Optimization of Post Delineator Placement from a Visibility Point of View

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An analytical computer optimization of the height, spacing, and lateral offset of post delineators for tangent sections and horizontal curves on two-lane and four-lane highways was developed in this study, and a small-scale field demonstration and evaluation were performed. The analytical optimization was based solely on visibility considerations, or more precisely, on a driver's reception of 60 multiples of threshold illumination from the fourth post delineator reflector ahead of the automobile. It was concluded that post delineators with 18 in.^{2} of encapsulated lens sheeting material with a specific intensity of 309 cd/fc/ft^2 (–4-degree entrance, 0.2-degree observation angle) should be placed every 275 ft along tangent sections of four-lane divided highways, whereas post delineators with prismatic sheeting material with specific intensities of 825 and 1,483 cd/fc/ft^2 (–4-degree entrance, 0.2-degree observation angle) should be placed every 350 and 400 ft, respectively. Mathematical relationships are presented from which optimal spacings can be calculated for curves of various radii on two-lane and four-lane highways. Height and lateral offset effects on visual detection for the placements investigated are negligible. The use of silver prismatic retroreflectors measuring 18 × 1 in. on the front, a red prismatic retroreflector of the same size on the back side of post delineators near intersections on four-lane divided highways (as a wrong way indicator), and two black diagonal bands for contrast enhancement in snow is recommended.

The *Manual on Uniform Traffic Control Devices* (*1*) defines road delineators as retroreflecting devices mounted at the side of the roadway to indicate road alignment. These delineators have an advantage over many other forms of delineation, such as pavement markings, in that they remain visible when the roadway is wet or snow covered. Guidelines for the installation of these delineators are given in sections 3D-2 through 3D-5 of the manual (*1*). However, many of these guidelines are very vague. For example, according to Section 3D-5, the delineators should be spaced such that the lateral distance between each post is from 200 to 528 ft on tangent sections of highway, and Table III-1 gives spacings for curve sections of highway with radii from 50 to 1,000 ft. There is no discussion of when specific spacings between 200 and 528 ft should be used along tangent sections of highways, and the manual does not address curves with radii greater than 1,000 ft.

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In an attempt to make the placement of post delineators consistent within the state of Ohio, the Ohio Department of Transportation (ODOT) clarifies a few of these federal guidelines in sections AS 4C-5, AS 4C-7, and AS 4C-8 of the Ohio Department of Transportation's *Traffic Control Application Standards Manual* (*2*) and in section 4B-5 and figures CD-5, CD-6, CD-8, CD-9, and CD-11 of the *Ohio Manual of Uniform Traffic Control Devices* (*3*). According to these manuals, the top of the retroreflective sheeting patch, with dimensions of 3 × 6 in., should be 48 in. plus or minus 1 in. above the pavement surface. For tangent sections of four-lane divided highways, these post delineators are to be spaced 400 ft apart at a maximum of 12 ft, 6 in. from the edge of the pavement such that their placement is uniform over the entire section of the highway. These manuals present tables of recommended post delineator spacings for curves with radii from 50 to 1,000 ft that are identical to the one shown in the *Manual on Uniform Traffic Control Devices* (*1*, Table III-1). Once again, there is no mention of curves with radii of greater than 1,000 ft.

A literature review failed to reveal any studies that have addressed, either on an experimental or analytical level, the effects from a visibility or driver performance point of view of the spacing of post delineators. In addition, there appears to be no technical information available that would enable justification of the 400-ft spacing for tangent sections or trade-offs to be made between post delineator height, lateral offset, spacing, retroreflector dimensions, and retroreflector photometric performance. There is therefore a need for studies such as the one reported by Zwahlen (*4*), in which the spacing and placement of snowplowable raised reflective pavement markers (RRPMs) are recommended with respect to a driver's visual information needs, capabilities, and limitations. Such an optimal placement of post delineators not only may lead to a placement scheme that would result in adequate driver performance and safety but also might minimize the relatively high life cycle cost of the post delineators.

The objectives of this study were

- To use a computer model to evaluate analytically, from a visual detection point of view, the reflective performance of post delineators as a function of height, retroreflector dimensions, photometric performance, lateral offset, and spacing;
- To conduct a small-scale field demonstration with ODOT and FHWA personnel to evaluate various retroreflector patch configurations; and

• To recommend to ODOT a set of specifications for post delineator height, retroreflector dimensions, lateral offset, and spacing.

GENERAL OPTIMIZATION APPROACH

The analytical optimization approach was aided by the use of a program developed for an Apple Macintosh microcomputer. This program allows the user to vary the headlamp beam type, atmospheric transmissivity, vehicle-driver dimensions, lateral offset of the post, and post height, as well as the type and dimensions of the retroreflector. Once the levels for each of the variables have been chosen, the program calculates the amount of light that is reflected back to the driver's eyes from each of the vehicle's headlamps for various retroreflector spacings. This program is based on Allard's law (*5*), which is used to calculate the illuminance of an object as long as the background luminance is small compared to the average luminance of the light source.

To provide a framework in which the very small illumination values in footcandles (fc) at a driver's eyes can be compared on a one-to-one basis with visual backgrounds that have different luminance levels and to obtain numbers tied to human detection performance, the final results of the photometric calculations are expressed as multiples of threshold (number of times above the illumination threshold for 98 percent plus detection of a white point source against a uniform background in the laboratory). To relate the illumination at a driver's eyes to multiples of threshold (MOT), a luminance level of the dark road background must be assumed. This level can then be related to a 98 percent threshold detection illumination value for a white point source. The multiple of threshold concept has been discussed by Zwahlen (*6*).

