Tangent as an Independent Design Element

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Reviews of design guidelines for rural roads in Germany, France, and Switzerland reveal that highway designers adhere to controls on maximum and minimum lengths of tangents between successive curves. Minimum tangent lengths are prescribed to promote operating speed consistency, and maximum lengths are suggested to combat driver fatigue. Current U.S. practice does not set maximum or minimum lengths of tangents; instead current AASHTO policy favors long tangent sections for passing purposes on two-lane, rural roads. This paper presents a recommended strategy for U.S. highway designers to consider tangent lengths explicitly in rural highway design. The proposed approach uses recommended operating speed differences between successive horizontal geometric elements (curves and tangents) and acceleration or deceleration profiles derived from car-following tests to establish limits. Recommendations are also provided for transition lengths (tangent length) between successive curved roadway sections for (a) tangents that should be regarded as "non-independent" design elements; that is, the sequence "curve-to-curve" is the most important element of the design process and (b) tangents that should be regarded as "independent" design elements; that is, the sequence "tangent-to-curve" is the most important element of the design process.

In the highway geometric design process, tangents and horizontal curves with or without transition curves are regarded as design elements. Most of the reviewed highway geometric design guidelines (*1–7*) give recommendations for maximum or minimum tangent lengths.

For example, in the Federal Republic of Germany (*2, 3*) tangent lengths between curves are limited by the design speed. The maximum length in meters of tangent sections between two curves may not exceed twenty times the design speed of that roadway. In this way long tangents are controlled and a curvilinear environment is encouraged.

Minimum tangent lengths must be at least six times the design speed. For a typical design speed of 100 km/h (~60 mph) this would correspond to a maximum tangent length of 2,000 meters (6,500 feet) and a minimum tangent length of 600 meters (2,000 feet).

To avoid driver fatigue, it is recommended in France (*6*) that tangent sections be limited to a maximum of 40 to 60 percent of long roadway sections with maximum single tangent lengths between 2,000 and 3,000 meters (6,500 to 10,000 feet).

Swiss highway officials (*3, 4*) also limit tangent lengths to limit driver fatigue. Designs that permit more than one minute of driving on a straight section are not permitted. Minimum tangent lengths are related to "project speeds," which roughly translate to American practice as "theoretical operating speeds." For example, for a project speed of 100 km/h (~60 mph) a minimum tangent length of 150 meters (500 feet) would be permitted.

In the 1984 AASHTO Policy on Geometric Design of Highways and Streets (*1*), specific values for maximum or minimum tangent lengths are not specified. But the following statement is listed under General Controls for Horizontal Alignment: "Although the aesthetic qualities of curving alignment are important, passing necessitates long tangents on two-lane highways with passing sight distance on as great a percentage of the length of highway as feasible." This statement clearly supports the application of long tangents, especially for the design of two-lane, rural highways.

The only method developed to evaluate acceleration or deceleration movements between sequences of curve-to-curve or tangent-to-curve was found in the geometric design guidelines of Switzerland (*3, 4*). The Swiss have developed a formula for calculating transition lengths (tangent length), that is, the distance required for acceleration or deceleration of a vehicle as it approaches or leaves a curve based on the project speed difference between two curves or between a tangent and a curve. Unallowable ranges, or those that should be avoided for these transition lengths, are also tabulated (*8*).

BACKGROUND AND OBJECTIVE

In several publications and research reports (*8–15*) the authors recommend the following boundaries for changes in degree of curve and operating speed between successive design elements for good, fair and poor design practices. With the exception of some very good designs, the existing American design for low-volume, two-lane rural roads consists of sequences of curves and tangents where the transitions are rarely equipped with transition curves.

- Good design is present where successive changes in degree of curve are limited to 5°, and changes in operating speeds are limited to 6 mph (10 km/h) between successive design elements. The horizontal alignment operates well.
- Fair designs exist where changes of 5–10° in degree of curve are present, and changes of 6 mph to 12 mph (20 km/h) in operating speeds between successive design elements are permitted. Normally, low-cost projects such as traffic warning devices are warranted unless there is a documented safety problem.
- Poor designs show changes of more than 10° in degree

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of curve and differences of more than 12 mph (20 km/h) in operating speeds. Normally, high-cost projects such as redesign of at least hazardous road sections are recommended, unless there is no documented safety problem.

Furthermore, the following prediction equation was developed in references (13–15) for the relationship between expected operating speed and degree of curve, including all investigated lane widths from 10 feet to 12 feet.

$$V85 = 58.656 - 1.135DC;\ R^2 = 0.787 \qquad (1)$$

where

- $V85$ = Estimate of operating speed, expressed by the 85th-percentile speed for passenger cars (mph),
- DC = Degree of curve (degree/100 ft), range: 0° to 27°, and
- R^2 = Coefficient of determination.

