

Minimum Light Above Horizontal of Low-Beam Headlamps  
for Nighttime Legibility of Traffic Signs

Michael Sivak  
Andrew W. Gellatly  
Michael Flannagan

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16. Abstract  <p>Retroreflectorized traffic signs rely on illumination from headlamps for their nighttime conspicuity and legibility. However, the current low-beam photometric standard specifies no minima for light above the horizontal. The only limitations above horizontal are several maxima, designed to provide glare protection. Consequently, it would be entirely legal to sell a low-beam headlamp which provides no light above the horizontal. Such a situation would make all retroreflective traffic signs virtually useless at night.</p> <p>The present analytical study was designed to provide a method for determining minimum levels of low-beam illumination above horizontal, as well as initial guidance concerning actual values. The sign characteristic considered in this research was legibility; conspicuity was not dealt with. The approach involved determining (1) relevant angles above the horizontal, (2) desirable sign luminance, and (3) relationship between headlamp intensity and sign luminance for the relevant angles and different types of sign material.</p> <p>Using this approach, relevant angles and corresponding required headlamp intensity were derived. Two examples of possible strategies for modifying the current low-beam standard (adding minima to existing test regions that currently deal only with maxima, and adding new test regions for minima only) were discussed in relation to several unresolved issues. These issues include the conflict between sign requirements and glare-protection requirements, and manufacturing tolerances.</p>					
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## INTRODUCTION

Retroreflectorized traffic signs rely on illumination from headlamps for their nighttime conspicuity and legibility. However, the current low-beam photometric requirements specify no minima for light above horizontal. The only limitations above horizontal are several maxima, designed to provide glare protection for oncoming drivers. Consequently, it would be entirely legal to sell a low-beam headlamp which provides no light above horizontal. Such a situation would make all retroreflective traffic signs virtually useless at night.

The present analytical study was designed to provide a method for determining minimum levels of low-beam illumination above horizontal, as well as initial guidance concerning actual values. The sign characteristic considered in this research was legibility; conspicuity was not dealt with. The general approach was as follows:

- (1) Select a representative set of road profiles, sign placements, and headlamp-to-sign distances.
- (2) Determine the relevant angles above horizontal by computing the angles between the headlamps and signs for the set of situations in (1).
- (3) Determine desirable minimum sign luminance (in  $\text{cd}/\text{m}^2$ ).
- (4) Determine the relations between headlamp intensity (in  $\text{cd}$ ) and sign luminance (in  $\text{cd}/\text{m}^2$ ) for the set of angles in (2) and for three types of retroreflective material.
- (5) Using the information from (3) and (4), compute the desirable minimum headlamp intensity (in  $\text{cd}$ ) for the set of angles in (1).

## SELECTED SET OF GEOMETRIES

The selected set of geometries corresponds to the set used by Woltman and Szczech (1989) to derive sign luminance values. Woltman and Szczech considered geometries defined by the following set of variables on a two-lane roadway:

- (a) three sign positions (right shoulder, center, and left shoulder), (see Figure 1),
- (b) five road profiles (straight, right and left curves with 2,000-ft radii, and hill and sag with 6000-ft radii), and
- (c) six headlamp-to-sign distances (1200, 1000, 800, 600, 400, and 200 feet).

