may cause abrupt operating speed changes, would be beneficial. Such a mechanism would enable the engineering agency to provide cost-effective horizontal alignment modifications consistent with the resurfacing, restoration, and rehabilitation (RRR) program and thereby enhance traffic safety on two-lane, rural highways. An objective method of identifying hazardous elements that require abrupt operating speed changes would enable the agency to make geometric revisions at the same time that other deficiencies are being remedied.

REVIEW

An international review of existing design guidelines (*8–14*) has shown that European countries directly or indirectly address three design issues in their guidelines much more explicitly than U.S. agencies (*2, 15–19*). French, German, Swedish, and Swiss designers are provided with geometric criteria which direct them toward—

- achieving consistency in horizontal alignment,
- harmonizing design speed and operating speed, and
- providing adequate driving dynamic safety.

The objective of this research was to explore whether these guidelines could be adopted for U.S. practice in new design, major reconstruction, and, especially, RRR projects.

Prior studies by the authors (*15–21*) were relied on to develop the proposed methodology. Research that evaluated the impact of design parameters (degree of curve, length of curve, superelevation rate, lane width, shoulder width, sight distance, gradient, and posted recommended speed) and traffic volume on 261 two-lane, rural highway sections in New York state demonstrated that the most successful parameters in explaining the variability in operating speeds and accident rates were degree of curve and posted recommended speed limits. The relationship of operating speed and degree of curve is quantified by the following regression model (*15–18*) between operating speed and various design and traffic volume parameters:

$$V85 = 34.700 - 1.005DC + 2.081LW + 0.174SW + 0.0004AADT \qquad R^2 = 0.842 \qquad SEE = 2.814$$

where

- $V85$ = Estimate of operating speed, expressed by the 85th-percentile speed (mph) of passenger cars under free-flow conditions,
- DC = Degree of curve (deg./100 ft.) (range: 0° to 27° for investigations on operating speeds, and 1° to 27° for investigations on accident rates, since the accident situation on tangents is clearly affected by variables other than those on curves),
- LW = Lane width (ft.),
- SW = Shoulder width (ft.),
- $AADT$ = Average Annual Daily Traffic [range: 400 to 5,000 vehicles per day (vpd)],
- R^2 = Coefficient of determination, and
- SEE = Standard error of estimate (mph).

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The independent variables in the above equation were selected by the step-wise regression technique in the order: *DC*, *LW*, *AADT*, and *SW*. For instance, *DC* had the highest correlation with the dependent variable (*V*85); thus, it was the first variable included in the equation, and so forth.

Design parameters, sight distance, length of curve, and gradient (up to 5 percent) were not included in the regression model because the regression coefficients associated with these parameters were not significantly different from zero at the 95 percent level of confidence. Superelevation rate and posted recommended speed were withheld from the regression analysis because they are highly correlated with degree of curve.

However, in comparing the above equation with the following equation, which only includes the design parameter degree of curve, note from the coefficients of determination (R^2) that the influence of *LW*, *SW* and *AADT* in the above equation explains only an additional of about 5.5 percent of the variation in the expected operating speeds.

$$V85 = 58.656 - 1.135\,DC \qquad R^2 = 0.787 \quad SEE = 3.259 \tag{1}$$

Note that this regression equation has an R^2 value of 0.787 and its standard error for estimating the observed operating speed is 3.259 mph. It is clear including the additional design and traffic volume parameters adds little to the predictive capability of the model.

Similar relationships were established between operating speeds and posted recommended speeds, and accident rates and degrees of curve; table 1 shows some of the results. Note that (1) the models are valid for road sections with grades up to 5 percent, and low and intermediate traffic volumes (between 400 and 5,000 vpd); and (2) a cross-validation of the models on a new sample of 61 rural, two-lane, curved sections determined that they can be used, with a marked degree of confidence, for prediction purposes. It is likely that grades over 5 percent and *AADT* volumes greater than 5,000 vpd will measurably influence operating speeds and accident rates on two-lane, rural highways; however, because of a lack of data (less than 20 percent of the two-lane, rural highway network in New York is made up of sections where grades are greater than 5 percent and traffic volume exceeds 5,000 vehicles per day), these effects were not analyzed.

TABLE 1 PREDICTIVE REGRESSION EQUATIONS OF OPERATING SPEEDS AND ACCIDENT RATES FOR DIFFERENT LANE WIDTHS (*16–18*)

All lanes

$V85 = 58.656 - 1.135DC;\ R^2 = 0.787$ (1)
$V85 = 25.314 + 0.554RS;\ R^2 = 0.719$ (2)
$ACCR = -0.880 + 1.410DC;\ R^2 = 0.434$ (3)

10-ft lanes

$V85 = 55.646 - 1.019DC;\ R^2 = 0.753$ (1a)
$V85 = 27.173 + 0.459RS;\ R^2 = 0.556$ (2a)
$ACCR = -1.023 + 1.513DC;\ R^2 = 0.300$ (3a)

11-ft lanes

$V85 = 58.310 - 1.052DC;\ R^2 = 0.746$ (1b)
$V85 = 29.190 + 0.479RS;\ R^2 = 0.744$ (2b)
$ACCR = -0.257 + 1.375DC;\ R^2 = 0.462$ (3b)

12-ft lanes

$V85 = 59.746 - 0.998DC;\ R^2 = 0.824$ (1c)
$V85 = 26.544 + 0.562RS;\ R^2 = 0.835$ (2c)
$ACCR = -0.546 + 1.075DC;\ R^2 = 0.726$ (3c)

where

V85 = Estimate of the operating speed, expressed by the 85th-percentile speed for passenger cars (mph),

DC = Degree of curve (degree/100 ft), range: 0° to 27°,

R^2 = Coefficient of determination,

ACCR = Estimate of accident rate for all vehicle types (acc./10^6 vehicle-miles), range: 1° to 27°,

RS = Posted recommended speed in the curve or curved section (mph).

