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Design Issues in Widening of Unspiraled Horizontal Curves

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Abstract

In highway alignment, when the traveled way is widened for unspiraled horizontal curves, a linear increase, widening from zero to its maximum value along the application length, leads to an undesired straight edge or an apparent kink, since there is no transition curve between the tangent section of the road and the main circular curve (unlike spiraled horizontal alignment where gradual and proportional offsets of widening can easily be accomplished with respect to the transition curve). Although compound curves or modified spirals can be employed to solve this problem, using complex curves for simple (unspiraled) alignment has not been a favored approach. This paper addresses this issue and proposes using a single circular arc on the inside edge of widening where possible. On trying many circular arcs iteratively until certain conditions are met, within a given range of superelevation runoff length, several arcs have been produced for each cell of the widening table provided by AASHTO. All the arcs satisfied the all-governing condition of sharing the same tangent with the main circular curve at the end of the application distance. Provided that the superelevation runoff length falls within the limits determined in the paper, the work presents a simple and time saving approach for designers to adapt. Although the computations are based on 7.2 m traveled way width, similar arcs can easily be produced by others for various widths. The paper, therefore, shows how to map the application domain of such arcs for given curve parameters.

Keywords

roadway design, cross-sectional, curves, horizontal alignment, lane width, methodologies used for analysis and research of geometric design, superelevation

The traveled way width on the horizontal curves of highways is usually widened for several reasons: (i) off-tracking (i.e., additional width needed by vehicles when negotiating horizontal curves, as front and rear wheels do not follow the same path); (ii) psychological lateral discomfort (i.e., tendency for drivers to shy away from the pavement edge and from other vehicles, especially those traveling in the opposite direction); and (iii) inaccurate steering (i.e., difficulty in positioning the vehicle while traversing the horizontal curve, given the slanted position of the vehicle when compared with driving along tangent sections). In recognition of these reasons, Khanna and Justo (*1*) named two types of widening: mechanical and psychological. Widening also becomes an important design feature at intersections (or on turning roadways) (*2*) and it incidentally improves sight distance and significantly reduces curve crashes (*3*).

The amount of widening is based on several parameters such as: (i) sharpness of horizontal curve (radius); (ii) speed; (iii) vehicle class (length and width of design vehicle); (iv) lane width; (v) driver characteristics (age, experience, reaction time, vision, etc.); (vi) whether the road is unidirectional or two-way; and (vii) driving environment (day or night time driving, weather and traffic conditions, etc.). As will be outlined below, while some of these factors are trigonometrically quantifiable, others are empirically encompassed in formulation. It is well established that the amount of widening increases with size of design vehicle and decreases with radius of curvature. AASHTO (*4*) formulated the required traveled way width (W_c), which is the sum of several components:

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i) the track width of each vehicle (meeting or passing),

$$U = u + R - \sqrt{R^2 - \sum L_i^2}$$

where
u = track width on tangent,
R = radius of curve, and
L_i = wheelbase of design vehicle between consecutive axles; (all in meters);

ii) the lateral clearance allowance per vehicle, in meters:

$$C = \begin{cases} 0.60 \text{ m for } 6.0 \text{ m traveled way width (in tangent)} \\ 0.75 \text{ m for } 6.6 \text{ m} \quad '' \quad '' \quad '' \\ 0.90 \text{ m for } 7.2 \text{ m} \quad '' \quad '' \quad '' \end{cases}$$

iii) the width of front overhang of the vehicle occupying the inner lane or lanes:

$$F_A = \sqrt{R^2 + A(2L + A)} - R$$

where
A = front overhang of inner lane vehicle,
L = wheelbase of single unit, and
R = as defined previously; (all in meters);

iv) a width allowance for the difficulty of driving on curves, in meters:

$$Z = 0.1\left(V_d/\sqrt{R}\right)$$

where V_d = design speed (km/h), and R = as defined previously.

The widening of the traveled way on a horizontal curve, therefore, becomes:

$$w = W_c - W_n$$

where W_n = width of traveled way on a tangent, and W_c = width of traveled way on a curve (all in meters).

To determine W_c, an appropriate design vehicle is first selected. AASHTO (*4*) produced a table for the values of w, based on WB-19 design vehicle and provided adjustments for various other vehicle types. It was also stated that widening values less than 0.6 m may be disregarded (*4*). Depending on the country's regulations, widening may not be necessary if low design speeds are combined with large curve radii (*5*, *6*). Policy documents from various other countries or jurisdictions have presented similar widening (w) tables (e.g., *7–11*). For forest roads, where speeds are low, vehicles are oversized and curves are sharp, Sessions (*12*) and New Zealand FOA (*13*), in a slightly different fashion, formulated off-tracking, which becomes the dominant factor in curve widening.

The application of widening from zero in the approach tangent to its full value, w, in the main circular curve must be gradual so that the alignment of the traveled way edge is reasonably smooth and graceful. This is easily achieved along the transition curve for spiraled horizontal alignments, and this perfectly corresponds to the superelevation runoff length.