(The above equation is valid for road sections with grades less than or equal to 5 percent and annual average daily traffic (ADT) values between 400 and 5,000 vehicles per day.)

To illustrate the application of equation (1), the following operating speeds could be expected in a sequence from a tangent to a curve with a degree of curve of 15° or vice versa:

Tangent: $DC = 0° \rightarrow \rightarrow V85 \sim 58$ mph

Curve: $DC = 15° \rightarrow \rightarrow V85 \sim 41$ mph

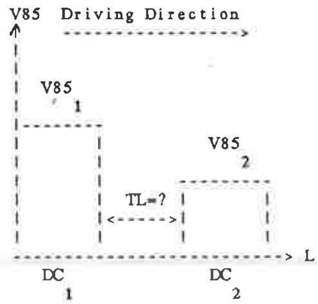
The speed change from the tangent to the curve is $\Delta V85$ = 17 mph. This value is far beyond the maximum allowable change in operating speeds, even for fair design practices defined above where $\Delta V85 \leq 12$ mph.

However, this statement would be true only for a relatively long tangent. The tangent must be long enough that a driver can reach the top 85th-percentile speed of 58 mph expressed by equation (1) for $DC = 0°$. For shorter tangents between succeeding curves, it would be expected that the average driver in a typical vehicle would not be able to accelerate or decelerate in such a way that the boundaries for good design practices ($\Delta V85 \leq 6$ mph) or even for fair design practices ($\Delta V85 \leq 12$ mph) may be exceeded. In those cases, operating speed changes would be related to the two successive curves, and the relatively short tangent between could be neglected in the design process for evaluating horizontal design consistency or inconsistency and for harmonizing design speed and operating speed. Therefore, the task of this research is to provide recommendations for transition lengths (tangent lengths) between successive curves for

- Tangents that should be regarded as non-independent design elements and the sequence curve-to-curve controls the design process, and
- Tangents that should be regarded as independent design elements and the sequence tangent-to-curve controls the design process.

ACCELERATION AND DECELERATION RATES

The transition length (TL) is that road section where the operating speed is changing between two design elements with the operating speeds $V85_1$ and $V85_2$ as assumed in the following sketch (3, 4). The transition length is given by



$$TL = (v_1^2 - v_2^2)/2a = \frac{v_1 + v_2}{2} \cdot \frac{v_1 - v_2}{a} = \frac{\overline{V85} \cdot \Delta V85}{0.465a} \qquad (2)$$

where

- $\overline{V85}$ = average 85th-percentile speed between successive curves (mph),
- $\Delta V85$ = difference between the 85th-percentile speeds (mph),
- TL = transition length (tangent length) (ft), and
- a = acceleration/deceleration rate (ft/sec^2).

When the degrees of curve of two successive design elements are known, the expected 85th-percentile speeds can be determined by equation (1). To evaluate the transition lengths from equation (2), acceleration or deceleration rates between successive design elements must be known.

To determine an estimate of the coefficient a in equation (2), typical accelerations and decelerations were studied between tangents and specific curved sections of two-lane rural highways (13–15). Because of financial and time constraints, acceleration and deceleration movements from tangents-to-curves or curves-to-tangents were made at curves where speeds of 30 mph (three sections), 35 mph (two sections), and 40 mph (one section) were recommended. The study sites were located in St. Lawrence County in New York.

The optimal procedure required that the speeds of individual vehicles be recorded. To accomplish this, an investigation car (the "follow car"), a car observed in the field (the "test car"), and a tape recorder on which to place any relevant information were used. Note that two persons, a driver and an observer, were required in the "follow car" to allow observation of the situation while speed data were being recorded.

Measurements of travel speeds were made at particular points along the routes. The measurement points were uniform in characteristics:

- Sections were horizontal (longitudinal grades less than 1.5%).
- Intersections and places where an influence on traffic flow might be expected through changes in the highway surroundings were not present in the sections.
- Cross sections were representative with regard to the width of the roadway. Three sections with 10-ft lane width and three sections 11-ft lane width were selected.
- Sight conditions at measuring points were adequate.
- Points of measurements were equipped so as not to be recognizable as such by drivers but obvious enough to be seen by the observers in the follow car.

