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

Ruediger Lamm, Elias M. Choueiri, John C. Hayward, and Anand Paluri

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 accident rates 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 accident rates 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, super-elevation 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:

\[ V_{85} = 34.700 - 1.005DC + 2.081LW + 0.174SW + 0.0004AADT \]

\[ R^2 = 0.842 \]

\[ SEE = 2.814 \]

where

- \( V_{85} \) = 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).
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 (V85); 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.

\[
V85 = 58.656 - 1.135\text{DC} \quad R^2 = 0.787 \quad \text{SEE} = 3.259
\]  

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>
<thead>
<tr>
<th>All lanes</th>
<th>10-ft lanes</th>
<th>11-ft lanes</th>
<th>12-ft lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V85 = 58.656 - 1.135\text{DC}; R^2 = 0.787$</td>
<td>$V85 = 55.646 - 1.019\text{DC}; R^2 = 0.753$</td>
<td>$V85 = 58.310 - 1.052\text{DC}; R^2 = 0.746$</td>
<td>$V85 = 59.746 - 0.998\text{DC}; R^2 = 0.824$</td>
</tr>
<tr>
<td>$V85 = 25.314 + 0.554\text{RS}; R^2 = 0.719$</td>
<td>$V85 = 27.173 + 0.459\text{RS}; R^2 = 0.556$</td>
<td>$V85 = 29.190 + 0.479\text{RS}; R^2 = 0.744$</td>
<td>$V85 = 26.544 + 0.562\text{RS}; R^2 = 0.835$</td>
</tr>
<tr>
<td>$\text{ACCR} = -0.880 + 1.410\text{DC}; R^2 = 0.434$</td>
<td>$\text{ACCR} = -1.023 + 1.513\text{DC}; R^2 = 0.300$</td>
<td>$\text{ACCR} = -0.257 + 1.375\text{DC}; R^2 = 0.462$</td>
<td>$\text{ACCR} = -0.546 + 1.075\text{DC}; R^2 = 0.726$</td>
</tr>
</tbody>
</table>

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./10⁶ vehicle-miles), range: 1° to 27°,
- RS = Posted recommended speed in the curve or curved section (mph),
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 curves 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: \(\Delta DC \leq 5^\circ\).
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: \(5^\circ < \Delta DC \leq 10^\circ\).
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: \(\Delta DC > 10^\circ\).
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 \(5^\circ\) 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 \(5^\circ\) and \(10^\circ\) between successive design elements (defined as fair designs), the average accident rate in table 2 is twice as high as for those between \(1^\circ\) and \(5^\circ\). For changes between \(10^\circ\) and \(15^\circ\) of curve (defined as poor designs), the accident rate is four times the rate associated with degrees of curve between \(1^\circ\) and \(5^\circ\). 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 \(10^\circ\) should be interpreted as poor designs while those in the range between \(5^\circ\) and \(10^\circ\) 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
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 ≤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 ∆DC > 10°, as compared to sections with a change in degree of curve of ∆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 \( \sim 350 < R < 900 \) feet and
- fair designs: with a range of radii between \( \sim 270 < R < 3,500 \) feet.

Regarding a sequence tangent-to-curve, the boundaries of good designs (\( DC \leq 5^\circ \)) 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 (\( 5^\circ < DC \leq 10^\circ \)) 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
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

<table>
<thead>
<tr>
<th>V85 in Curve</th>
<th>34</th>
<th>40</th>
<th>46</th>
<th>52</th>
<th>58</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>250</td>
<td>425</td>
<td>625</td>
<td>850</td>
<td>1100</td>
</tr>
<tr>
<td>28</td>
<td>325</td>
<td>500</td>
<td>725</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>375</td>
<td>600</td>
<td>850</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>425</td>
<td>675</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;46</td>
<td></td>
<td></td>
<td>475</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 direc-
tions 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 hor-
izontal 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-tocurve 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 oper-
ating 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 ($\Delta DC$), and the
change in operating speeds ($\Delta V_{85}$) for the independent tan-
gent-to-curve or curve-to-curve sequence.

Good Design Practices

(f1) 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: $\Delta DC \leq 5^\circ$.
- Range of change in operating speed: $\Delta V_{85} \leq 6$ mph (10
  km/h).

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 ($R \geq 1,200$ 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

(f2) 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: $5^\circ < \Delta DC \leq 10^\circ$.
- Range of change in operating speed: $6$ mph $\leq \Delta V_{85} \leq 12$
  mph.

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.

To achieve a high level of driving safety, superelevation
rates and stopping-sight distances should be related to the
expected operating speeds wherever possible.
Step (a)
State of New York,
County No. 3604,
Route Number SR34 (mile markers 3094-3115),
Lane Width 11 feet.