For "spiraled" horizontal curves, widening can be applied fully on the inside edge, as well as distributed equally ($w/2$) on both edges of the traveled way. In the latter case, particular attention is given to the outer widening edge so that the sharpness of the reverse curve formed at the beginning of widening does not reach disturbing levels. For spiraled alignment, it is not difficult to position the widening edge, since the centerline is a spiral. What needs to be done is to mark offset distances from the centerline proportional to the distance traveled along the superelevation runoff. This will make another spiral on the inner edge (or both edges if widening is fulfilled on both sides). For example, for a spiral length of L_r (at centerline), for l amounts of increments of travel along this superelevation runoff, when $l = 0$, then $w = 0$, when $l = L_r/3$, then $w = w/3$, when $l = L_r/2$, then $w = w/2$, when $l = L_r$, then $w = w$. This can be done, say, for every 10 m or for every cross section taken.

However, for certain combinations of R and V_d, many highway authorities do not require transition curves (spirals), as drivers usually follow a natural path which resembles a spiral in any case (*14*). Under these conditions the tangent is joined directly with the main circular curve and this method is not uncommon. But the centerline pavement marking (and the center joint especially in rigid pavements) should still be placed equidistant from both edges (*4*, *6*, *15*). The difficulty therefore with "unspiraled" horizontal curves in relation to widening is threefold:

(a) As was stated in various documents (e.g., *4*, *16*), widening is made on the inside of unspiraled curves, leading to a non-symmetrical design issue across the roadway.
(b) More importantly, since there is no transition curve between the tangent and the main circular curve, the gradual increase of widening is accomplished over the superelevation runoff length which is usually split between the tangent and the circular arc in a 0.67 and 0.33 ratio, respectively, (half-half split is also practiced). A linear increase of w, therefore, leads to a straight edge of traveled way (Figure 1) before the point of curvature (PC), which should be avoided.
(c) In relation to the previous item (b), a linear increase of widening from zero at the beginning of the superelevation runoff to its (non-zero)

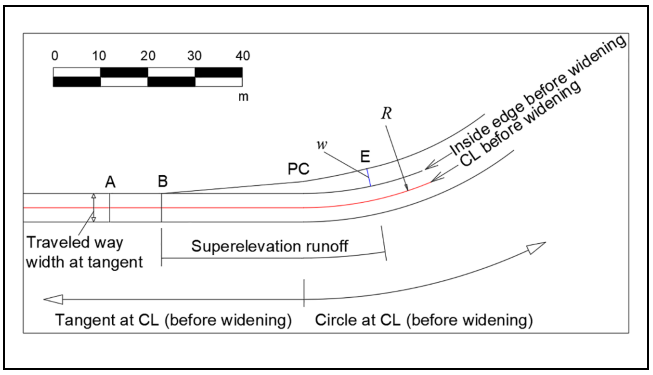


Figure 1. Undesired angular breaks especially at B (to scale).
Note: PC = point of curvature; CL = centerline.

value at PC, may result in an apparent kink (angular break at the edge) which is also not desired. Placing a curve between PC and E by offsetting the centerline proportional to the longitudinal distance traveled along the centerline will solve the linearity problem only between PC and E. But setting offsets of w (proportional to the distance traveled along the superelevation runoff between B and PC) will still be a straight line, giving rise to an angular break at B and perhaps at PC as well.

It should be noted that issue (a) is also valid for spiraled horizontal curves if widening is made only on the inside edge. These three issues will be addressed in more detail later in the paper.

Figure 1 illustrates how widening on the inside edge will actually look if a straight line is used to join Points B and PC, for an unspiraled horizontal curve. The figure is to scale and some of the dimensions are: curve radius, R (at CL before widening) = 70 m; traveled way width at tangent = 6.0 m; superelevation runoff = 45 m; and full widening (w) at E = 3.8 m. The distances AB and BE (at CL) are superelevation runout and runoff lengths, respectively. It should be noted that distance AB is not our concern and will not be shown in the remaining figures of the paper. These intentionally selected dimensions represent a particular case taken from AASHTO (*4*) Table 3–24b with $w = 3.8$ m corresponding to $R = 70$ m and $V_d = 50$ km/h; and to $e = 8.4\%$ design superelevation rate, one lane rotating, taken from Table 3–16b, (*4*). The notation used (i.e., A, B, PC, and E) in all figures of the paper are particularly selected to be in harmony with AASHTO style (*4*, Figures 3–8).

Need for Research

Although curve widening, with respect to calculating its magnitude (w), has been discussed in highway engineering sources (as summarized above), the three issues listed above with particular reference to design details for unspiraled applications are barely mentioned in the literature. Only a small number of documents have referred to certain aspects of the problem. For example, Hickerson (*17*) formulated a compound circular curve for the widened inside edge, while both the centerline and the outer edge remain concentric circular curves, as was also suggested by O'Flaherty (*18*). However, although his formulation is detailed and successful, the compound curve approach he proposed was not very simple and had rather dependent beginning and end points without any control over the curve length. Similar formulations, with various number of cases of known and unknown compound curve parameters, had been given by Allen (*19*) with the same limitations. Meyer and Gibson (*20*) recommended an easement curve (such as a spiral) at the inside edge of the pavement. An independent spiral may be needed, they said, for the outside edge as well to be in harmony with vehicle tracks. Attention was drawn to the behavior of curve cutting as drivers tend to shift their vehicles laterally across the lane when negotiating horizontal curves (*21–23*). However, using a spiraled pavement edge (or a modified spiral, derived from parabolic, cubic or compound curves) for an unspiraled horizontal curve has not attracted much interest, probably because it undermined the simplicity of unspiraled layout design. Another disadvantage would be that if the main circular curve is short, there may not be enough length to place a spiral to reach the required w. Besides, it is evident that geometric and mathematical calculations of spirals, as well as their drafting, are time consuming in highway design.