A MOT value that will be acceptable in the detection of post delineators must be selected. Because a driver sees the post delineator that is closest to the vehicle rather clearly most of the time and has a good indication of where the second, third, and possibly fourth post delineator will be in the visual field, the minimum values for the multiples of threshold need not be as high as those that a driver needs to detect a single unexpected point source. This situation could require a multiples of threshold value of up to 1,000 to assure timely detection [a MOT of 1,000 corresponds to a human brilliancy rating between satisfactory and bright, according to Breckenridge (*7*)]. The study dealing with the optimal placement of snowplowable raised reflective pavement markers, referred to earlier (*4*), used a MOT value of 30 as an acceptable value for the detection of the fourth raised reflective pavement marker ahead of the automobile. However, for post delineators a higher MOT value should be used for the following reasons:

• Within a driver's visibility range, post delineators are located farther away from the driver in comparison with RRPMs, and because the highway geometry is more likely to change over the longer distance, the driver is less able to predict the location of the next post delineator.

• The post delineator may be located in the driver's peripheral visual field, where the detection sensitivity is reduced.

• The retroreflectors on post delineators are ~3–4 ft above the pavement surface, where they may blend in with other point sources in the background near the horizon; they are therefore not as conspicuous as RRPMs.

• Post delineators must be able to provide drivers with guidance in snow conditions, where most other delineation elements are no longer visible. The post delineators therefore constitute somewhat of a last defense.

• On the basis of these reasons, a MOT value of 60 (17.1×10^{-8} fc or 1.84 km candles), which, according to Breckenridge (*7*), corresponds to a human brilliancy rating between faint (0.9 km candles) and weak (4 km candles), was used as the minimum level for detection of the fourth post delineator. According to Kaufmann (*5*, p. 3-25) the retroreflective sheeting patches can be assumed to be point sources beyond distances of 500 ft for a 3 × 6–in. patch, beyond 1,000 ft for a 12 × 1.5–in. patch, and beyond 1,500 ft for an 18 × 1–in. patch. If the MOT level for shorter distances is to be calculated, a correction factor must be incorporated into the calculations. As an example of the effect of this correction factor, a distance of 250 ft for a 3 × 6–in. patch, 500 ft for a 12 × 1.5-in. patch, or 750 ft for an 18 × 1–in. patch would require about a 5 percent reduction in the MOT value. The fourth post delineator is usually located at a calculated distance of 1,100 to 1,650 ft.

In optimizing the spacings of the post delineators, it was necessary to consider the following restrictions:

• On a straight and level highway the minimum number of post delineators visible to a driver should be at least four to ensure that the driver has a comfortable preview time and that a change in direction of the road (left or right curve ahead) will be detected in a timely manner. The post delineators should also provide some visual lateral position control cues. In case an occasional post delineator is missing or has lost nearly all of its reflectivity, a driver would still see three post delineators, which should be enough for perception of the approximate course of the road ahead.

• A straight and level Interstate highway with a lane width of 12 ft is assumed. It is further assumed that an automobile would be driven exactly in the middle of the right-hand lane.

• A uniform dark background with a luminance value of 0.01 foot-Lambert (fL) has been assumed (clear, moonlight, lower end of night driving range), which corresponds to an illumination threshold value (for 98 percent detection of a white point source in the laboratory) of 0.28493×10^{-8} fc.

• The headlamps and the silver retroreflectors on the post delineators are clean and operating at the prescribed output (100 percent), and the windshield is also assumed to be clean, with a transmission factor of 1. It was decided that instead of using arbitrarily degraded transmission and efficiency factors for the windshield, the retroreflectors, and the beams, the selection of a minimum acceptable MOT value of 60 would take some of the possible headlamp, windshield, and retroreflector deficiencies, as well as some background variations and driver deficiencies due to information processing load, age, and so on, into account.

• The headlamps of the vehicle are assumed to be properly aimed (i.e., approximately 2 degrees to the right and approximately 2 degrees down for the low beams).

• The vehicle operator is assumed to be seated fairly erectly in the driver's seat, which is assumed to be on the left side of the vehicle.

The independent variables, which were investigated for tangent sections of four-lane highways, left and right curve sections of four-lane highways, and left and right curve sections of two-lane highways, include

- The type of retroreflector,
- The height of the retroreflective patch (measured from the surface of the road to the top of the retroreflective patch),
- The lateral offset (measured from the edge of the highway to the center of the retroreflective patch),
- The dimensions of the retroreflective patch, and
- The longitudinal spacing of the post delineators.

On the curve sections of four-lane divided highways it is assumed that the post delineators are always on the right side of the two lanes regardless of whether the highway curves to the left or right. In this case, as for the tangent sections of four-lane highway, the post delineators are offset 12 ft from the right-hand edge of the highway. The spacing of post delineators along curved sections of four-lane highways is not explicitly addressed by the *Ohio Manual of Uniform Traffic Control Devices* (*3*). On curve sections of two-lane rural highways it is assumed that bidirectional post delineators are placed on the outside edge of the curve only. In this situation, the post delineators (set 2 ft from the edge of the roadway) would be 8 ft to the right of the longitudinal center of the vehicle for a left curve and 20 ft to the left of the longitudinal center of the vehicle for a right curve on a highway with an assumed lane width of 12 ft.

Because the low beams of the vehicle are aimed approximately 2 degrees to the right horizontally, the post delineator spacings on right- and left-hand curves must be analyzed separately. Therefore the computer optimization calculations were carried out for four different curve situations: first for left- and right-hand curves on four-lane divided highways and second for left- and right-hand curves on two-lane rural roads.

COMPUTER OPTIMIZATION RESULTS

During the initial stages of this study the effect of variables that were not directly related to the post delineators was studied, including the vehicle-driver dimensions, the type of headlamp used, and the transmissivity of the atmosphere. A more thorough discussion of the entire optimization study has been presented by Zwahlen (*8*).

Three sets of vehicle-driver dimensions were investigated: those of a 95th percentile man in a typical semitractor, a 50th percentile person in a typical large automobile, and a 5th percentile woman in a typical small automobile. The results indicate that on tangent sections of highways when post delineators are installed according to the guidelines established by ODOT, the delineation conditions favor the 5th percentile woman in a typical small automobile and are somewhat less favorable for the 95th percentile man in a semitractor.