TABLE 2 T-TEST RESULTS OF ACCIDENT RATES FOR DIFFERENT DEGREE OF CURVE CLASSES (*16–18*)

Degree of Curve Classes	Mean Accident Rate	t calc.		t crit.	Significance	Remarks
tangent (0°)	1.87					Considered as
		4.00	>	1.96	Yes	
1° - 5°	3.66					---- Good Design
		7.03	>	1.96	Yes	
> 5° - 10°	8.05					---- Fair Design
		6.06	>	1.99	Yes	
> 10° - 15°	17.55					---- Poor Design
		3.44	>	1.99	Yes	
> 15° - 26.9°	26.41					---- Poor Design

In addition, the research studies (*15–21*) determined that

1. No statistically significant difference exists between operating speeds on dry and wet pavements, as long as visibility is not affected decisively.
2. The gap between operating speeds of passenger cars and trucks increases with increasing degree of curve, but not in a manner that could create critical driving maneuvers on gradients up to 5 percent.
3. Accident rates increase with increasing degree of curve, despite the presence of stringent traffic warning devices at curved sites.
4. Vehicle acceleration and deceleration end or begin about 700 to 750 feet from the end of an observed curved road section.
5. Consistency in horizontal alignment, as reflected by a smooth operating speed profiles, can be achieved by examining the degree of curve.
6. For evaluating horizontal design consistency or inconsistency, the following changes in degrees of curve and their subsequent impact on changes in operating speeds, based largely on mean accident rates (see table 2), provide a reasonable (and quantifiable) classification system for differentiating good design and poor design:

Case 1 (good design):

Range of change in degree of curve: $\Delta DC \leq 5°$.
Range of change in operating speed: $\Delta V85 \leq 6$ mph (10 km/h).

For these road sections, consistency in horizontal alignment exists, and the horizontal alignment does not create inconsistencies in vehicle operating speeds.

Case 2 (fair design):

Range of change in degree of curve: $5° < \Delta DC \leq 10°$.
Range of change in operating speed: 6 mph $< \Delta V85 \leq 12$ mph (20 km/h).

These road sections have at least minor inconsistencies in geometric design.

Case 3 (poor design):

Range of change in degree of curve: $\Delta DC > 10°$.
Range of change in operating speed: $\Delta V85 > 12$ mph (20 km/h).

These road sections have strong inconsistencies in horizontal geometric design combined with breaks in the speed profile that may lead to critical driving maneuvers.

As shown in table 2, the results indicate significant increases (at the 95 percent level of confidence) in the mean accident rates among the different degree of curve classes compare. In other words, higher accident rates can be expected with higher degree of curve classes, despite stringent traffic warning devices often installed at the curve sites.

The results of table 2 indicate that gentle curvilinear horizontal alignments consisting of tangents or transition curves combined with curves up to 5° showed the lowest average accident risk. These observations agree well with the findings of some European guidelines (*8, 10, 11*) and the statements of AASHTO 1984 (14, pp. 248f) concerning "General Controls for Horizontal Alignment."

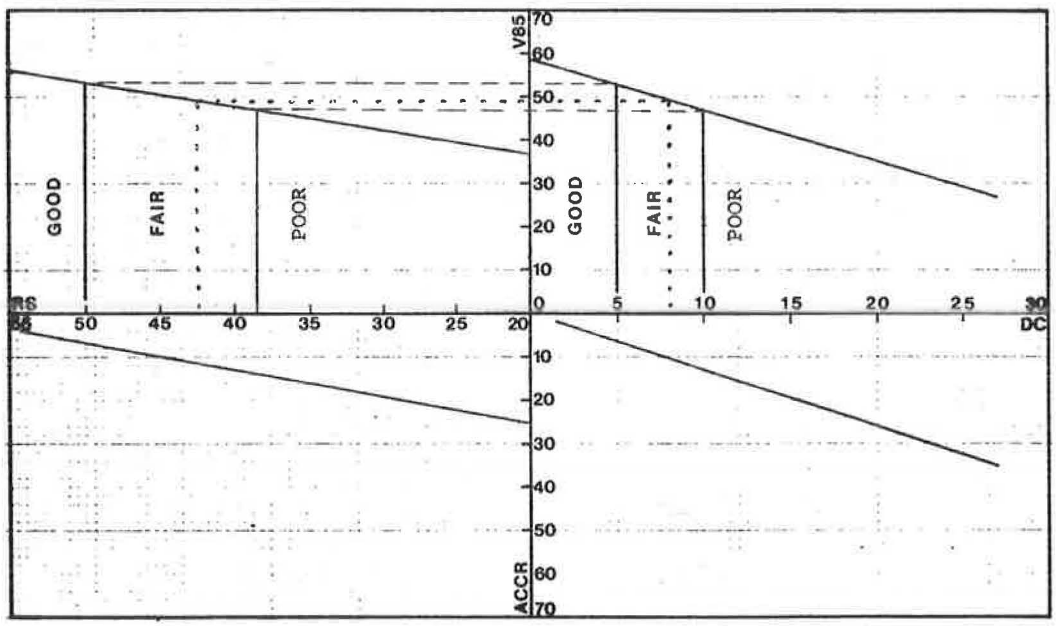
For horizontal alignments with changes in degrees of curve between 5° and 10° between successive design elements (defined as fair designs), the average accident rate in table 2 is twice as high as for those between 1° and 5°. For changes between 10° and 15° of curve (defined as poor designs), the accident rate is four times the rate associated with degrees of curve between 1° and 5°. For greater changes in degree of curve, the average accident rate is even higher. This confirms that changes in degree of curve between successive design elements that exceed 10° should be interpreted as poor designs while those in the range between 5° and 10° can still be judged as fair designs.