In all cases, eleven spots (from the beginning of the curve into the tangent section) marked with driveway reflectors were set up along the routes investigated on both sides of the roadway. The distance between two spots was 250 feet; thus, the measurement sections were about ½-mi long. On the average, the recommended speed plates were located about 500 feet (0.1 mile) from the curves in the deceleration direction, while in the acceleration direction at this spot the normal speed limit of 55 mph was posted.

The car speeds were measured during off-peak periods of the week, during dry conditions, and in daylight. The traffic flows were light, and cars were capable of attaining the speeds they desired under the conditions of the site; in other words, a car was selected for speed survey if it had sufficient headway to be considered travelling at its own free speed.

With regard to the analysis process, the observer in the follow car observing the cars crossing his field of view had to select the cars to be sampled. Once a car was spotted under free-flow conditions, an initial acceleration by the driver of the follow car was made in order to catch up and adjust his speed to that of the test vehicle. Then, at each of the study spots along the highway, the observer in the follow vehicle would record the speed of the test vehicle by reading the speed from the speedometer of the follow car. Other relevant information, such as the sex and approximate age of the driver of the test vehicle and the type and mark of the test vehicle, were also recorded, but their effect was not considered in this study. A distance of at least one mile was necessary for the follow car to accelerate and adjust its speed to that of the test car.

All conflicts in which evasive action was taken, such as turning maneuvers into driveways before the end of the speed measurements, were recorded, but those measurements were not considered in the analysis.

Normally the speeds of at least twenty passenger cars (test cars) were recorded on the tape recorder at each of the eleven test points along the routes investigated from the tangent to the curve (deceleration) and from the curve to the tangent (acceleration). The data on the tape recorder was later analyzed, and the 85th-percentile speed at each of the set-up test spots was determined.

Regression equations relating the 85th-percentile speeds to distances travelled are as follows:

Acceleration:
Recommended Speed in Curve: 30 mph

$$V85 = 37.0 + 0.05DT - 0.00002DT^2 \quad (3a)$$

Recommended Speed in Curve: 35 mph

$$V85 = 42.0 + 0.04DT - 0.00002DT^2 \quad (3b)$$

Recommended Speed in Curve: 40 mph

$$V85 = 47.0 + 0.04DT - 0.00002DT^2 \quad (3c)$$

Deceleration:
Recommended Speed in Curve: 30 mph

$$V85 = 33.0 + 0.05DT - 0.00002DT^2 \quad (4a)$$

Recommended Speed in Curve: 35 mph

$$V85 = 38.0 + 0.04DT - 0.00002DT^2 \quad (4b)$$

Recommended Speed in Curve: 40 mph

$$V85 = 43.0 + 0.04DT - 0.00002DT^2 \quad (4c)$$

where

$V85$ = estimate of 85th-percentile speed (mph), and
DT = distance travelled (feet).

The above equations are plotted in figures 1 and 2. The acceleration and deceleration processes are clearly indicated to end or begin at about 700 to 750 feet from the end of the observed curved sections. This means that any reaction from

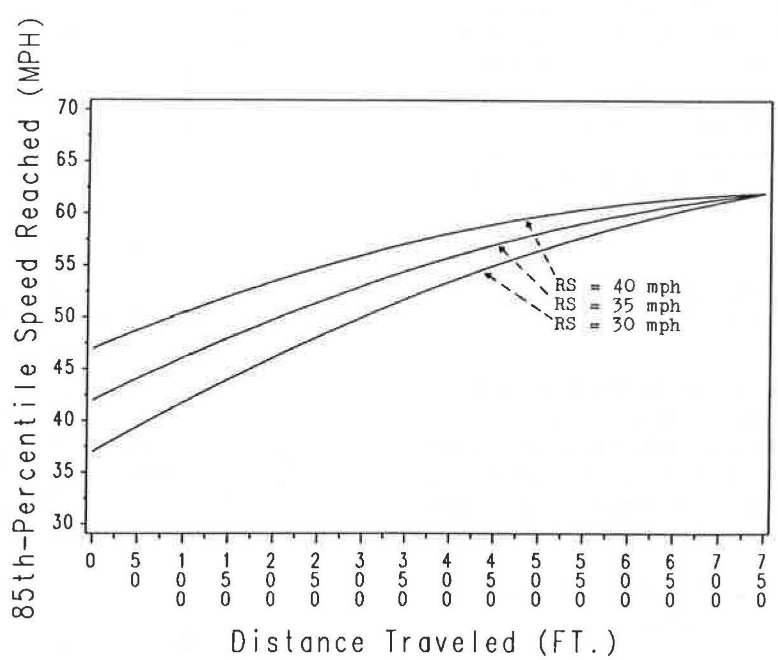


FIGURE 1 85th-Percentile speed vs. distance traveled; passenger cars (acceleration).