Three common types of headlamps were also investigated, the halogen 6054 high beam, the halogen 6054 low beam, and the 6052 low beam. Of these three headlamp beam types the 6052 low beam provided the least favorable illumination conditions. Therefore, to make the results applicable to a high percentage of the driving population, the results presented in this paper will apply to a 95th percentile man in a typical semitractor equipped with 6052 low beams. The study also included two levels of transmissivity, 0.99 per 100 ft (relatively clear conditions) and 0.8946 per 100 ft (1 in. of rainfall per hour or light fog). Although lower levels of illumination were present for the 0.8946 level of transmissivity, illumination levels for the 0.99 level of transmissivity are presented throughout the results because this is the more common condition, and it is felt that the drivers will adjust their driving strategies and speed during conditions of heavy rain, snow, or fog.

During the computer optimization, two types of retroreflective materials were studied. These include encapsulated lens sheeting material (such as 3M high intensity) with a specific intensity of 309 candela per footcandle per square foot (cd/fc/ft^2) and prismatic sheeting material (such as Reflexite A/C 1000) with a specific intensity of 825 cd/fc/ft^2 at a 0.2-degree observation angle and a −4-degree entrance angle. During the study, actual measurements of the prismatic sheeting materials in the field indicated that they had an average specific intensity of 1,483 cd/fc/ft^2 at a 0.2-degree observation angle and a −4-degree entrance angle; therefore many of the theoretical results also include numbers for prismatic materials with this specific intensity.

As shown in Figure 1, which shows MOT values at various distances for prismatic sheeting with a specific intensity of 825 cd/fc/ft^2 and encapsulated lens sheeting with a specific intensity of 309 cd/fc/ft^2, the minimum selected 60 MOT value for the prismatic sheeting material (825 cd/fc/ft^2) corresponds to a detection distance of ~1,390 ft or a spacing of ~348 ft for the 100 percent (ideal) efficiencies and windshield transmittance stated in the assumptions. For the encapsulated lens sheeting material the 60 MOT value is reached at ~1,090 ft, which would correspond to a spacing of ~273 ft for the 100 percent (ideal) efficiencies and windshield transmittance stated in the assumptions. If the spacing for encapsulated and prismatic sheeting materials were calculated with the assumption of a windshield transmittance of 0.7 and a retroreflector efficiency of 90 percent, then these distances would be about 86 to 88 percent of the distances calculated under the ideal conditions. Because it would be possible to place post delineators with prismatic sheeting material further apart than post delineators with encapsulated lens sheeting material while still fulfilling the minimum selected MOT value, it would seem that the prismatic sheeting is superior to the encapsulated lens sheeting material for post delineator applications.

Three retroreflector heights were evaluated (34, 40, and 46 in., measured from the surface of the road to the top of the retroreflective patch), and the MOT values were plotted against detection distance for both tangent (straight) and curve (2.6-degree curvature, radius of 2,200 ft) sections of highway. Figure 2 shows that at any given distance the MOT value is slightly higher for the 34-in. post delineator height than it is for the 40- or 46-in. post delineator height on both tangent and curved sections of highway. It should also be noted that as the retroreflective patches are mounted closer to the ground, shorter delineator posts, which require less material, may be used (a 40-in. reflector height with the reflector mounted 2 in. below the top of the delineator post will use about 8 percent less material than the 46-in. retroreflector height that is currently used); however, other considerations, such as guardrail height, grass growth, snow, dirt and spray accumulation, make it inadvisable to decrease the retroreflector height below ~40 in.

Lateral offset values of 10, 12, and 14 ft (measured from the edge of the road) were investigated. Figure 3 shows the MOT level at various distances for each of these three lateral offsets and for straight and curved sections (2.6-degree curvature, radius of 2,200 ft) highway. It can be seen that there is practically no difference between the three lateral offset distances until the distance to the fourth delineator post is less than 400 ft. However, the MOT values for distances less than 400 ft are

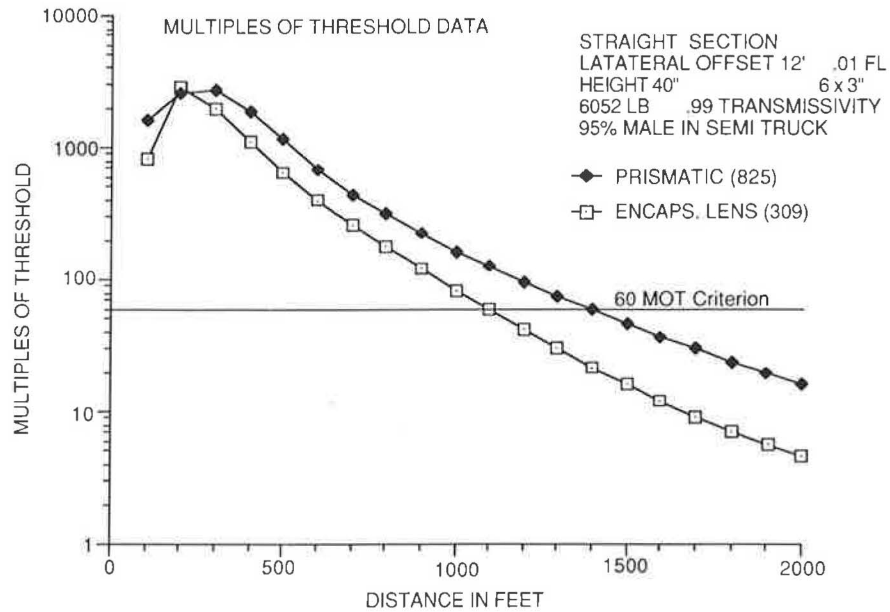

FIGURE 1 MOT versus distance for prismatic and encapsulated lens sheeting materials.