Step (b)

<table>
<thead>
<tr>
<th>Section</th>
<th>Design Element</th>
<th>Degree of</th>
<th>Curve</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-B</td>
<td>Tangent</td>
<td>0</td>
<td>0.2 mi - 1,060 ft</td>
<td></td>
</tr>
<tr>
<td>B-C</td>
<td>Curve</td>
<td>6.4</td>
<td>0.2 mi - 1,080 ft</td>
<td></td>
</tr>
<tr>
<td>C-D</td>
<td>Tangent</td>
<td>0</td>
<td>0.1 mi - 530 ft</td>
<td></td>
</tr>
<tr>
<td>D-E</td>
<td>Curve</td>
<td>8.0</td>
<td>0.1 mi - 530 ft</td>
<td></td>
</tr>
<tr>
<td>E-F</td>
<td>Tangent</td>
<td>0</td>
<td>1.5 mi - 7,920 ft</td>
<td></td>
</tr>
</tbody>
</table>

Step (c)

<table>
<thead>
<tr>
<th>Expected 85th-Percentile Speed</th>
<th>From Figure 2 or Equation</th>
<th>Measured 85th-Percentile Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve BC</td>
<td>52 mph</td>
<td>Figure 2 or Eqn. (1b)</td>
</tr>
<tr>
<td>Curve DE</td>
<td>50 mph</td>
<td>53 mph</td>
</tr>
</tbody>
</table>

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 \( V_{85} = 58 \) 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:

\[
X = \frac{(52 + 50) \cdot (52 - 50)}{2 \cdot 1.302} = 80 \text{ ft}
\]

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

\[
\Delta V_{85r} = \frac{-2 \cdot (52) \pm \sqrt{4 \cdot (52)^2 + 5.208 \cdot (450)}}{2}
\]

This implies the operating speed in Tangent CD is

\[
V_{85T} = 52 + 5 = 57 \text{ mph}
\]

**Tangent EF (7,920 feet)** Independent, \( V_{85} = 58 \) mph.

Step (e)

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Change in Degree of Curve ( \Delta DC )</th>
<th>Change in Operating Speed ( \Delta V_{85} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent AB to Curve BC</td>
<td>[0-6.4] = 6.4</td>
<td>[58-52] = 6 mph</td>
</tr>
<tr>
<td>Curve BC to Tangent CD</td>
<td>[6.4-6] = 6.4</td>
<td>[52-57] = 5 mph</td>
</tr>
<tr>
<td>Tangent CD to Curve DE</td>
<td>[0-8.0] = 8.0</td>
<td>[57-50] = 7 mph</td>
</tr>
<tr>
<td>Curve DE to Tangent EF</td>
<td>[8.0-0] = 8.0</td>
<td>[50-58] = 8 mph</td>
</tr>
</tbody>
</table>

Step (f2)

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:

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

where

\[
ACCR = \text{number of accidents per 1 million vehicle miles,}
\]

\[
\text{No. Acc.} = \text{number of accidents per years investigated,}
\]

\[
\text{No. Years} = \text{number of years investigated,}
\]

\[
L = \text{length of curve or curved section in miles, and}
\]

\[
AADT = \text{Average Annual Daily Traffic (vehicles in both directions).}
\]

This implies that

<table>
<thead>
<tr>
<th>Sequence</th>
<th>Expected Accident Rate</th>
<th>Observed Accident Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curve BC</td>
<td>8.5</td>
<td>6.9</td>
</tr>
<tr>
<td>Curve DE</td>
<td>10.7</td>
<td>9.1</td>
</tr>
</tbody>
</table>

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
Poor Design Practices

(f3) 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: $\Delta DC > 10^\circ$.
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 ($10^\circ$ to $15^\circ$) have about four times an average accident rate as those that
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 \( R \leq 600 \text{ feet} \) 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 \( (V_{85}) \) must be well balanced to ensure 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 judgment 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 \( (V_{85}) \) 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. \( V_{85} - V_d \leq 6 \text{ mph} \) (good design); no adaptations or corrections are necessary.
2. \( 6 \text{ mph} < V_{85} - V_d \leq 12 \text{ mph} \) (fair design); superelevation rates in curves or curved sections and stopping sight distances must be related to the expected 85th-percentile speed.
3. \( V_{85} - V_d > 12 \text{ mph} \) (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, redemissions 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,

<table>
<thead>
<tr>
<th>Section</th>
<th>$V_{85} - V_d$ (mph)</th>
<th>$\Delta V$ (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tangent AB</td>
<td>58 - 50</td>
<td>8</td>
</tr>
<tr>
<td>Curve BC</td>
<td>52 - 50</td>
<td>2</td>
</tr>
<tr>
<td>Tangent CD</td>
<td>57 - 50</td>
<td>7</td>
</tr>
<tr>
<td>Curve DE</td>
<td>50 - 50</td>
<td>0</td>
</tr>
<tr>
<td>Tangent EF</td>
<td>58 - 50</td>
<td>8</td>
</tr>
</tbody>
</table>

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 $< V_{85} - V_d \leq 12$ 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 redemissions. 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 reconstructions, and, especially, RRR projects. It is hoped that such procedures will be adopted and will ultimately become a part of national and state guidelines.

ACKNOWLEDGMENTS

This study was sponsored by the New York State Governor's Traffic Safety Committee, Albany, New York, and by the National Science Foundation. The senior author wishes to thank the members of the TRB Geometric Design Committee for their encouragement and their valuable discussions while the research on consistency of highway geometric design was being conducted. Special thanks go to Prem Goyal for his assistance in preparing the example applications.

REFERENCES

References with an asterisk (*) have been translated from their original language into English for easy reference in the United States. The authors apologize for any inaccuracies that may have resulted as a consequence of the process of translation.


Publication of this paper sponsored by Committee on Geometric Design.