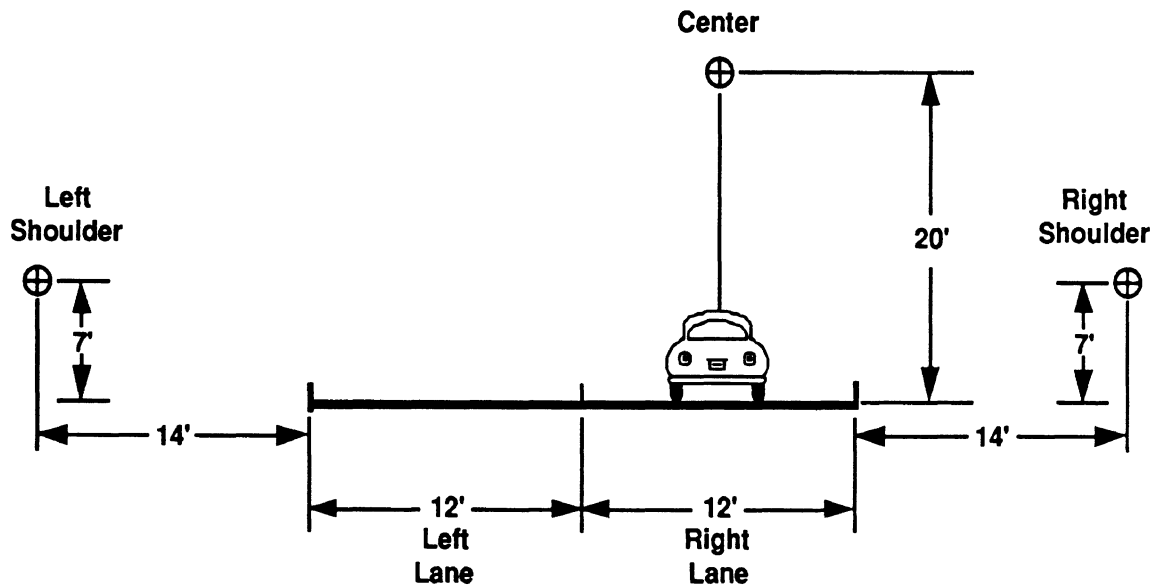


Figure 1. Sign positions (after Woltman and Szczech, 1989).

## RELEVANT ANGLES

The computed angles for the selected set of geometries are shown in Figures 2 through 6 separately for the left and the right headlamp. The angles in these figures are for headlamp-to-sign distances from 1200 to 200 feet, in 200-ft decrements. These angles are in respect to the axes of each headlamp, and they are for the particular mounting height (27 inches) and lateral separation of the headlamps (5 feet) used by Woltman and Szczech (1989).