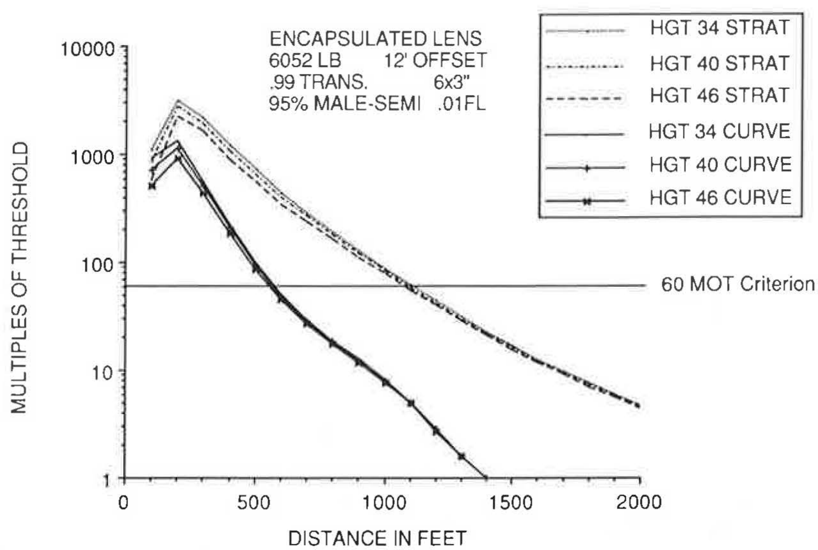

FIGURE 2 MOT versus distance for variable height and road geometry.

greater than 200, and therefore any differences are of no great practical significance because the retroreflectors on the post delineators should be clearly distinguishable under all conditions.

It might be noted that because lateral offset does not seem to influence the illuminance level at the driver's eyes near the 60 MOT line, the spacing optimization that is carried out for four-lane divided highways might be generalized to include tangent sections of two-lane highways as well because the only difference between the conditions for the two types of roadways would be the lateral offset.

The photometric effect of changing the current dimensions of the retroreflective patch (3 in. in width by 6 in. in length) to a patch 1.5 in. wide and 12 in. long was investigated. This patch size allowed the use of the same amount of reflective area (18 in.^{2}) as well as posts of equal height. The calculations were done by dividing each retroreflector into four equally wide, independent horizontal, rectangular patches and determining the illumination at a driver's eyes for each separate patch. Thesums of the illuminations from these four equally wide patches, each with a different vertical centroid height above the road surface, were then plotted in Figure 4. It should be noted that although there is no practical difference in the MOT values at corresponding detection distances for the two different retroreflector patches from an illumination or photometric point of view, there may well exist a difference from a driver's perceptual point of view (see the results of the field evaluation).

An evaluation of the spacings that have been or are presently being used by ODOT in conjunction with encapsulated lens sheeting material was made, with interesting results. Post delineator spacings of 400 and 528 ft were evaluated with a post delineator height of 40 in. (measured from the highway's surface to the top of the retroreflective patch), a 3 × 6–in. encapsulated lens retroreflective patch, 6052 low beams, lateral offset of 12 ft, and vehicle-driver dimensions for a 95th percentile man in a semitractor. The MOT for the first four retroreflectors

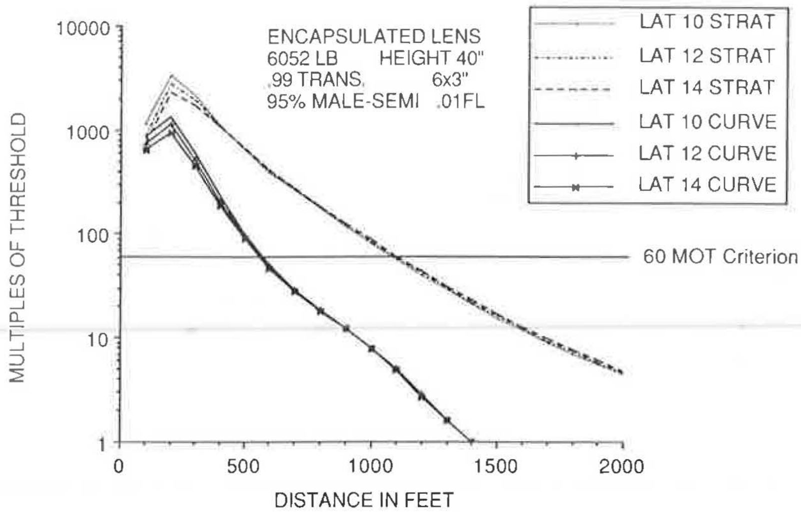

FIGURE 3 MOT versus distance for variable offset and road geometry.

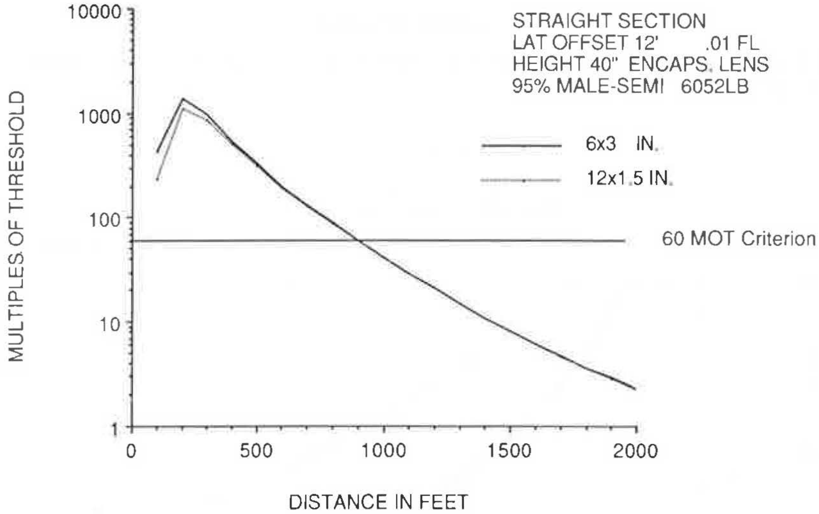

FIGURE 4 MOT versus distance for variable patch dimensions.

were then calculated for each of these two post delineator spacings. For a 0.99 transmissivity (clear conditions) and a post delineator spacing of 528 ft, the MOT values were 595 for the first post delineator, 69 for the second, 12.9 for the third, and only 3.6 for the fourth.