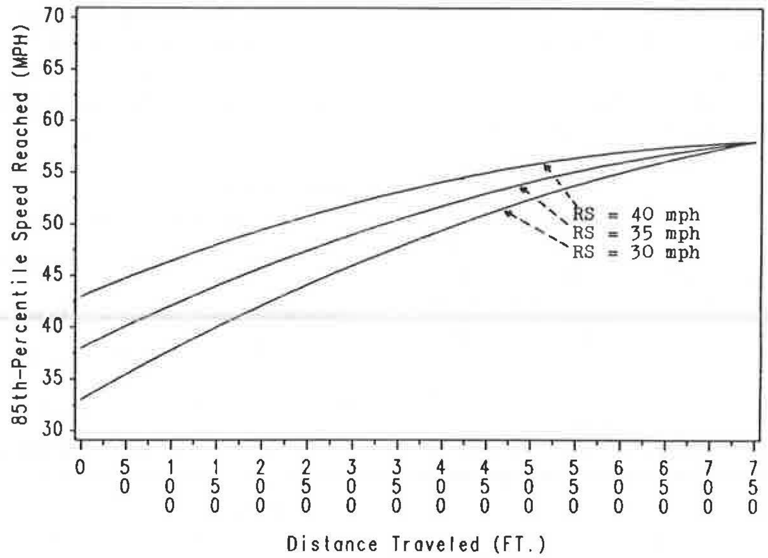


FIGURE 2 85th-Percentile speed vs. distance traveled; passenger cars (deceleration).

the driver in the deceleration direction begins nearly 200 to 250 feet from the recommended speed plates, which are normally posted 500 feet in front of a curve or a curved section. Another finding is that the operating speeds at the beginning of a curve in the deceleration direction are nearly 4 to 5 mph lower (figure 2), than those at the end of the curve in the acceleration direction (figure 1).

Related to the distance of 750 feet, the average deceleration and acceleration rates ranged between 2.8 and 2.9 ft/sec^2 for the tested six road sections consisting of tangents (length of at least ½ mile) followed by curves with recommended speeds between 30 and 40 mph. Since the differences between deceleration and acceleration rates are more or less negligible, an average acceleration or deceleration rate of 2.8 ft/sec^2 was selected for the following analysis. This value agrees well with the deceleration and acceleration rate of 0.8 m/sec^2 (2.64 ft/sec^2) on which the design of transition lengths in the Swiss Standard (*3, 4*) is based. Furthermore, this value agrees well with the values in the AASHTO design guide (*1*), table III-4, where average acceleration rates of about 2.1 ft/sec^2 for passing maneuvers in the speed groups 30 to 40 mph and 40 to 50 mph are tabulated.

DETERMINATION OF NECESSARY TRANSITION LENGTHS (TANGENT LENGTHS)

For traffic safety reasons driving behavior during the deceleration process is a particularly important factor.

As previously outlined, operating speed differences $\Delta V85$ between two successive design elements greater than 6 mph should be avoided for good designs and greater than 12 mph for fair designs. An illustration of the above conclusion is given in figure 3.

With an average acceleration or deceleration rate of a = 2.8 ft/sec^2 the transition length in equation (2) now reads:

$$TL = \frac{\overline{V85} \cdot \Delta V85}{1.302} \quad (5)$$

where

$\overline{V85}$ = average 85th-percentile speed between successive curves (mph),

$\Delta V85$ = difference between the 85th-percentile speeds (mph), and

TL = transition length (tangent length)(in feet).

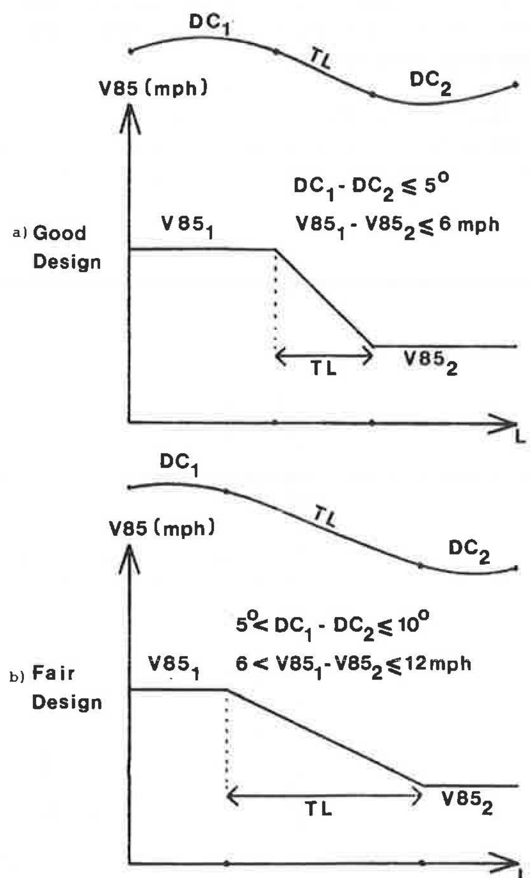


FIGURE 3 Transition length between successive design elements.