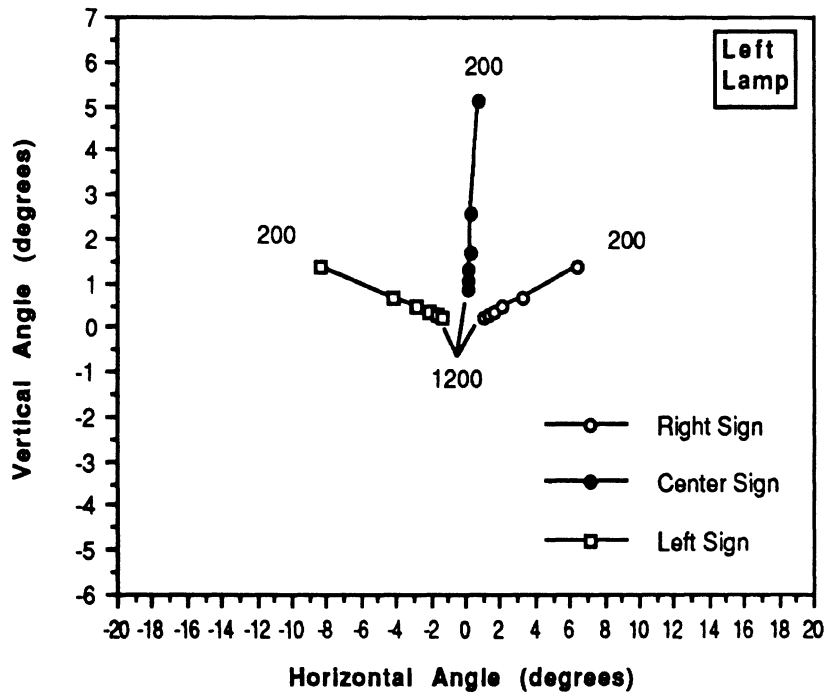
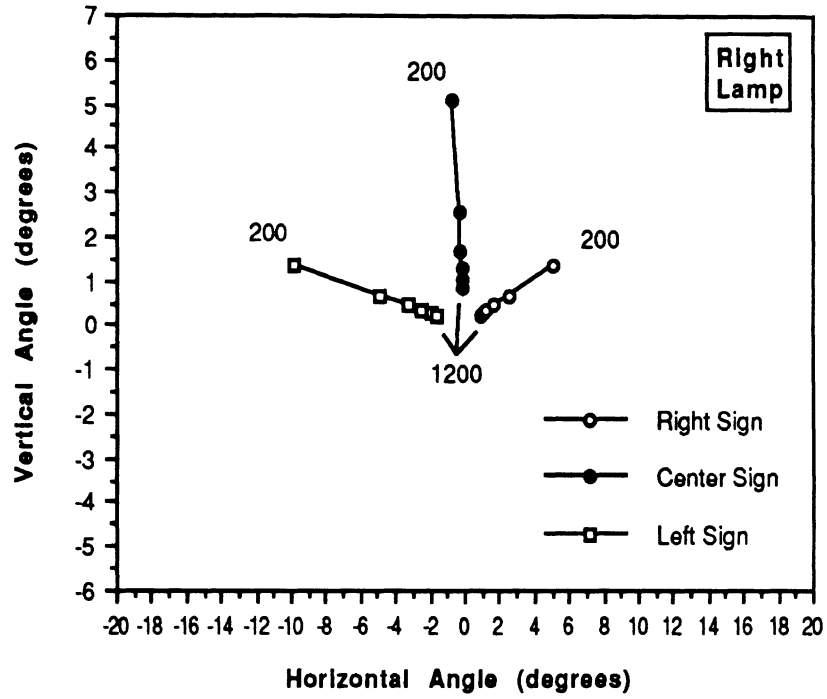


Figure 2. Relevant angles on a straight road. (The numbers are distances in feet.)