With somewhat degraded atmospheric conditions (0.8946 transmissivity), the MOT values show a further decline, with a MOT value of 203 for the first post delineator, 8.1 for the second, 0.5 (not visible under laboratory conditions) for the third, and 0 for the fourth post delineator. If the 400-ft spacing is evaluated in the same way, using a transmissivity of 0.99, the MOT value is 1,159 for the first post delineator, 185 for the second, 42.2 for the third, and 12.4 for the fourth. Once again, these values decline further for the degraded weather conditions (0.8946 transmissivity), with a MOT value of 511 for the first post delineator, 36.3 for the second, 3.7 for the third, and 0.5 (not visible under laboratory conditions) for the fourth. The use of this retroreflective encapsulated lens sheeting material for a post delineator spacing of 528 or 400 ft clearly does not fulfill the chosen minimum MOT value of 60 and therefore is probably unsatisfactory from a driver visibility or detection point of view.

If the post delineators equipped with encapsulated lens sheeting material were to fulfill the minimum MOT value of 60, the posts could be no farther than 273 ft apart along tangent sections of highway for a transmissivity of 0.99, 6502 low beams, a 95th percentile man in a typical semitractor, lateral offset of 12 ft, retroreflector height of 40 in., and a 3 × 6-in. patch. If the post delineators were equipped with prismatic sheeting material with a specific intensity of 825 cd/fc/ft^2, then the retroreflectors could be placed 348 ft apart, and if they were equipped with prismatic sheeting material with a specific intensity of 1,483 cd/fc/ft^2, then they could be placed 413 ft apart and still satisfy the minimum value of 60 MOT for a transmissivity of 0.99 per 100 ft.

Table 1 and Figure 5 show post delineator spacings at which a MOT value of 60 is obtained at the fourth post delineator for both left and right curves on four-lane highways for various curve radii and for three different retroreflective intensities (309, 825, and 1,483 cd/fc/ft^2 at a 0.2-degree observation angle and −4-degree entrance angle). Detection distance values could not be obtained for radii below 550 ft due to lack of beam pattern data for slightly positive vertical beam angles, combined with large horizontal beam angles, and collection of such

TABLE 1 SPACINGS FOR RIGHT AND LEFT HORIZONTAL CURVES

Curve Radius (ft)	Retroreflector[a]	Right Curve Spacing (ft)	Left Curve Spacing (ft)
3,000	EL	165	135
	P1	195	160
	P2	221	188
2,200	EL	145	125
	P1	170	155
	P2	199	173
1,800	EL	130	115
	P1	160	141
	P2	190	162
1,400	EL	120	110
	P1	149	128
	P2	172	150
1,000	EL	110	100
	P1	128	113
	P2	141	130
750	EL	95	90
	P1	108	100
550	EL	80	85

NOTE: Recommendations for four-lane divided highways, using encapsulated lens and prismatic sheeting materials as retroreflectors, vehicle-driven dimensions of a 95th percentile man driving a typical semitractor, and 0.99 per 100 ft transmissivity. No data are available for curve radii smaller than 550 ft due to lack of available candle power values for large horizontal angles and slightly positive vertical beam angles.

[a]EL = encapsulated lens sheeting (silver), assumed specific intensity 309 cd/fc/ft^2; P1 = prismatic sheeting (silver), assumed specific intensity 825 cd/fc/ft^2; and P2 = prismatic sheeting (silver), measured specific intensity in field 1,483 cd/fc/ft^2.

photometric data was beyond the scope of this study. In Table 1 and Figure 5 it can be observed that with the exception of radii below 550 ft, the post delineator spacings for left curves are significantly shorter than those for post delineators for right curves, due to the geometric interaction of the driver-vehicle-retroreflector dimensions and the aim of the low beam pattern.

Functional relationships for the spacing of post delineators on curves in four-lane highways with various radii were obtained for the three different retroreflective intensities. The main objective when formulating these relationships was to obtain a relatively good fit over the radius range from 550 to 2,200 ft by fitting the curve to the 60 MOT detection distances (for the fourth delineator post location) for radii of 550, 750, 1,000, 1,400, 1,800, 2,200, and 3,000 ft for left and right curves. However, no photometric data from the computer model exist to allow justification of the use of this relationship for spacings along curves with radii of less than 550 ft, therefore an arbitrary minimum spacing of 20 ft for a 50-ft-radius curve, which is presented in both the *Manual on Uniform Traffic Control Devices* (*1*) and the *Ohio Manual of Uniform Traffic Control Devices* (*3*), was used.

The relationships that exist between post delineator spacings and curve radii not only are different for different retroreflective materials but also are different for left and right curves. However, to eliminate confusion that may result from the application of the different relationships for post delineator spacings along left and right curves, the relationships given for four-lane highways have been fitted for each type of retroreflective material so that they are adequate regardless of the direction of the curve. These relationships are as follows: 9.8 $(R\text{-}40)^{1/3}$ for encapsulated lens sheeting (309 cd/fc/ft^2), 11.5 $(R\text{-}45)^{1/3}$ for prismatic sheeting material (825 cd/fc/ft^2), and 13.5 $(R\text{-}47)^{1/3}$ for prismatic sheeting (1,483 cd/fc/ft^2). These relationships can then be applied from a 50-ft radius (20-ft spacing) up to a radius value that provides spacings of 275 ft for encapsulated lens sheeting, 350 ft for prismatic sheeting at 825 cd/fc/ft^2, or 400 ft for prismatic sheeting at 1,483 cd/fc/ft^2. The derived constants are to be considered tentative at this point and will change somewhat if other specific intensity values are used. However, the basic functional relationship of using a multiplicative constant to multiply the cube root of a difference appears to be quite robust.