NOMOGRAMS FOR EVALUATING OPERATING SPEEDS AND ACCIDENT RATES

The regression models for all lanes combined, formulated in table 1, are depicted in figure 1. From the resulting nomogram, the designer is able to roughly predict operating speeds (85th-percentile speeds) and accident rates on curves or curved sections of two-lane, rural highways from beforehand knowledge of the degree-of-curve or posted-recommended-speed parameters.

On the other hand, the regression models for the individual lane widths formulated in table 1 are depicted in figure 2. As the figure shows, operating speeds decrease with increasing degree of curve, for different lane widths, in a nearly parallel manner.

With respect to the relationship "accident rate vs. degree of curve" figures 1 and 2 reveal that accident rates increase



DC = Degree of curve (degree/100 feet),
V85 = Estimate of operating speed, expressed by the 85th-percentile speed (mph) (range up to 27°),
ACCR = Estimate of accident rate (acc./10^6 vehicle-miles)(range: 1° - 27°),
RS = Estimate of recommended speed (mph).

FIGURE 1 Nomogram for evaluating operating speeds and accident rates in curves or curved sections as related to degree of curve and posted recommended speed for all lane widths (*17*).

with increasing degree of curve, despite the presence of posted advisory speeds at curved sites (see figure 1). Furthermore, as figure 2 reveals, for degrees of curve $\leq 5°$, there appear to be non-significant differences in accident rates between the individual lane widths. For higher degrees of curve, the gap between accident rates on 12-foot and 11/10-foot lanes becomes wider and wider.

For all lanes combined, one can expect, as figure 1 reveals, an accident rate of about six accidents per million vehicle miles (mvm) for a 5° of curve, and an accident rate of about thirteen accidents per mvm for a 10° curve. That means that the accident risk on sections with a change in degree of curve of $\Delta DC > 10°$, as compared to sections with a change in degree of curve of $\Delta DC > 5°$ is at least twice as high. For higher degrees of curve, these comparisons are even more unfavorable. Similar results are obvious from figure 2, too, when comparing the accident rates for individual lane widths. Note that the differences between 12-foot and 11-foot lane widths are, more or less, more pronounced than those between 11-foot and 10-foot lane widths.

These relationships between roadway geometry, operating speeds and accidents in conjunction with the classification system form the basis for a design methodology. From geometric definition, the designer may predict operating speeds. Wide variations in operating speeds are shown to be further indicators of accidents. Reasonable judgments can then be applied to discriminate good, fair, and poor design on the basis of safety indicators but using only design information.

TUNING OF RADII-SEQUENCES

For an easy illustration of the following design procedure, the recommended boundaries for good, fair, and poor designs, as related to degree of curve, were converted to radii of curve. For instance, figure 3 shows the tuning of radii-sequences for succeeding curves, in the same or in the opposite direction, for different design cases. As figure 3 demonstrates, a radius of $R = 500$ feet can be combined, for example, in the case of—

- good designs: with a range of radii between $\sim 350 < 500 < 900$ feet and
- fair designs: with a range of radii between $\sim 270 < 500 < 3{,}500$ feet.

Regarding a sequence tangent-to-curve, the boundaries of good designs ($DC \leq 5°$) correspond to radii of curve ($R \geq 1{,}200$ ft); thus, curves with radii $R \geq 1{,}200$ feet should follow an "Independent Tangent" in order to not create inconsistencies in vehicle operating speeds. The boundaries of fair designs ($5° < DC \leq 10°$) correspond to radii of curve ($1{,}200$ ft $> R \geq 600$ ft); radii within this range should follow an "Independent Tangent" in the sequence tangent-to-curve for fair design practices. These values agree well with the minimum radii for design speeds of 60 mph (good design) and of about 45 mph (fair design) for a superelevation rate of 8 percent in table III-6 (*14*).