TABLE 1 NECESSARY TRANSITION LENGTHS (TANGENT LENGTHS) FOR GOOD AND FAIR DESIGN PRACTICES

V85 1 resp. V85 2 (mph) \ V85 2 resp. V85 1 (mph)	22	28	34	40	46	52	58
22							
28	115*						
34	260	145*					
40	430	315	170*				
46	625	510	370	200*			
52	850	735	595	425	225*		
58	1105	990	850	675	480	255*	

* good designs

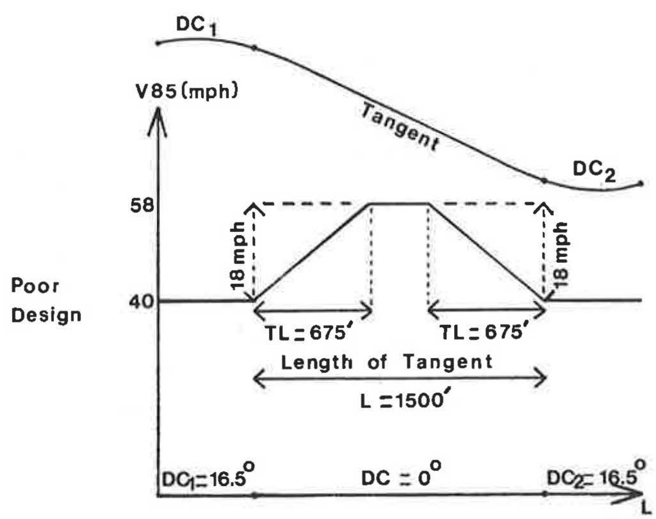
|___| fair designs

Based on the above equation, necessary transition lengths for good and fair design practices are shown in table 1. The values with an asterisk represent good design practices, meaning a driver is able to decelerate or accelerate within the range of operating speed changes of up to 6 mph. The values within boxes represent fair design practices, meaning a driver is able to decelerate or accelerate within the range of operating speed changes of up to 12 mph (see figure 3).

Thus, from the viewpoint of reasonable changes in degree of curve and the corresponding changes in operating speeds, the transition lengths (mostly expressed by tangents) in table 1 should represent maximum boundaries for good and for fair design practices.

In all the other cases (see, for example, the unmarked values in table 1), a driver is able to exceed the recommended operating speed changes, which may result in critical driving maneuvers, especially during the deceleration process.

An illustration of the above statement is given in figure 4 for a sequence of two curves ($DC = 16.5°$) joined by a relatively long tangent ($DC = 0°$, $L = 1{,}500$ ft). The 85th-percentile speeds can be determined from equation 1. As can be seen from figure 4, a driver is able to accelerate within the tangent from an operating speed of 40 mph in the curve to the highest operating speed of 58 mph in the tangent, for which, according to table 1, a transition length of 675 ft is needed. In this example the maximum allowable operating speed change even for fair designs of $\Delta V85 \leq 12$ mph has thus been exceeded, a clear indication of poor design practices.



$\Delta DC = 16.5° > 10°$ (poor design)

$\Delta V85 = 18$ mph > 12 mph (poor design)

FIGURE 4 Example of poor design practices.

RECOMMENDATIONS FOR TANGENTS

The majority of transitions between curves on the two-lane, rural highway network in the United States consist of tangents, with the exception of very good designs where transition curves are applied and operating speed changes exceeding the boundaries for good design or even fair design normally do not exist.

With regard to tangents between succeeding curves the following criteria must be distinguished:

1. The transition lengths (tangent lengths) given in table 1 represent maximum boundaries to allow non-critical deceleration or acceleration movements between successive curves for good or fair designs. In order not to be too conservative, tangent lengths between two successive curves, which fall in the range of fair design practices (table 1) may be considered as non-independent design elements. That means, changes in degrees of curve and operating speeds between two successive curves may be calculated directly without regarding the tan-

gent in-between as an independent design element. By this assumption the most critical case for fair design practices, especially during a deceleration process ($\Delta V85$ = 12 mph, see figure 3b) is covered. In all the other cases ($\Delta V85$ < 12 mph) the tangent lengths are not sufficient for the average driver to decelerate or accelerate in such a way that the assumed boundaries of operating speed changes for fair or even good designs are exceeded.