To test the accuracy of these relationships, the computer model was used to perform photometric calculations for a left curve with a radius of 10,000 ft. These calculations yield a post delineator spacing of 211 ft (201 ft using the appropriate formula given earlier) for the encapsulated lens sheeting, 227 ft (247 ft using the appropriate formula given earlier) for the prismatic sheeting at 825 cd/fc/ft^2, and 257 ft (290 ft using the appropriate formula) for the prismatic lens sheeting at 1,483 cd/fc/ft^2. When these calculated post delineator spacings for a radius of 10,000 ft (0.6-degree curve) are compared with the distances obtained through the mathematical relationships, an error of only 5 percent is observed for the encapsulated lens sheeting, 9 percent for the prismatic sheeting at 825 cd/fc/ft^2, and 13 percent for the prismatic sheeting at 1,483 cd/fc/ft^2. Thus for a 10,000-ft-radius left curve, the difference is fairly small and is acceptable when it is considered that in deriving the multiplicative constant, the exponent, and the amount to be subtracted from the radius, trade-offs were made that kept the functional relationship fairly simple and minimized the error for curve radii between 550 and 3,000 ft (10.4–1.9 degrees of curvature) for which calculated 60 MOT detection distances were available.

Table 2 shows post delineator spacings where 60 MOT detection distances for the fourth post delineator are obtained for radii ranging from 500 to 2,000 ft, two different transmissivities, and left and right curves on two-lane highways. These spacings are compared with recommended spacings from Figure CD-5 of the *Ohio Manual of Uniform Traffic Control Devices* (*3*) in Figures 6 and 7. It should be noted that the spacings recommended by ODOT for curve radii greater than 1,000 ft are calculated from a formula given in the footnote of Figure CD-5, which was to be used to calculate spacings of post delineators leading into and out of the curve. In Table 2 of this paper, it can be observed that in all cases the post delineator spacings for the left curves are significantly lower than those for the right curves. In fact, in Figure 6, which shows spacings for a right curve, it can be seen that the spacings recommended by ODOT are much shorter than the spacings required to obtain an illuminance level at a driver's eyes of 60 MOT for any of the three types of material. However, if the spacings for the left curve in Figure 7 are examined, it can be seen that the spacings recommended by ODOT would not satisfy the 60 MOT value for the encapsulated lens material on curves with radii larger than 1,300 ft.

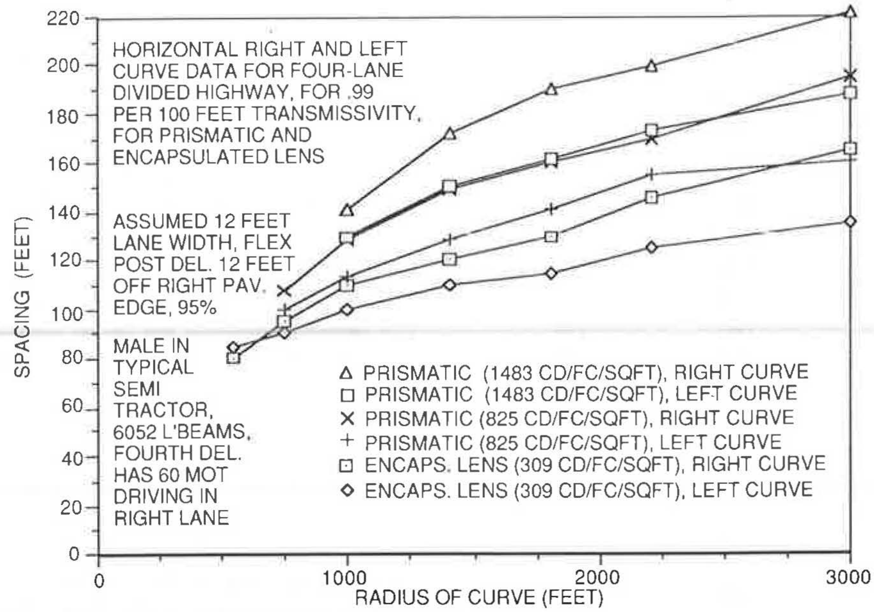

FIGURE 5 Computed optimal spacings for flexible post delineators for right and left horizontal curves on four-lane divided highways.

TABLE 2 FLEXIBLE POST DELINEATOR SPACINGS FOR LEFT AND RIGHT CURVES ON TWO-LANE RURAL ROADS

		Retroreflector Transmissivity[a]					
Radius (ft)	Curve	EL 0.99	EL 0.8946	P1 0.99	P1 0.8946	P2 0.99	P2 0.8946
500	Right	88		92			
	Left						
600	Right	99	85	103	92	112	100
	Left	81	76				
700	Right	107		113		123	
	Left	87					
800	Right	113		122		133	
	Left	91		101			
900	Right	116		129		143	
	Left	94		107		120	
1,000	Right	121		135		152	
	Left	97		112			
2,000	Right	168	141	185	155	205	165
	Left	116	93	153	108	166	124

[a]EL = encapsulated lens sheeting at 309 cd/fc/ft^2; P1 = prismatic sheeting at 825 cd/fc/ft^2; and P2 = prismatic sheeting at 1,483 cd/fc/ft^2. 0.99 = transmissivity of 0.99 per 100 ft (clear); 0.8946 = transmissivity of 0.8946 per 100 ft (1 in. of rain per hour or light fog).

Because the illumination values are dependent on the curve radius and the type of retroreflective material, it is once again necessary to present mathematical relationships from which post delineator spacings can be calculated for various curve radii. However, it should be noted that a curve on a two-lane highway that is approached as a right curve while traveling in one direction will be approached as a left curve when traveling in the opposing direction. If these post delineators are placed only on the outside edge of the curve, the same delineators (bidirectional) will be used by motorists approaching the curve from either direction. To provide a satisfactory visual stimulus to a driver who approaches the curve from either direction, it is necessary to use the mathematical relationships that yield the shortest spacings.