By applying figure 3, the designer could immediately decide

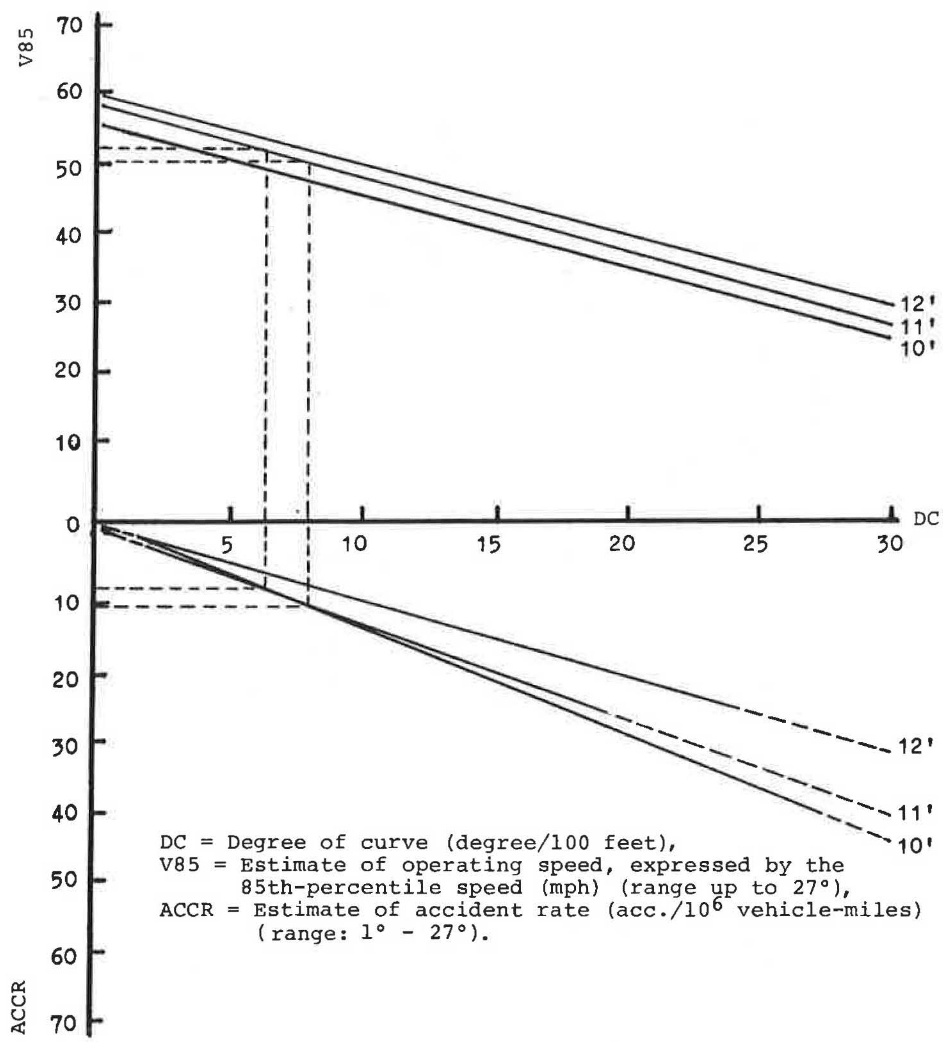


FIGURE 2 Nomogram for evaluating operating speeds and accident rates as related to degree of curve for individual lane widths.

whether or not certain radii of succeeding curves fall into the range of good, fair or poor design practices. For example, combining a radius of 1,000 feet—

- with 300-foot radius would be a poor design,
- with a 500-foot radius would be a fair design, and
- with a 700-foot radius would be a good design.

EVALUATION OF TANGENTS IN THE DESIGN PROCESS

Lamm et al. (companion paper in this Record) have established boundaries for tangent-lengths that are to be regarded as "independent" or "non-independent" design elements. For independent tangents, the sequence "tangent-to-curve" controls the design process, while for non-independent tangents, it is the sequence "curve-to-curve" that controls the design process.

Table 3 shows maximum allowable lengths of tangents that are regarded as non-independent design elements. The values with an asterisk represent lengths of tangents on which 85th-percentile speeds of 58 mph can be reached, as determined by Lamm et al. in a companion paper in this Record.

When dealing with tangent lengths, the following three cases must be distinguished.

Case 1

The existing tangent length is smaller than the maximum allowable one in table 3 that corresponds to the nearest 85th-percentile speed of the curve with the higher degree of curve. From this it follows that the tangent is to be regarded as non-independent (companion paper in this Record by Lamm et al.). Changes in degree of curve and operating speeds must be related to any two successive curves since the tangent in-between can be assumed to be negligible in the design process; that is, the sequence curve-to-curve controls the design process in this case.

Case 2

The existing tangent length is at least twice as long as the values listed in the last column of table 3, again related to the

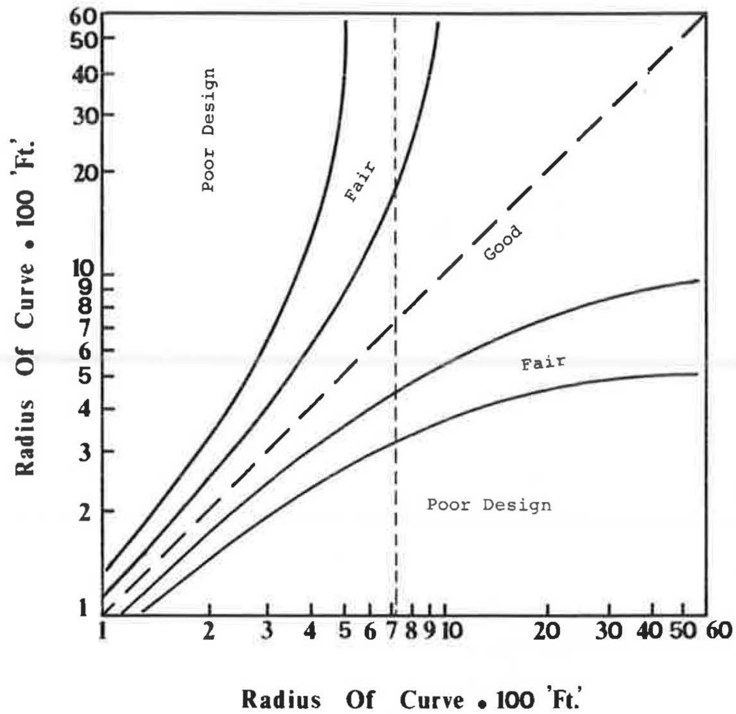


FIGURE 3 Tuning of radii-sequences of succeeding curves for good and fair design practices.