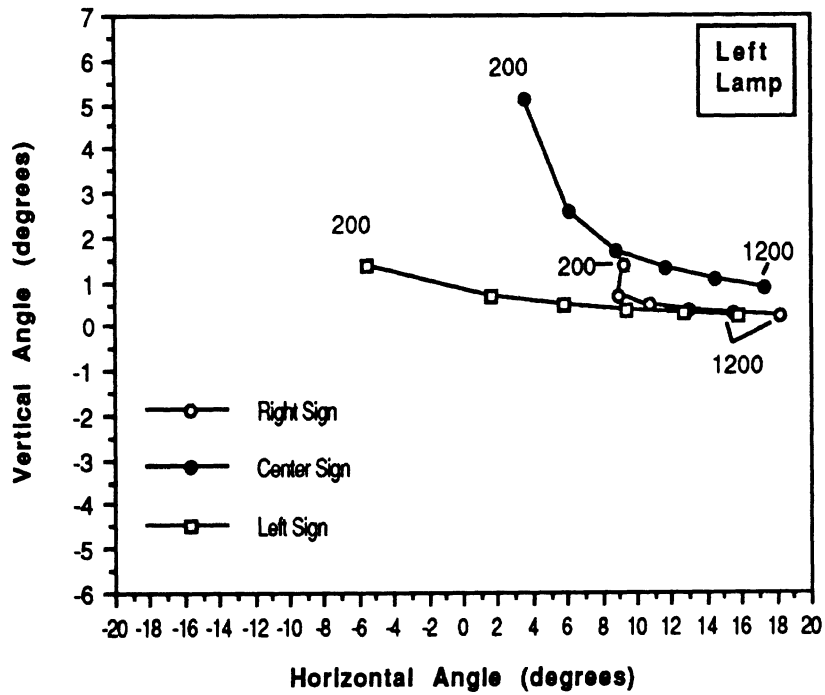
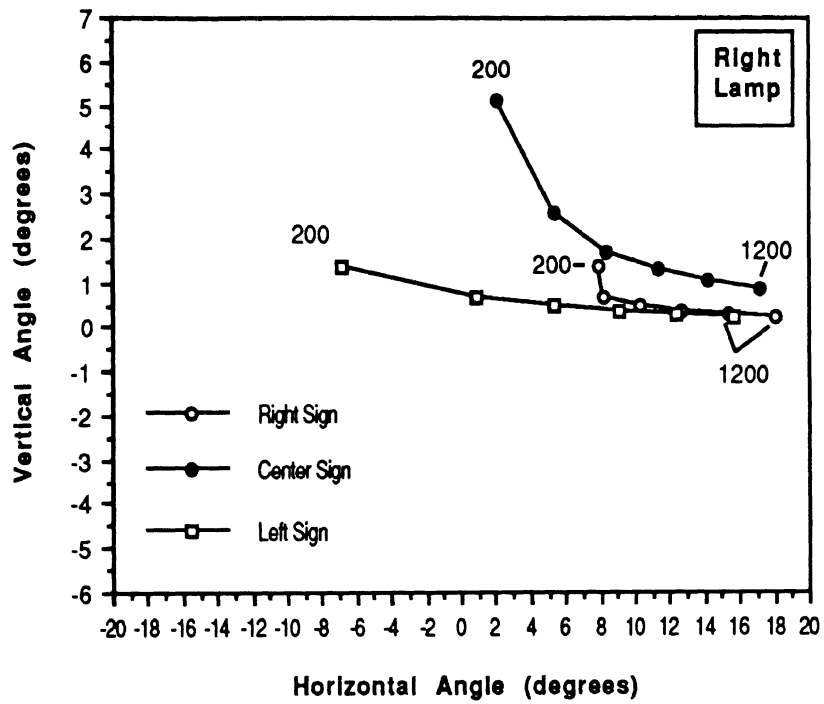


Figure 3. Relevant angles on a right curve. (The numbers are distances in feet.)