The functional relationships for the spacing of post delineators on curves along two-lane rural highways were obtained in the same manner as for the four-lane divided highways. These relationships were based on a minimum arbitrary spacing of 20 ft for a 50-ft-radius (114 degrees of curvature) curve and 60 MOT detection distances (at the fourth post delineator location) obtained for left curves for the radii shown in Table 2. For all curves on two-lane highways the mathematical relationships are $10\,(R\text{-}43)^{1/3}$ for encapsulated lens sheeting, $11.5\,(R\text{-}44)^{1/3}$ for prismatic sheeting at 825 cd/fc/ft^2, and $13\,(R\text{-}46)^{1/3}$ cd/fc/ft^2 for prismatic sheeting at 1,483 cd/fc/ft^2.

Photometric calculations that were carried out with the computer model for a curve with a 10,000-ft radius resulted in flexible post delineator spacings of 181 ft for encapsulated sheeting material, 208 ft for prismatic sheeting at 825 cd/fc/ft^2, and 241 ft for prismatic sheeting at 1,483 cd/fc/ft^2. These compare with spacings of 215 ft for encapsulated lens sheeting material, 247 ft for prismatic sheeting material at 825 cd/fc/ft^2, and 280 ft for prismatic sheeting material at 1,483 cd/fc/ft^2 calculated from the mathematical relationships. No photometric data from the computer model are available to justify the use of these mathematical relationships for curve radii of less than 500 ft. Although the differences of 19 percent, 19 percent, and 16 percent that exist between the results from the computer model and the mathematical relationships for a curve radius of 10,000 ft seem rather large, they may be acceptable given that most curves on two-lane rural highways fall within a range of radii from 200 to 2,000 ft [28.6 to 2.8 degrees of curvature; see Zwahlen (*9*)].

TANGENT SECTION FIELD DEMONSTRATION AND EVALUATION RESULTS

A small-scale field demonstration and evaluation was conducted with ODOT and FHWA personnel. The 10 test sections

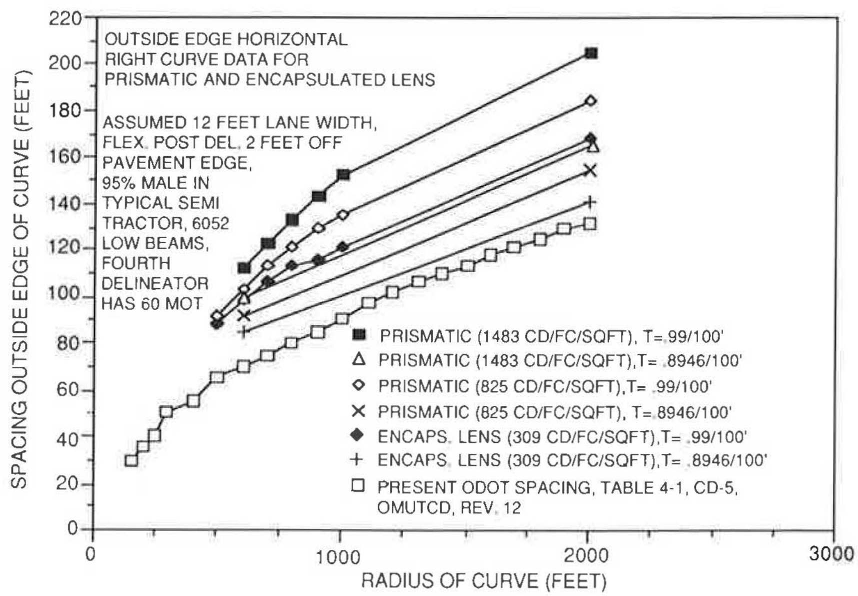

FIGURE 6 Comparison of computed optimal spacings for flexible post delineators for right horizontal curves (on outside edge only) on two-lane rural roads with present ODOT spacings.

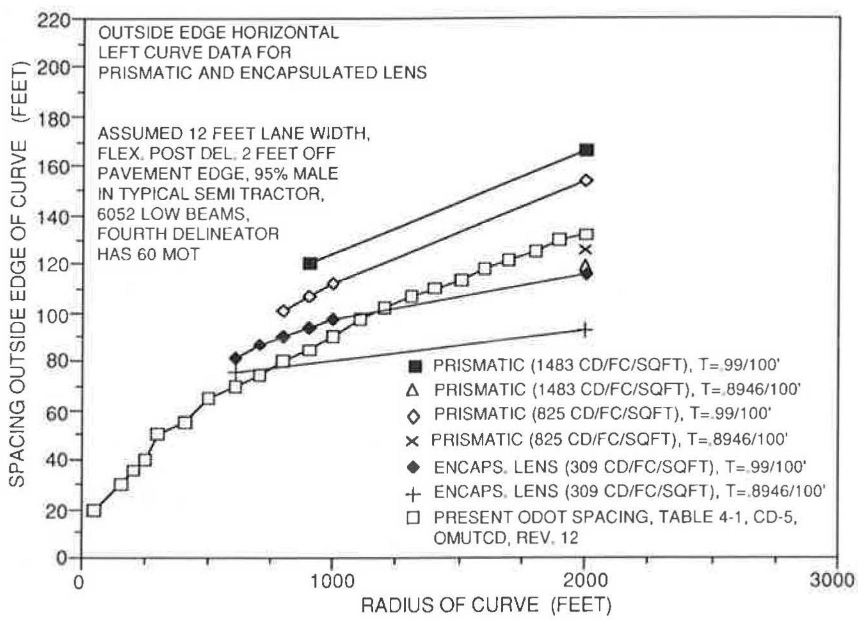

FIGURE 7 Comparison of computed optimal spacings for flexible post delineators for left horizontal curves (on outside edge only) on two-lane rural roads with present ODOT spacings.