As an alternative and practical solution in the field, AASHTO mentions the possibility of setting out the inner edge of the widened pavement by the naked eye. But for the sheets of plans, the designer must provide precise drawings so that cross-section areas (and subsequent volumes between cross sections) along the widened length can be accurately calculated before field surveys.

There are various highway geometric design software packages available, which are able to produce curve design with minimum human involvement and time. Also, some programs have specialized in swept path analysis, which can calculate the widening needed for a curve and produce the necessary drafts. These specific programs are also used in urban road and intersection design. In difficult topography, where switch-backs or hairpins, as Lamm et al. (*24*) point out, are unavoidable, swept path programs play an important role. However, despite the existence of such software, for several reasons, there is still a need for a conventional approach for the widening procedure. First of all, academically, the gap in the literature and the need for further research

should be addressed. Engineering students should be able to learn all aspects of highway design transparently. Even if the issues identified above are not major difficulties in highway design, they cannot be left vague and unresolved. Secondly, in an appraisal document when expert judgment is sought for an existing highway, the engineer should be able to compare the results of conventional methods with that of these packages. Finally, not every designer has access to these programs (and there may certainly be no obligation to use one). A simple and accurate way of drawing the inner edge of widening is, therefore, always appealing.

The issue in question is also valid for turning roadways and interchange ramps (*4*, *25–27*). In particular, semi-directional interchange ramps, which loop around the intersection of the highway with partial deviation from the intended path, may exhibit temporary use of hard shoulder. Widening should be carefully planned for both left- and right-turning sections of the same ramp. A reverse horizontal curve may be present within a limited length and limited superelevation runoff distance. The importance of consistent ramp patterns was discussed in the literature (*15*, *28*). However the investigation of such cases is outside the scope of the present paper as it focuses on scrutinizing the core of the problem.

The main motive of the present paper is, therefore, to provide designers with a clear understanding of the difficulties in drawing the inside edge of widened pavement for unspiraled horizontal curves. As will be discussed below, the paper will ascertain to what extent a single circular arc can be facilitated to join the tangent and the main circular curve, as a simpler solution than even a compound curve. The geometric limits of the opportunity to avoid compound or spiral curves will, therefore, be revealed to highway researchers and designers.

Circular Easement

The paper will investigate the mechanism of fitting a circular arc as the inside edge of the widened pavement between the beginning and end of the superelevation runoff distance, that is, B and E, respectively (Figure 1). The aim therefore is to find the limits of placing a circular arc which has a graceful beginning and end (as depicted in Figure 2). Ideally, three desirable conditions should be present for such an arc:

(I) the tangent section of the road should be tangential to this arc at Point B;
(II) the arc should share the common tangent with the main circular curve at Point E; and
(III) the arc should satisfy the above two conditions for all lengths of superelevation runoff.

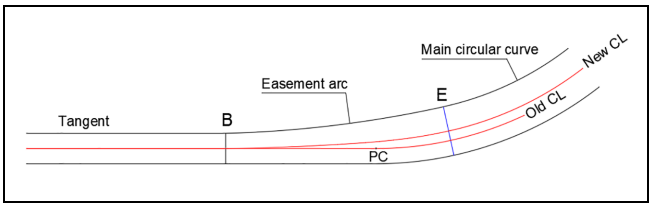


Figure 2. Placing a single circular arc as the inside edge of the widened pavement between B and E.
Note: PC = point of curvature; CL = centerline.

However, it might not be possible to meet all three conditions concurrently. Conditions (I) and (II) depend on the superelevation runoff length (L_r), the radius of the horizontal curve (R), traveled way width (W_n), and maximum widening needed (w) at E. The superelevation runoff length itself depends on factors such as design speed (V_d), superelevation rate (e), and the number of lanes rotated. For two-lane highways with three different traveled way widths of 7.2 m, 6.6 m, and 6.0 m, AASHTO (*4*) lists widening values (w) as a function of curve radii (R) ranging from 70 to 3,000 m; and design speed (V_d) ranging from 50 to 100 km/h. These w values can reach up to 3.8 m depending on R, and V_d.

The gradual increment of curve widening from 0 at B to its maximum value, w, at E, as was discussed previously, is accomplished over the superelevation runoff distance for unspiraled horizontal curves. AASHTO (*4*) Table 3–16b provides superelevation runoff lengths ranging from as low as 8 m for 1.5% design superelevation rate and 50 km/h design speed; to as high as 86 m for 12% design superelevation rate and 100 km/h design speed. The question now is to identify the fitting parameters of a circular arc as an easement curve between B and E. In the present paper, 2/3 and 1/3 split of the superelevation runoff distance (L_r) was adapted before and after the PC, respectively. To demonstrate this aim, the traveled way width of 7.2 m part of the AASHTO Table 3–24b (Table 1 here) was used as the base for our calculations.