TABLE 3 RELATIONSHIP BETWEEN TANGENT LENGTHS AND 85TH-PERCENTILE SPEED CHANGES FOR SEQUENCES: TANGENTS TO CURVES

V85 in Curve	V85 in Tangent				
	34	40	46	52	58
22	250	425	625	850	1100*
28		325	500	725	1000*
34			375	600	850*
40				425	675*
≥46					475*

[box] Maximum allowable Lengths of Tangents, regarded as "Non-Independent Design Elements", (ft)

V85 = 85th-Percentile speed in curve or tangent (mph)

*For these values the highest operating speed in tangents V85 = 58 mph can be expected.

nearest 85th-percentile speed of the curve with the higher degree of curve. In this case, it can be assumed, without any calculations, that the tangent is independent (Lamm et al.), and that operating speeds of 56 to 60 mph are good estimates, depending on the individual lane widths (see equations (1a) through (1c) of table 1). In other words, the sequence tangent-to-curve controls the design process.

Case 3

The existing tangent length lies somewhere between Case 1 and Case 2. The operating speed in the independent tangent can be estimated from figure 4 and equations (2) through (4), as derived by Lamm et al.; in other words, the sequence tangent-to-curve controls the design process for both directions of travel.

PROCESS FOR EVALUATING HORIZONTAL DESIGN CONSISTENCY WITH EXAMPLE APPLICATIONS

Primarily at lower design speeds, the changing alignment may cause variations in operating speeds, which may, in turn, increase the accident risk by substantial amounts. Therefore, one of the important tasks in modern rehabilitation of the two-lane, rural road network in the United States is to ensure design consistency and to detect critical inconsistencies in horizontal alignment, especially with regard to RRR projects.

In what follows, the various steps of the design procedure are presented:

(a) Assess the road section where new designs, major reconstructions, or redesigns, such as in the case of RRR projects, may be considered.

(b) Determine for this road section the degree of curve of each curve within the section and the existing tangent length.

(c) Determine the expected 85th-percentile speed for each curve, in accordance with degree of curve, by applying figure 1 for a rough estimate or figure 2 for a more accurate estimate depending on the lane width. Compare equations (1a) through (1c) also.

(d) Conclude whether or not each tangent is an independent design element. For independent tangents, the tangent-to-curve sequence is of prime importance in the design process. For non-independent tangents, it is the sequence curve-to-curve. For independent tangents, determine the corresponding operating speeds according to Case 2 or Case 3 of the previous section.

(e) In accordance with the results of step (c) and step (d), calculate the change in degree of curve (ΔDC), and the change in operating speeds ($\Delta V85$) for the independent tangent-to-curve or curve-to-curve sequence.

Good Design Practices

(f_1) Determine all road sections where changes in degree of curve and changes in operating speeds correspond to the boundaries of good design practices:

Range of change in degree of curve: $\Delta DC \leq 5°$.

Range of change in operating speed: $\Delta V85 \leq 6$ mph (10 km/h).

Result

For these road sections, consistency in horizontal alignment exists and the horizontal alignment does not adversely detract from the expected operating speed profiles. Thus, RRR improvements can be made in most cases without considering traffic warning devices or horizontal alignment redesign. The majority of existing state routes in the United States exhibit these characteristics.

Note

The radii of successive curves should fall into the range of good design practices as shown in figure 3. For a tangent-to-curve sequence, at least curves with radii ($R \geq 1{,}200$ ft) should follow an independent tangent.

Rough estimates of expected accident rates may be made possible from figures 1 and 2 or equations (3a) through (3c) in table 1, depending on the lane width.

Fair Design Practices

(f_2) Determine all road sections where changes in degree of curve and changes in operating speeds correspond to the boundaries of fair design practices:

Range of change in degree of curve: $5° < \Delta DC \leq 10°$.

Range of change in operating speed: 6 mph $\leq \Delta V85 \leq 12$ mph.

Result

These road sections exhibit at least minor inconsistencies in geometric design. Normally, correcting the existing alignment is not necessary since low cost projects such as traffic warning devices may, to a certain extent, be successful in correcting these defects. For instance, RRR improvements can be installed which consider appropriate recommended speeds (see figure 1), unless a safety problem has been documented. One should note that despite traffic warning devices, road sections with changes in degree of curve that fall into the range (5° to 10°) have average accident rates that are about twice as high as those falling into the range of good design (see table 2).

Note

The radii of successive curves should fall into the range of fair design practices, as shown in figure 3. For a tangent-to-curve sequence at least curves with radii (1,200 ft $> R \geq 600$ ft), equipped with posted recommended speeds (see figure 1) and arrow designations, should follow an independent tangent.

Rough estimates of expected accident rates may be made from figures 1 and 2 or equations (3a) through (3c) in table 1, depending on the lane width.

To achieve a high level of driving safety, superelevation rates and stopping-sight distances should be related to the expected operating speeds wherever possible.