were on highways 50 and 32 west of Athens, Ohio, in Athens and Meigs counties. Test section A used post delineators with 6 × 3–in. retroreflectors made of encapsulated lens sheeting material and a longitudinal spacing of 275 ft. Test section B was equipped with post delineators with 12 × 1.5–in. encapsulated lens sheeting material retroreflectors and a longitudinal spacing of 275 ft. Post delineators with 12 × 1.5–in. retroreflectors made of enclosed (embedded, engineering grade) lens sheeting and a spacing of 275 ft were used at test section C, while test section D had post delineators with 6 × 3–in. retroreflectors made of prismatic sheeting material and a spacing of 350 ft. Test sections E and F were equipped and post delineators with an 18 × 1–in. silver prismatic retroreflector and two black 6–in. strips near the top of the post slanted at a 30-degree angle on the front of each post and an 18 × 1–in. red retroreflector on the back. The two black 6–in. strips were slanted away from the road in test section E and toward the road in test section F. The post delineators on test sections E and F were spaced 350 ft apart. The post delineators on test section G had 12 × 1.5–in. retroreflectors made of prismatic sheeting material and were spaced 350 ft apart. Test section H was equipped with post delineators with 12 × 3–in. encapsulated lens retroreflectors and were spaced 350 ft apart. Test section I used post delineators with 24 × 3/4–in. silver prismatic retroreflectors and two black 6-in. strips near the top of the post. The strips were slanted 30 degrees toward the highway on the front. These post delineators were spaced 350 ft apart. Post delineators with 18 × 1–in. prismatic retroreflectors and two black 6-in. strips near the top of the post slanted 30 degrees toward the highway on the front were used on test section J and were spaced 350 ft apart. Each test section contained approximately 10 flexible delineator posts. All posts were 42 in. high (measured from the pavement edge to the top of the retroreflective delineator post) and 12 ft away from the right-hand pavement edge. On the basis of field measurements, the encapsulated lens sheeting had a specific intensity of about 296 cd/fc/ft^2 at a 0.2-degree observation angle and –4-degree entrance angle. The enclosed lens sheeting had a specific intensity of ~95 cd/fc/ft^2 at a 0.2-degree observation angle and –4-degree entrance angle. The prismatic sheeting had a specific intensity of about 1,483 cd/fc/ft^2 at a 0.2-degree observation angle and –4-degree entrance angle.

During the demonstration, 13 ODOT and FHWA employees evaluated the 10 test sections at night. The first evaluation run in a passenger automobile was with low beams, while the second evaluation run was with high beams. For each run, a two-page Post Delineator Rating Form was filled out. The results of this small evaluation indicated that sections E and F (prismatic sheeting, 18 × 1–in. vertical silver strip, 350-ft spacing) were subjectively judged to be the best from the appearance and guidance viewpoint. This type of retroreflector, with dimensions of 18 × 1 in., seems to provide drivers with an excellent shape cue, an excellent distance estimation cue, and an excellent guidance cue. The bottom of this patch is still at least 22 in. above the pavement surface when the top of the patch is 40 in. above the pavement surface and is therefore very functional in the road environment. A vertical strip of 18 × 1 in. would also allow the design of a narrower post that would be subject to less wind stress and might result in an additional post material savings of up to 12 percent.

The least satisfactory post delineator configuration was the enclosed lens material 12 × 1.5–in. vertical silver strip with a 275-ft spacing. The results were very similar for high beams and for low beams. Sections E and F were between two intersections, and the post delineators had a red 18 × 1–in. vertical prismatic sheeting strip on their backs as a means to warn motorists that they were driving in the wrong lane. On the basis of the evaluation results, such a red strip would help considerably, especially during a dark night or a wet dark night or on a snow-covered road, to inform drivers that they were in the wrong lane and going in the wrong direction. In addition, sections E, F, I, and J had post delineators with a black and white pattern (two black diagonal bands, each 6 in. wide, and 6 in. apart, starting 1 in. below the top, slanted at a 30-degree angle toward the road). On the basis of the evaluation results, such a contrast pattern was judged to be useful during the daytime and in snow.

CONCLUSIONS

Post delineator placement and spacing recommendations for tangent sections and left and right curve sections of two-lane and four-lane highways have been derived on the basis of explicit procedures, calculations, and visual detection assumptions. This analytical optimization was used to determine a preferred retroreflector height of 42 in. (measured from the pavement surface to the top of the post). No practical differences were found between lateral offsets of 10, 12, and 14 ft. Therefore, if it is beneficial to place the posts at any given distance between 10 and 14 ft from the pavement edge of the right lane (to minimize damage during repaving, shoulder rehabilitation operations, or snow removal), such a lateral offset is acceptable.

To minimize the number of post delineators per mile, retroreflective sheeting should be made of prismatic material and should measure 18 × 1 in. The top of the sheeting strip should be no more than 2 in. below the top of the post. An 18 × 1–in. red retroreflective prismatic sheeting strip should be placed on the back side of the five post delineators closest to an intersection on both sides of a four-lane highway as a wrong way indicator. If the post delineator is to be placed in a geographic region where snow is common, then a black and white pattern (two black diagonal bands, each 6 in. wide, and 6 in. apart, starting 1 in. below the top of the post, slanted at a 30-degree angle toward the road) should be used to enhance contrast and delineation against a white, snow-covered background.

Along tangent sections of highways the post delineators should have a longitudinal spacing of 275 ft for encapsulated sheeting material with a specific intensity of 309 cd/fc/ft^2, 350 ft for prismatic sheeting material with a specific intensity of 825 cd/fc/ft^2, and 400 ft for prismatic sheeting with a specific intensity of 1,483 cd/fc/ft^2. The recommended spacing of the post delineators along curve sections of a four-lane divided highway and the recommended spacing of the bidirectional post delineators (with 18 × 1–in. sheeting strips on both the front and the back of the delineator post) along curve sections of a two-lane highway should be calculated by using the mathematical relationships that were previously presented for each type of retroreflective sheeting material. These mathematical relationships have the general form of a constant multiplied by the cubed root of the curve radius minus some constant. Because the optimization results of this study are based primarily on visibility calculations and because the recommendations for the shape of the retroreflective strip, the red retroreflective sheeting strip on the back of posts near intersections, and the black diagonal bands for contrast enhancement in snow have not yet been fully evaluated from a driver performance and safety point of view, it is recommended that further, more comprehensive field validation studies be conducted before these recommendations are implemented.

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