Note that the values of the transition lengths for fair design practices (table 1) agree well with the lengths of superelevation runoffs provided in table III-14 (*1*) in case of a reversal in alignment, for example, for a maximum superelevation rate of 8 percent.

2. Tangent lengths between successive curves that exceed the values of fair design (table 1) should be regarded as independent design elements. In these cases a driver is able to accelerate or decelerate in such a way that even the maximum allowable operating speed changes for fair designs ($\Delta V85 \leq$ 12 mph) may be exceeded; that means, critical driving maneuvers already have originated. Therefore, in case of a relatively long tangent between two successive curves, changes in degrees of curve and operating speeds on this section must be calculated by regarding the tangent in between as an independent design element (see, for example, figure 4).

DESIGN PROCEDURE WITH EXAMPLE APPLICATIONS

The results of table 1 are rounded in table 2, where the values within boxes represent the maximum allowable lengths of tangents regarded as non-independent design elements, as outlined in the previous section. The values with an asterisk represent lengths of tangents for which, related to the speed changes of table 2, 85th-percentile speeds of 58 mph can be reached. As the research of the authors (*11, 15*) has revealed, on long tangents an 85th-percentile speed value of 58 mph is a good estimate for a degree of curve DC = 0°, see equation (1). Thus, the maximum operating speed in tangents will be confined in what follows to this value.

To evaluate a tangent between two successive curves as independent and to estimate the expected operating speed in the tangent ($V85_T$), the following procedure is recommended:

(1) Assess the tangent length (TL) between the two successive curves (these may be in the field, as in the case of RRR projects, or in the design stages for new designs, major reconstructions, or redesigns).

(2) Determine for the degree of curve 1 (DC_1) and the degree of curve 2 (DC_2) the corresponding 85th-percentile speeds ($V85_1$ and $V85_2$) by applying equation (1).

(3) Compare the existing tangent length between the two successive curves with the maximum allowable tangent length (from table 2) that corresponds to the nearest 85th-percentile speed of the curve with the higher degree of curve.

(4) Conclude that if the existing tangent length is smaller than the maximum allowable one, then the tangent is to be regarded as non-independent. That means changes in degree of curve and operating speed will be especially related to the two successive curves since the tangent can be assumed to be negligible. Note that the requirements for sufficient lengths of superelevation runoffs should be fulfilled.

TABLE 2 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*

[ ] 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.

Example

$TL = 300$ ft,
$DC_1 = 3° \rightarrow\rightarrow\rightarrow V85_1 = 55$ mph,
$DC_2 = 9° \rightarrow\rightarrow\rightarrow V85_2 = 48$ mph, see equation (1).

The 85th-percentile speed in table 2 that is closest to 48 mph in the curve with the higher degree of curve is 46 mph. (This simplification was done for an easier application of table 2.) For 46 mph the maximum length of tangents regarded as non-independent is 475 feet. Since $TL = 300$ feet < 475 feet, the tangent has to be evaluated as non-independent design element, and no individual operating speed ($V85_T$) is to be assigned to the tangent.

Thus, only the sequence curve-to-curve with the corresponding operating speeds ($V85_1$ and $V85_2$) plays an important role in the design process for evaluating horizontal design consistency or inconsistency, since the tangent in between can be assumed to be negligible. For the example discussed a change in degree of curve and operating speed

$\Delta DC = |3° - 9°| = 6°$, and

$\Delta V85 = |55 - 48 \text{ mph}| = 7$ mph

can be expected on the above road section. In conformity with the recommended boundaries for good, fair, and poor design practices, the existing horizontal alignment thus corresponds to fair designs ($\Delta V85 > 6$ mph).

(5) Conclude that if the existing tangent length between successive curves is greater than the maximum allowable (table 2), then the tangent is to be regarded as an independent design element. That means, changes in degree of curve and operating speed are to be especially related to the sequence tangent-to-curve. The 85th-percentile speed in the tangent ($V85_T$) can be estimated as outlined in the following examples, see figure 5.