For each cell of this table, an infinite number of circular arcs can be drawn between B and E with various length and curvature combinations. However, if this arc is made to share a common tangent with the main circular curve at E (condition II above satisfied), then the number of possibilities reduces sharply. Using CAD software, in an iterative manner, by trying various superelevation runoff lengths, several circular arcs have been placed between B and E. Then the shortest and the longest among these lengths, which comply with certain conditions that will be discussed below, have been identified. Six parameters can be computed for each of these possible easement arcs. Then, an associated table can be

Table 1. Traveled Way Widening (*w*) Values on Open Two-Lane Highway Curves for 7.2 m Traveled Way Widths Only, from AASHTO (*4*)

	Traveled way width = 7.2 m					
	Design speed (km/h)					
Radius of curve, *R*, (m)	50	60	70	80	90	100
500					0.6	0.6
400		0.6	0.6	0.7	0.7	0.8
300	0.7	0.8	0.8	0.9	1.0	1.0
250	0.9	1.0	1.0	1.1	1.1	na
200	1.1	1.2	1.3	1.3	na	na
150	1.5	1.6	1.7	1.8	na	na
140	1.6	1.7	na	na	na	na
130	1.8	1.8	na	na	na	na
120	1.9	2.0	na	na	na	na
110	2.1	2.2	na	na	na	na
100	2.3	2.4	na	na	na	na
90	2.5	na	na	na	na	na
80	2.8	na	na	na	na	na
70	3.2	na	na	na	na	na

Note: na = not applicable.
The source AASHTO table uses shading for the widening values of < 0.6 m.

populated (Table 2) where these parameters (as *a* to *f*) are explained on the actual table.

To elaborate on the items (*a*) and (*d*), when the superelevation runoff length, L_r, is too small, the arc does not face inside of the curve. Similarly, when L_r is too large, the arc crosses a horizontal line drawn laterally from B. For example, as depicted in the top drawing of Figure 3, any value of L_r smaller than the lower limit calculated in Table 2 will result in the arc becoming a straight line first and with further decreasing values of L_r, the arc will start to face outward. Similarly, as a second boundary condition, any L_r value bigger than the upper limit calculated in Table 2 will cause the arc to cross over the horizontal line, as depicted in the bottom drawing of Figure 3.

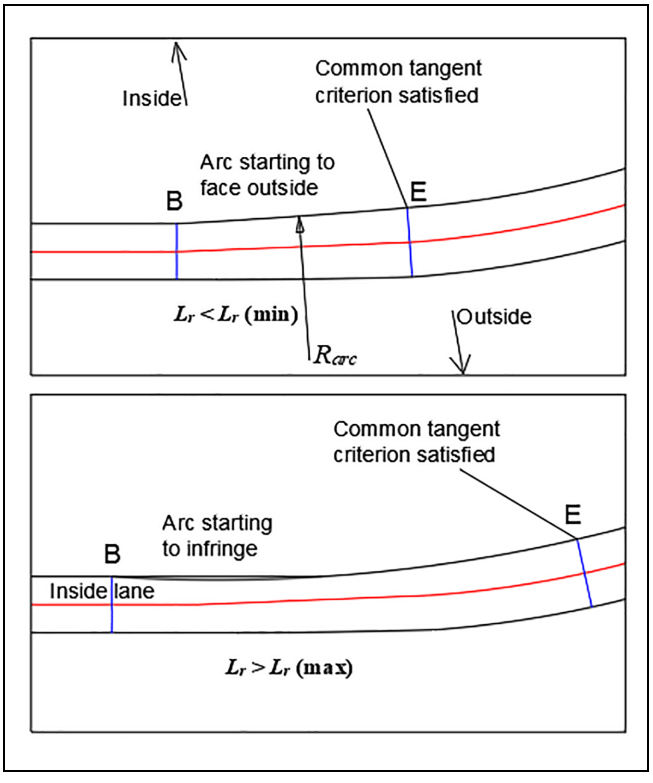


Figure 3. Exceeding the limits of L_r (demonstration).

Key Findings

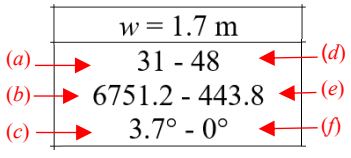
Item (II) of the three conditions given at the beginning of this section had been set as the only strict criterion. In both drawings of Figure 3, this criterion at E has been satisfied. In other words, for all cells of Table 2, the arc in question always shared the common tangent with the main circular curve at E. This was particularly intended because of the importance of continuity in highway alignment as vehicles negotiating a horizontal curve experience the most driving difficulty within the curve. Therefore, for Table 2, no angle of deflection had to be calculated at Point E. The first condition (I) was met in most arcs with an absolute (and nearly absolute) tangency ($\alpha < 1°$). But in some others, varying deflections from tangency (reaching up to $\alpha = 7.5°$ in the bottom left corner of Table 2) were noted, as the radius of the main curve (R) continued to reduce for small L_r (min) values. Therefore, depending on the designer's definition