Example Related to Figure 5

Step (a)
State of New York,
County No. 3604,
Route Number SR34 (mile markers 3094–3115),
Lane Width 11 feet.

Step (b)

Section	*Design Element*	*Degree of Curve*	*Length*
A–B	Tangent	0	0.2 mi ~ 1,060 ft
B–C	Curve	6.4	0.2 mi ~ 1,060 ft
C–D	Tangent	0	0.1 mi ~ 530 ft
D–E	Curve	8.0	0.1 mi ~ 530 ft
E–F	Tangent	0	1.5 mi ~ 7,920 ft

Step (c)

Expected 85th-Percentile Speed	*From Figure or Equation*	*Measured 85th-Percentile Speed*	
Curve BC	52 mph	Figure 2 or Eqn. (1b)	
Curve DE	50 mph		53 mph

Step (d)

Tangent AB (1,060 feet) In accordance with Case 2, see the section on "Evaluation of Tangents." The expected operating speed in the following curve is 52 mph; the nearest value in table 3 is 46 mph; two times the value of the last column of table 3 is 950 feet < 1060 feet. That means that tangent AB is independent. It follows that $V85 = 58$ mph, according to figure 2 or equation (1b) for a lane width of 11 feet.

Tangent CD (530 feet) In accordance with Case 3, see the section on "Evaluation of Tangents." The expected operating speed in the curve with the higher degree of curve is 50 mph; the nearest value in table 3 is 46 mph; the maximum length of tangent regarded as non-independent is 475 feet < 530 feet. That means that tangent CD is independent. Thus, the operating speed in the tangent can be estimated, according to Figure 4 (from the companion paper in this Record), as follows:

$$X = \frac{(52 + 50) \cdot (52 - 50)}{2 \cdot 1.302} \approx 80 \text{ ft} \quad (2)$$

$$TL - X = 530 - 80 = 450 \text{ ft}$$

$$\Delta V85_T = \frac{-2 \cdot (52) \pm \sqrt{4 \cdot (52)^2 + 5.208 \cdot (450)}}{2} \quad (3)$$

This implies the operating speed in Tangent CD is

$$V85T = 52 + 5 = 57 \text{ mph} \quad (4)$$

Tangent EF (7,920 feet) Independent, $V85 = 58$ mph.

Step (e)

Sequence	*Change in Degree of Curve ΔDC*	*Change in Operating Speed ΔV85*
Tangent AB to Curve BC	|0–6.4| = 6.4	|58–52| = 6 mph
Curve BC to Tangent CD	|6.4–0| = 6.4	|52–57| = 5 mph
Tangent CD to Curve DE	|0–8.0| = 8.0	|57–50| – 7 mph
Curve DE to Tangent EF	|8.0–0| = 8.0	|50–58| = 8 mph

Step (f_2)

For the existing alignment of figure 5, step (e) reveals that changes in degree of curve, and changes in operating speeds between tangent AB and curve BC in the direction AF, between tangent CD and curve DE in the direction AF, and between tangent EF and curve DE in the direction FA fall into the range of fair design.

Note that the degrees of curve of 6.4° and 8.0° correspond to radii of 900 feet and 720 feet. Since these radii lie between 600 feet and 1,200 feet, curve BC and curve DE, combined with independent tangents, fall into the range of fair design. This can be determined from figure 3, too, when radii of 720 feet and 900 feet are combined with a tangent (R is greater than or equal to 6,000 feet), according to the scale. The existing recommended speed of 45 mph combined with arrow designations, see figure 5, agrees well with the value of about 45 mph that can be determined from figure 1 for curve DE with a degree of curve of 8°. The expected accident rate can be determined from figure 2 or calculated from equation (3b). The observed accident rate was calculated from the following equation:

$$ACCR = \frac{(\text{No. Acc.}) \cdot (10^6)}{(365) \cdot (\text{No. Years}) \cdot (L) \cdot (AADT)} \quad (5)$$

where

$ACCR$ = number of accidents per 1 million vehicle miles,
No. Acc. = number of accidents per years investigated,
No. Years = number of years investigated,
L = length of curve or curved section in miles, and
$AADT$ = Average Annual Daily Traffic (vehicles in both directions).

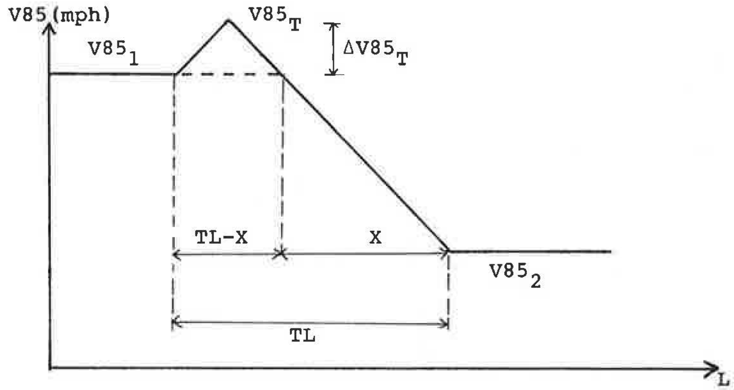
This implies that

	Expected Accident Rate	*Observed Accident Rate*
Curve BC	8.5	6.9
Curve DE	10.7	9.1

The expected accident rates agree, relatively well, with the observed ones and the mean accident rate for fair design of table 2.