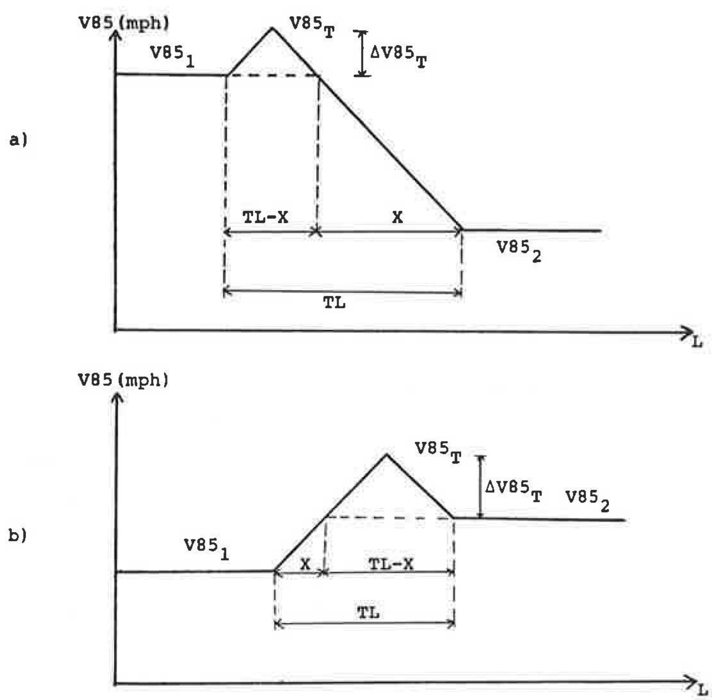
Example Related to Figure 5a

$TL = 0.20$ mi $\sim$ 1,050 ft,

$DC_1 = 6° \rightarrow\rightarrow\rightarrow V85_1 = 52$ mph,

$DC_2 = 22.4° \rightarrow\rightarrow\rightarrow V85_2 = 33$ mph, see equation (1).

The 85th-percentile speed in table 2 that is closest to 33 mph in the curve with the higher degree of curve is 34 mph. For 34 mph the maximum length of tangents regarded as non-independent is 375 feet.



Legend:

TL = Tangent length, greater than the maximum allowable lengths for "Non-Independent Tangents" of Table 2 (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).

FIGURE 5 Typical examples for estimating operating speed in independent tangents.

Since TL = 1050 feet > 375 feet the tangent has to be evaluated as an independent design element. Thus, the sequence tangent-to-curve plays an important role in the design process for evaluating horizontal design consistency or inconsistency for both directions of travel on this road section. The 85th-percentile speed in the tangent ($V85T$) can be estimated as shown below (see figure 5a).

Equation (5) is used to calculate the acceleration or deceleration distance (X) between curve 1 and curve 2. This implies

$$X = \frac{\overline{V85} \cdot \Delta V85}{1.302} \tag{5a}$$

$$X = \frac{42.5 \cdot 19}{1.302} = 620 \text{ ft}$$

Then, the remaining tangent length is

$$TL - X = 1050 - 620 = 430 \text{ feet}$$

along which a driver is able to perform additional acceleration or deceleration maneuvers. (Exceptional case: $DC_1 = DC_2 \rightarrow\rightarrow\rightarrow V85_1 = V85_2\ X = 0$; perform the calculations in the same way with $X = 0$). By transforming equation (5), in order to calculate the difference $\Delta V85_T$ between the operating speed in the curve with the lower degree of curve ($V85_1$) and the estimated operating speed in the tangent ($V85_T$), the formula now becomes (see figure 5a):

$$\frac{[V85_1 + (V85_1 + \Delta V85_T)] \cdot \Delta V85_T}{2 \cdot 1.302} = \frac{(TL - X)}{2}$$

or

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

It follows that

$$\Delta V85_T = \frac{-2 \cdot (52) \pm \sqrt{4(52)^2 + 5.208(430)}}{2} \approx 5 \text{ mph}$$

Thus, the operating speed in the independent tangent for evaluating the sequences tangent-to-curve in both directions of travel becomes $V85_T = V85_1 + \%V85_T = 52 + 5 = 57$ mph.

For the discussed example the following changes in degrees of curve and operating speeds can be expected between

tangent to curve 1:
$\Delta DC = |0° - 6°| = 6°$,
$\Delta V85 = |57 - 52 \text{ mph}| = 5$ mph, and
tangent to curve 2:
$\Delta DC = |0° - 22.4°| = 22.4°$,
$\Delta V85 = |57 - 33 \text{ mph}| = 24$ mph.

The changes in operating speeds reveal that the sequence independent tangent-to-curve 1 corresponds to good design practices ($\Delta V85 < 6$ mph), while the sequence independent tangent-to-curve 2 corresponds to poor design practices ($\Delta V85 > 12$ mph). In the event the calculated 85th-percentile speed in the independent tangent exceeds the value of 58 mph, it is recommended that the 85th-percentile speed in the examined tangent be confined to this value. As previously mentioned, 58 mph is a good estimate for the 85th-percentile speed in long tangents for the nationwide speed limit of 55 mph on two-lane, rural roads.