Table 2. Envelopes for L_r and R_{arc} (Traveled Way Width = 7.2 m) in Association with Table 1

	Design speed (km/h)					
R (m)	50	60	70	80	90	100
500					*w* = 0.6 m 33 – 52 132,606 – 1,494.5 1.2°– 0°	*w* = 0.6 m 33 – 52 132,606 – 1,494.5 1.2°– 0°
400		*w* = 0.6 m 30 – 46 18,772.2 – 1,212.8 1.3°– 0°	*w* = 0.6 m 30 – 46 18,772.2 – 1,212.8 1.3°– 0°	*w* = 0.7 m 32 – 50 52,046.4 – 1,202.2 1.5°– 0°	*w* = 0.7 m 32 – 50 52,046.4 – 1,202.2 1.5°– 0°	*w* = 0.8 m 34 – 53 471,638 – 1,216 1.6°– 0°
300	*w* = 0.7 m 28 – 42 16,151.8 – 940.8 1.7°– 0.1°	*w* = 0.8 m 30 – 46 14,298 – 908.4 1.8°– 0°	*w* = 0.8 m 30 – 46 14,298 – 908.4 1.8°– 0°	*w* = 0.9 m 32 – 48 11,099 – 929.7 1.9°– 0.1°	*w* = 1.0 m 33 – 52 94,494 – 894.7 2.1°– 0°	*w* = 1.0 m 33 – 52 94,494 – 894.7 2.1°– 0°
250	*w* = 0.9 m 29 – 45 13,176.9 – 745.7 2.1°– 0°	*w* = 1.0 m 31 – 47 7,380 –754.9 2.1°– 0°	*w* = 1.0 m 31 – 47 7,380 – 754.9 2.1°– 0°	*w* = 1.1 m 32 – 47 14,798.1 – 761.2 0.3°– 0.1°	*w* = 1.1 m 32 – 49 14,798.1 – 761.2 0.3°– 0.1°	
200	*w* = 1.1 m 29 – 44 6,533.6 – 604.7 2.5°– 0.1°	*w* = 1.2 m 30 – 46 9,854.1 – 603.9 2.7°– 0.1°	*w* = 1.3 m 31 – 48 16,142 – 601.6 2.9°– 0°	*w* = 1.3 m 31 – 48 16,142 – 601.6 2.9°– 0°		
150	*w* = 1.5 m 29 – 45 8,416.4 – 445.2 3.5°– 0°	*w* = 1.6 m 30 – 46 7,666.9 – 451.4 3.6°– 0.1°	*w* = 1.7 m 31 – 48 6,751.2 – 443.8 3.7°– 0°	*w* = 1.8 m 32 – 49 5,848.7 – 448.6 3.8°– 0°		
140	*w* = 1.6 m 29 – 44 6,988.3 – 426.9 3.7°– 0.2°	*w* = 1.7 m 30 – 46 5,861 – 418.5 3.8°– 0°				
130	*w* = 1.8 m 30 – 45 3,971.1 – 395.6 4°– 0.2°	*w* = 1.8 m 30 – 45 3,971.1 – 395.6 4°– 0.2°				
120	*w* = 1.9 m 29 – 45 12,334.6 – 358 4.5°– 0.1°	*w* = 2.0 m 30 – 45 6,387.8 – 371.5 4.5°– 0.3°				
110	*w* = 2.1 m 29 – 45 54,931.8 – 330.6 5°– 0.1°	*w* = 2.2 m 30 – 46 7,946.1 – 331.1 5°– 0.1°				
100	*w* = 2.3 m 29 – 45 25,318 – 299.8 5.5°– 0.1°	*w* = 2.4 m 30 – 46 5,568.6 – 298.6 5.4°– 0.1°				
90	*w* = 2.5 m 29 – 44 5,753.1 – 272.8 5.9°– 0.3°					
80	*w* = 2.8 m 29 – 44 4,605.4 – 240.8 6.6°– 0.3°					
70	*w* = 3.2 m 29 – 44 4,276 – 209.7 7.5°– 0.3°					

Syntactic explanation of cell members

(e.g., R = 150 m, V_d = 70 km/h)



(a) The lower limit of superelevation runoff, L_r(min), to give an inside facing arc (see Figure 3)
(b) The radius of this arc (in *a*), R_{arc}
(c) The angle of deflection from tangency at Point B for this arc (in *a*), α
(d) The upper limit of superelevation runoff, L_r(max), over which an arch can be placed without infringing the width of the innermost traffic lane (see Figure 3)
(e) The radius of this arc (in *d*), R_{arc}
(f) The angle of deflection from tangency at Point B for this arc (in *d*), α

The shaded area in the table refers to the empty cells of the source AASHTO table.