Thus, one can conclude that the horizontal alignment of figure 5 corresponds to fair design practices and does not necessarily need improvements in geometric design. But it should not be forgotten that at least minor inconsistencies in

a)



Legend:

TL = Tangent length, greater than the maximum allowable lengths for "Non-Independent Tangents" of Table 3 (ft),

X = Acceleration or deceleration distance between curve 1 and curve 2 (ft),

$V85_1, V85_2$ = Operating speeds in curves (mph),

$V85_T$ = Operation speed in tangent (mph),

$\Delta V85_T$ = Difference between the operating speed in the curve with the lower degree of curve and the operating speed in the tangent (mph).

$$X = \frac{(V85_1 + V85_2) \cdot (V85_1 - V85_2)}{2.604} \qquad (4)$$

$$V85_T^{*} = V85_1 + \Delta V85_T \qquad (5)$$

$$\Delta V85_T = \frac{-2 \cdot (V85_1) \pm \sqrt{4 (V85_1)^2 + 5.208 (TL-X)}}{2} \qquad (6)$$

*Note that for determining $V85_T$ always the operating speed of the curve with the lower degree of curve has to be selected.

FIGURE 4 Example for estimating the operating speed in an independent tangent.

horizontal alignment do exist. For instance, despite the presence of traffic warning devices (recommended speeds of 45 mph and arrow signs), the accident rates on the observed curved sites are about twice as high as the mean accident rate for good design, as shown in table 2.

To achieve a high level of driving dynamic safety, it is recommended to increase the existing superelevation rates from six percent to nine percent during the next resurfacing project, as shown for curve DE by the following calculation:

$$e_{\max} = \frac{DC \cdot V85^2}{85{,}660} - f_R$$

$$e_{\max} = \frac{8 \cdot 50^2}{85{,}660} - 0.14 = 0.09$$

where fR = side friction factor obtained from table III-6 (*14*); $fR = 0.14$ (estimated for an operating speed of 50 mph).

Similar calculations have to be performed if stopping sight distances are insufficient.

Poor Design Practices

(*f*3) Determine all road sections where changes in degree of curve and changes in operating speeds correspond to the boundaries of poor design practices:

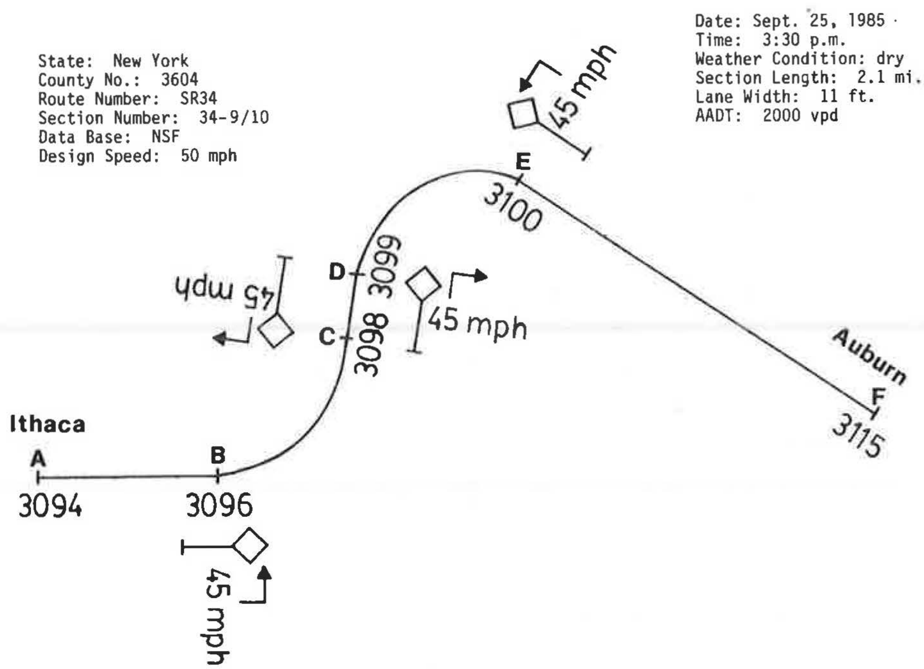
Range of change in degree of curve: $\Delta DC > 10°$.

Range of change in operating speed: $\Delta V85 > 12$ mph (20 km/h).

Result

These road sections represent strong inconsistencies in horizontal geometric design, combined with those breaks in the speed profile that may lead to critical driving maneuvers.

Despite stringent recommended speeds combined with arrow designations and chevrons (see figure 1), road sections with changes in degree of curve that fall into this range (10° to 15°) have about four times an average accident rate as those that



	Curve BC	Curve DE
Degree of Curve	6.4°	8.0°
Superelevation Rate	6%	6%
Measured 85th-percentile Speed* (Average for both directions)	--	53 mph
Stopping Sight Distance	0.1 mi.	0.1 mi.
Grade	0%	±0.5%
Recommended Speed	45 mph (Arrow Signs)	45 mph (Arrow Signs)
Number of Accidents++	3	2

*Not required for the design procedure, here only presented for comparison reasons.

++For an investigated period of three years (Jan. 1982 to Dec. 1984).

FIGURE 5 Case study of State Route 34 in the State of New York.

fall into the range of good design, and about twice as high as those that fall into the range of fair design (see table 2). Normally, for example, for RRR projects, high cost projects such as redesigns of at least hazardous road sections should be recommended, unless there was no documented safety problem.