Example Related to Figure 5b

TL = 0.15 mi = 790 ft,

$DC_1 = 27° \rightarrow\rightarrow\rightarrow V85 = 28$ mph,

$DC_2 = 22.4° \rightarrow\rightarrow\rightarrow V85 = 33$ mph, see equation (1).

The 85th-percentile speed in table 2 that is closest to 28 mph in the curve with the higher degree of curve corresponds exactly to 28 mph. For 28 mph the maximum length of tangents that is regarded as non-independent is 325 feet. Since TL = 790 feet < 325 feet, the tangent has to be evaluated as an independent design element.

The 85th-percentile speed in the tangent, related to figure 5b, can be estimated in the same way as discussed in the previous example.

According to equation (5a), the acceleration or deceleration distance between curve 1 and curve 2 is as follows:

$$X = \frac{30.5 \cdot 5}{1.302} = 117 \text{ ft.}$$

Therefore, the remaining tangent length becomes

$$TL - X = 790 - 117 = 673 \text{ feet}$$

According to equation (6), the difference between the operating speed in the curve with the lower degree of curve and the operating speed in the tangent now becomes

$$\Delta V85_T = \frac{-2(33) \pm \sqrt{4(33)^2 + 5.208(673)}}{2} \approx 11 \text{ mph}$$

Note that for the example of figure 5b curve 2 is the curve with the lower degree of curve.

It follows that the operating speed in the independent tangent is

$$V85_T = V85_2 + \Delta V85_T = 33 + 11 = 44 \text{ mph.}$$

For the discussed example the following changes in degrees of curve and operating speeds can be expected between

tangent to curve 1:
$\Delta DC = |\, 0° - 27° \,| = 27°$,
$\Delta V85 = |\, 44 - 28 \text{ mph} \,| = 16$ mph, and

tangent to curve 2:
$\Delta DC = |\, 0° - 22.4° \,| = 22.4°$,
$\Delta V85 = |\, 44 - 33 \text{ mph} \,| = 11$ mph.

The changes in operating speeds reveal that the sequence independent tangent-to-curve 1 corresponds to poor design practices ($\Delta V85 > 12$ mph), while the sequence independent tangent to curve 2 can be still evaluated as fair design ($\Delta V85 < 12$ mph).

(6) The calculations of step (5) must not be performed on long tangents between two successive curves. The length of those tangents must be at least twice as high as the values listed in the last column of table 2, related to the nearest 85th-percentile speed of the curve with the higher degree

of curve. In these cases, it can be assumed without any further calculation that the tangents are independent, and that an operating speed of 58 mph is a good estimate on those long tangents.

A typical example for such a case is shown in figure 4.

Example Related to Figure 4

$TL = 1500$ ft,

$DC_1 = 16.5° \rightarrow\rightarrow\rightarrow V85_1 = 40$ mph,

$DC_2 = 16.5° \rightarrow\rightarrow\rightarrow V85_2 = 40$ mph, see equation 1.

The 85th-percentile speed in table 2 that is closest to 40 mph is exactly 40 mph. To accelerate or decelerate from 40 mph to the highest operating speed of 58 mph in the tangent a distance of 675 feet is needed (compare corresponding value in the last column of table 2): $2 \cdot 675 = 1{,}350$ feet $< 1{,}500$ feet. Thus, it can be concluded that the tangent is independent and an operating speed of $V85_T = 58$ mph is a good estimate in the long tangent. For the example the following change in degree of curve and operating speed can be expected for this road section:

$\Delta DC = |\,0° - 16.5°\,| = 16.5°$,

$\Delta V85 = |\,58 - 40 \text{ mph}\,| = 18$ mph.

It follows that the existing horizontal alignment corresponds to poor design practices since $\Delta V85 > 12$ mph.

CONCLUSION

Several countries have limitations on maximum and minimum tangent lengths between curves. The procedure presented above is a rational method to set tangent guidelines for U.S. practice and to provide recommendations for transition lengths (tangent lengths) between successive curved roadway sections for

- tangents that should be regarded as non-independent design elements; that is, the sequence curve-to-curve is the most important element of the design process, and
- tangents that should be regarded as independent design elements; that is, the sequence tangent-to-curve is the most important element of the design process.

The method can be used for new design as well as evaluating in-place roadways in need of safety upgrades.

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