Table 3. For the L_r limits Calculated in Table 2, Corresponding Radii Domain

	Design speed (km/h)					
	Corresponding superelevation, e (%) and radius, *R* (m) in "e (*R*)" syntax					
L_r (m)	50	60	70	80	90	100
28	5.2 (81.4)	na	na	na	na	na
29	5.4 (80.7)	na	na	na	na	na
30	5.6 (80.0)	5.2 (127.7)	4.8 (194.9)	na	na	na
31	na	5.3 (127.1)	4.9 (193.9)	4.3 (275.4)	na	na
32	na	na	na	4.4 (273.9)	4.4 (366.5)	na
33	na	na	na	na	4.6 (362.4)	4.6 (474.3)
34	na	na	na	na	na	4.7 (471.5)
42	7.8 (73.5)	na	na	na	na	na
43	8.0 (72.9)	na	na	na	na	na
44	8.2 (72.4)	na	na	na	na	na
45	8.4 (71.8)	7.7 (114.8)	na	na	na	na
46	na	7.8 (114.3)	7.3 (173)	na	na	na
47	na	8.0 (113.4)	7.4 (172.2)	na	na	na
48	na	na	7.6 (170.7)	6.6 (244.6)	na	na
49	na	na	7.8 (169.2)	6.8 (242.3)	6.8 (322.1)	na
50	na	na	na	7.0 (240.0)	7.0 (318.9)	na
51	na	na	na	na	7.1 (317.3)	na
52	na	na	na	na	7.2 (315.7)	7.2 (410.1)
53	na	na	na	na	na	7.4 (405.9)

Note: na = not applicable.

of an apparent kink and of tolerance, they may not use certain arcs proposed by this table.

From the results of Table 2, it is also understood that (in a limited range of L_r values) it is perfectly possible to use a single arc as the inside edge of the widened pavement, as the simplest solution. To be more conclusive, to see how this range can be translated into a range of curve radii, another table is constructed (Table 3). It is known that the superelevation runoff length (L_r) is a function of design speed (V_d) and superelevation rate (e). For the L_r values presented in Table 2, by back calculation, corresponding e values can be read from Table 3–16b of AASHTO (*4*) and corresponding R values can be computed using

$$R = \frac{{V_d}^2}{127(0.01e + f)}$$

where f is the side friction factor, taken as 0.19, 0.17, 0.15, 0.14, 0.13, and 0.12 for 50, 60, 70, 80, 90, and 100 km/h design speeds, respectively, from AASHTO (*4*), Figures 3 and 4.

Table 3 allows a designer to be able to see the domain of using a circular arc as the inside edge of the widened pavement between B and E for the radius of the horizontal curve. Using the "Start-End-Radius" function of "Arc-drawing" in CAD software, this can easily be accomplished. For instance, for $V_d = 50$ km/h, a circular arc can be a solution for a range of radii between 71.8 m and 81.4 m. Similarly, for $V_d = 100$ km/h, the range is from 405.9 m to 474.3 m. Note that the L_r values appearing in the first column of the table are the limiting values coming from Table 2.

The Outside Edge and the Marked Centerline

Within the certain limits of L_r, having fitted a suitable arc for the inside edge of the widened pavement of an unspiraled horizontal curve, the designer should first offset the old centerline outward by a width of a lane to draw the outside edge of the pavement (for two-lane two-way highways). They should then delete the old centerline (between Points B and E) and draw a new one by making sure that it halves the pavement width along the superelevation runoff length for frequent increments (say for every cross section taken). This task is easy and needs no further academic discussion here. Only four examples are shown in Figure 4 for illustration purposes; these form the extreme corners of Table 2.

Other Widths of Traveled Way

The above calculations were based on 7.2 m wide traveled ways. In this section, a case for a narrower road