Note

- Ranges of radii of successive curves that would represent poor design practices are shown in figure 3. For a tangent-to-curve sequence, curves with radii ($R < 600$ feet) should not be allowed to follow an independent tangent.
- Rough estimates of expected accident rates may be made possible from figures 1 and 2 or equations (3a) through (3c) in table 1, depending on the lane width.

PROCESS FOR EVALUATING DESIGN SPEED AND OPERATING SPEED DIFFERENCES

All reviewed highway geometric design guidelines (*8–14*) indicate that the design speed should be constant along longer roadway sections. Furthermore, the design speed (V_d) and the 85th-percentile speed ($V85$) must be well balanced to insure a fine tuning between road characteristic, driving behavior, and driving dynamics. Experiences (*1, 5, 6*) have shown that the design speed is sometimes lower than driver expectations and judgement of what the logical speed should be, especially on independent tangents. Therefore, harmonizing design speed and operating speed is another important goal that should be considered in rehabilitation of two-lane, rural highways.

To achieve this goal, it is recommended that the designer refer to step (c) and step (d) of the previous section and determine the expected 85th-percentile speed of every independent tangent or curve in the observed road section.

The 85th-percentile speed ($V85$) of every independent tangent, curve, or curved section must be tuned with the existing or selected design speed (V_d) in the following manner:

1. $V85 - V_d \leq 6$ mph (10 km/h) (good designs); no adaptations or corrections are necessary.
2. 6 mph $< V85 - V_d \leq 12$ mph (fair design); superelevation rates in curves or curved sections and stopping sight distances must be related to the expected 85th-percentile speed. Thus, it is inferred that the driving dynamic safety demand will not exceed the driving dynamic safety supply under wet pavement conditions, compare step (f_2).
3. $V85 - V_d > 12$ mph (20 km/h) (poor design). The 85th-

percentile speed should not be allowed to exceed the design speed by more than 12 mph (20 km/h). If such a difference occurs, normally the design speed should be increased. For example, redesigns of hazardous road sections are recommended, unless there was no documented safety problem.

With regard to a well-balanced design one should strive for a uniform design speed within an observed road section of substantial length, especially between independent tangents and curves. This conclusion is well expressed in the AASHTO Design Guide (*14*), as follows:

> In horizontal alignment, predicted on a given design speed, consistent alignment always should be sought. Sharp curves should not be introduced at the end of long tangents. Sudden changes from areas of flat curvature to areas of sharp curvature should be avoided. Where sharp curvature must be introduced it should be approached, where possible, by successively sharper curves from the generally flat curvature.

This can be done by applying the ranges of good designs, or, if necessary, of fair designs in figure 3.

In an example related to figure 5, where the design speed is 50 mph,

Design Speed: 50 mph

Section	$V85 - V_d$ *(mph)*	ΔV *(mph)*
Tangent AB	58 − 50	8
Curve BC	52 − 50	2
Tangent CD	57 − 50	7
Curve DE	50 − 50	0
Tangent EF	58 − 50	8

The results are inconsistent. At least for three design elements the differences between operating speeds and design speeds correspond to fair design practices 6 mph $< V85 - V_d \leq$ 12 mph. That means that minor inconsistencies in horizontal alignment do exist. However, correcting the existing alignment is not necessary since a documented safety problem related to fair designs does not exist (compare step (f_2)). Superelevation rates on curves have to be adjusted to the expected operating speeds to achieve a high level of driving dynamic safety, as it was shown in step (f_2).

CONCLUSION

By applying this procedure, the highway engineer can easily control good and fair designs and can detect poor horizontal designs during RRR project planning. The procedure has been illustrated using existing alignments to verify its validity, but such a technique could be applied as well for new designs, major reconstructions, or redesigns. From knowledge of degree of curve of each curve, and the existing transition length (length of transition curves or length of tangent) between two curves, the highway engineer can evaluate the horizontal alignment during the design stages according to the discussed design procedure.

For example, where the design analysis reveals road sections of fair or even poor designs, these sections can be corrected by changing the design element sequences in question. Such changes may be an independent tangent-to-curve sequence, or a curve-to-curve sequence, according to design-element sequences for good design practices shown in figure 3.

The impact of tuning the alignment in this way would result, in general, in more curvilinear alignments. Furthermore, the designer can predict expected operating speeds and accident rates on curved sections by applying the nomograms of figures 1 and 2. However, because of the low coefficients of determination for the accident rate related regression equations, caution should be exercised when using the equations for prediction purposes. In addition, the designer can predict appropriate recommended speeds by using figure 1 in cases where fair designs have to be maintained, or even newly introduced, such as when poor designs can only be improved to fair designs because of terrain or other constraints.

Finally, the design speed concept can be applied in the future in a more appropriate way by harmonizing design speeds and expected operating speeds for the selected design element sequences, already during the design stages.

It is felt that routine use of a procedure such as this by design agencies could lead to more cost effective and safe geometry for new designs, major reconstruction, and, especially, RRR projects. It is hoped that such procedures will be adopted and will ultimately become a part of national and state guidelines.

Note, the prediction equations formulated and cross-validated in this study are based on data from a limited geographic area of the state of New York and may only be appropriate for investigations within that state or region. Some caution should be exercised in extrapolating the design procedure to other areas with differing laws, law enforcement, driver behavior, terrain, weather, and traffic control devices. The models are quite possibly applicable in wider areas (and that is certainly desirable), but testing will be required to determine their suitability in other geographical areas.

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