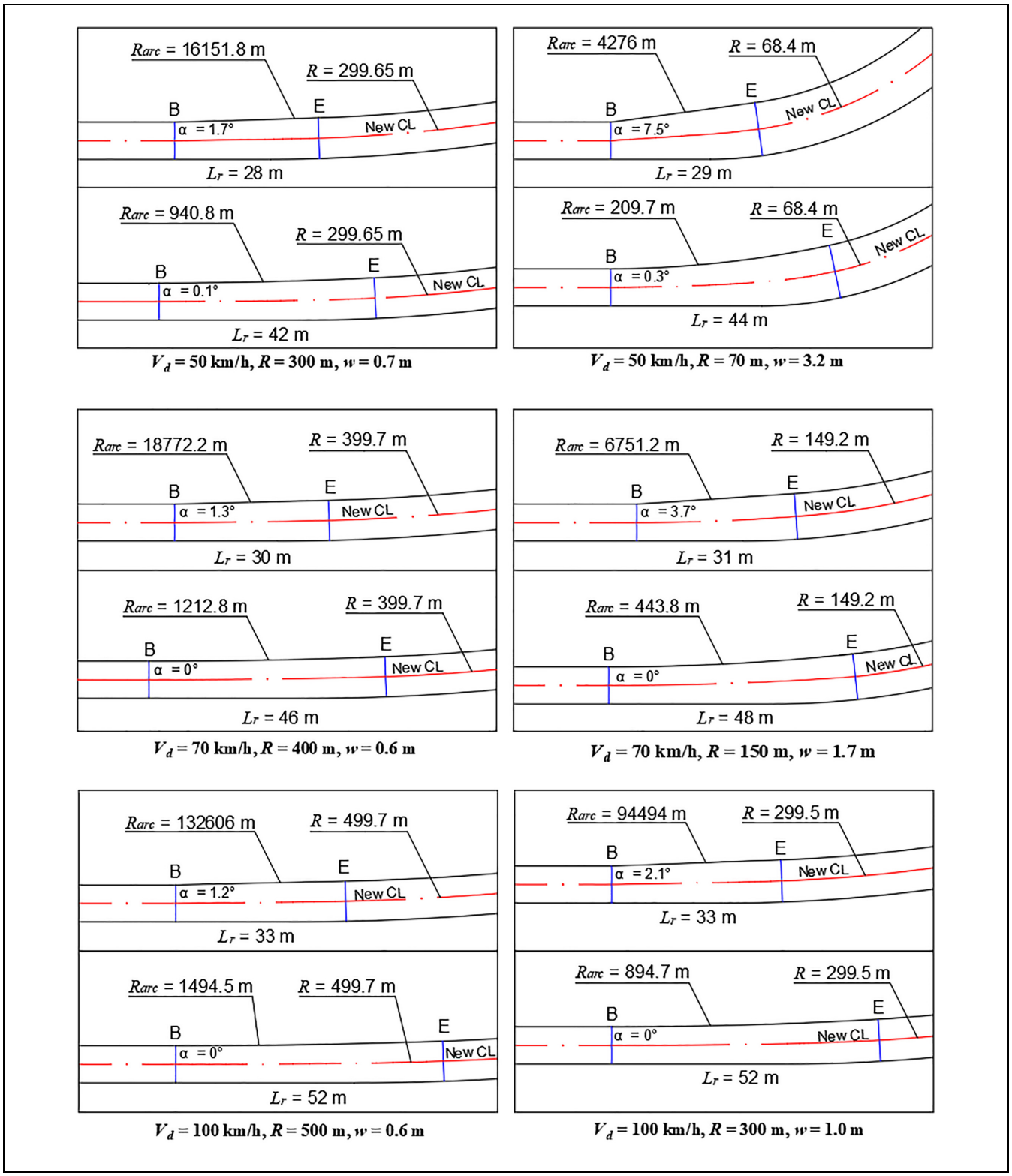


Figure 4. Examples from Table 2 (to scale).
Note: CL = centerline.

Table 4. Envelopes for L_r and R_{arc} (Traveled Way Width = 6.0 m)

R (m)	Design speed (km/h)					
	50	60	70	80	90	100
3,000		*w* = 0.6 m 81 – 126 444,723 – 9,120.6 0.5°– 0°	*w* = 0.6 m 81 – 126 444,723 – 9,120.6 0.5°– 0°	*w* = 0.6 m 81 – 126 444,723 – 9,120.6 0.5°– 0°	*w* = 0.6 m 81 – 126 444,723 – 9,120.6 0.5°– 0°	*w* = 0.6 m 81 – 126 444,723 – 9,120.6 0.5°– 0°
2,500	*w* = 0.6 m 74 – 111 329,745 – 8,007.6 0.6°– 0.1°					
300						*w* = 1.6 m 42 – 65 29,615.1 – 909.3 2.6°– 0.1°
250					*w* = 1.7 m 40 – 61 10,889.4 – 759.8 2.8°– 0.1°	
150			*w* = 2.3 m 36 – 55 7,221.2 – 453.2 4.3°– 0.1°	*w* = 2.4 m 37 – 56 5,487.8 – 455.2 4.3°– 0.2°		
100		*w* = 3.0 m 34 – 51 3,021.7 – 302.3 5.9°– 0.2°				
70	*w* = 3.8 m 32 – 48 2,275.4 – 209.4 7.9°– 0.3°					

The shading in the table refers to the empty cells appeared in the source AASHTO table.

(traveled way width = 6.0 m) will be demonstrated. For convenience, only a summary table (Table 4) will be given (two examples from each design speed, one for top one for bottom radius). However, other researchers and designers, for their own curve radius and traveled way width, will be able to calculate corresponding arc parameters using the proposed approach. The widening values (w) for 6.0 m traveled way width appearing in Table 4 are taken from AASHTO (*4*) Table 3–24b.

Note that the explanatory depiction provided within Table 2 is also valid for Table 4. Similar to Figure 4, examples are presented for 6.0 m traveled way width in Figure 5, where the outside edges and centerline shifts can also be seen.

Conclusion

When the tangent section of a highway is joined directly with the main circular curve without any spiral, widening is made on the inside. As a result, a nonsymmetrical design issue emerges and a curve with respect to the centerline on the inside edge of the widened pavement can no longer be an answer. A solution to the problem may, therefore, be found in three possible approaches. In order of increasing complexity, they are: a simple circular curve, a compound curve, and a modified spiral. This paper has investigated the possibility of using a simple circular curve (arc) and calculated such parameters as:

(I) the range of superelevation runoff length;
(II) corresponding arc radii; and
(III) deviation from tangency at the beginning of superelevation runoff.

The findings revealed that for certain application lengths of widening, it is possible to employ such a circular arc. When outside this range, other types of curve (e.g., compound or spiral) may be used. In the analyses, a perfectly graceful transition to the main circular curve from the arc was guaranteed for all arcs given the importance of correct vehicle positioning within the curve. The proposed approach and circular arcs may, in future literature, be called Gunay's Curve Envelopes.

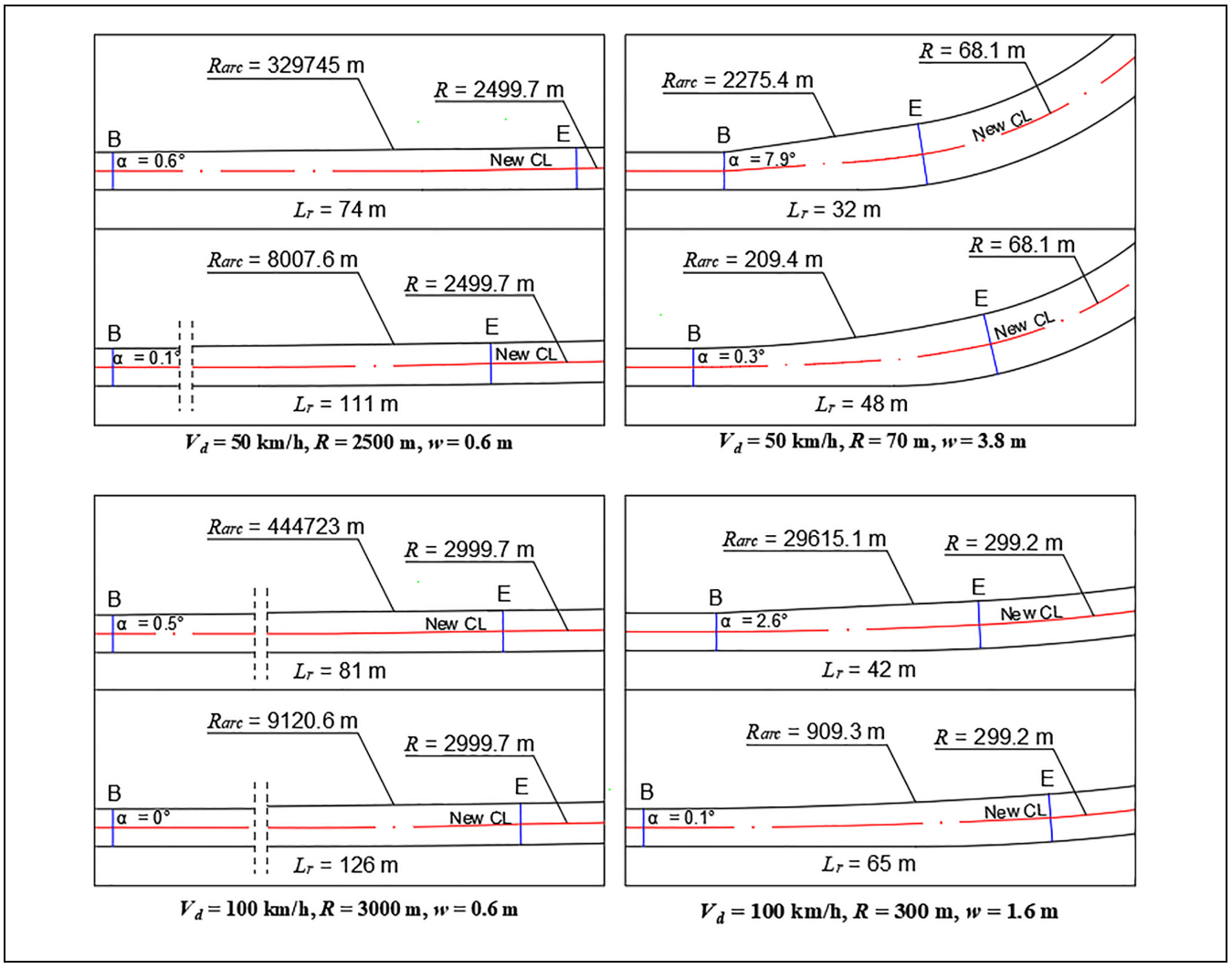


Figure 5. Examples from four corners of Table 4 for *Wn* = 6.0 m (to scale).
Note: CL = centerline.

A minor limitation of this study is the inability to interpolate between the values presented in Table 2 (and in Table 4). For example, to find the parameters of an arc between the given main curve radii, or between the given design speeds, it is not possible to use interpolation as the w values provided by AASHTO and the L_r, R, and α values calculated by the paper are rounded figures. For intermediate values, arc parameters have to be recalculated.

In addition to 7.2 m wide traveled way highways, the paper provided a summary table for 6.0 m traveled way width as a second case. For all other values of traveled way widths, researchers and designers may produce their own values with the help of the approach developed in this paper. The paper also demonstrated how the marked centerline is affected in the widening of unspiraled horizontal curves. This point had been an issue in design for non-symmetrical (widening on the inside only) cross sections.

Author Contributions

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Declaration of Conflicting Interests

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