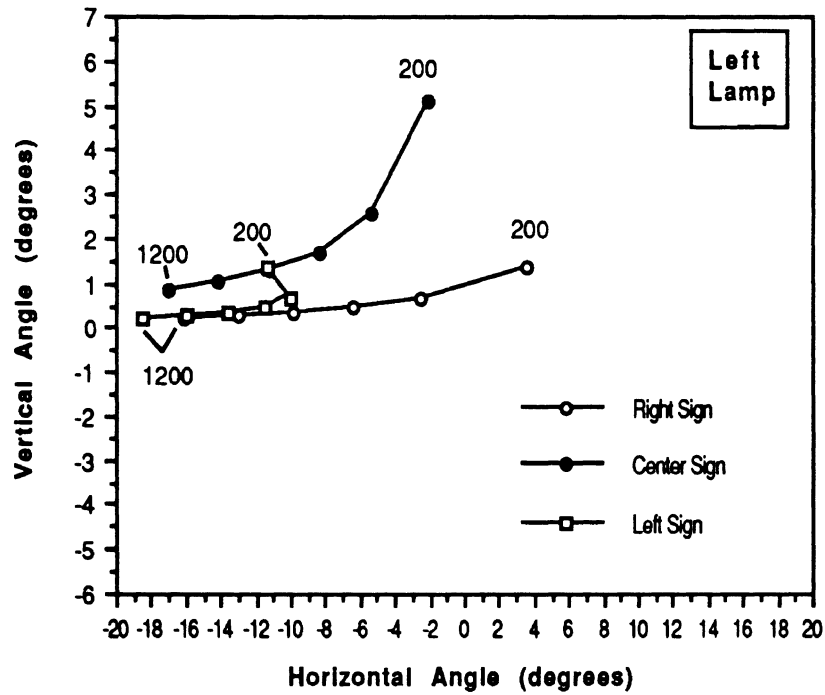
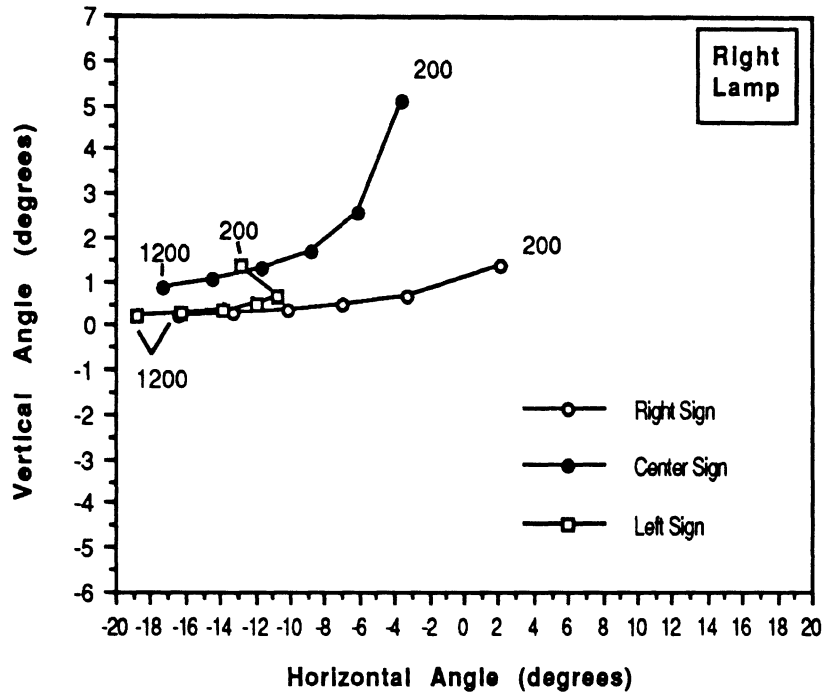


Figure 4. Relevant angles on a left curve. (The numbers are distances in feet.)

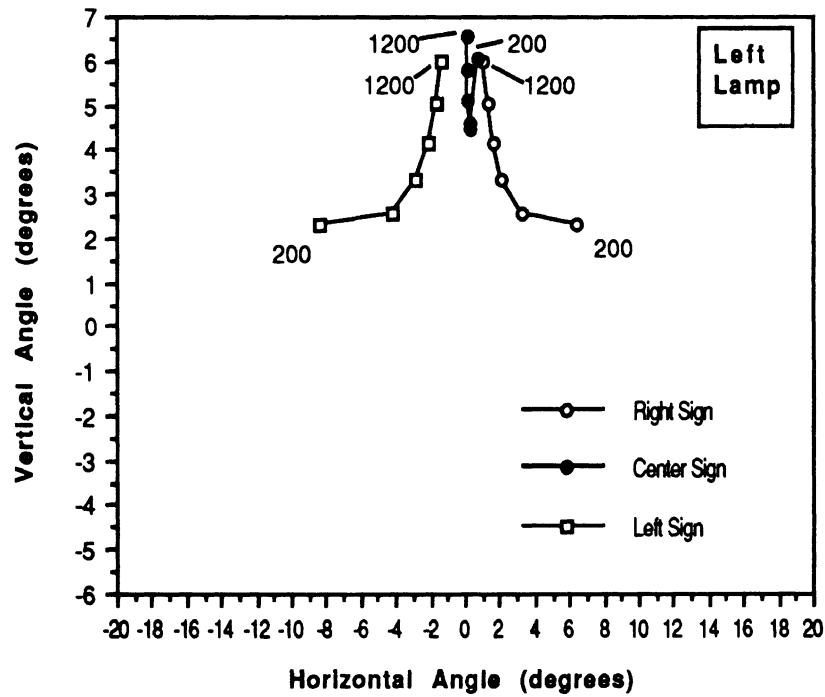
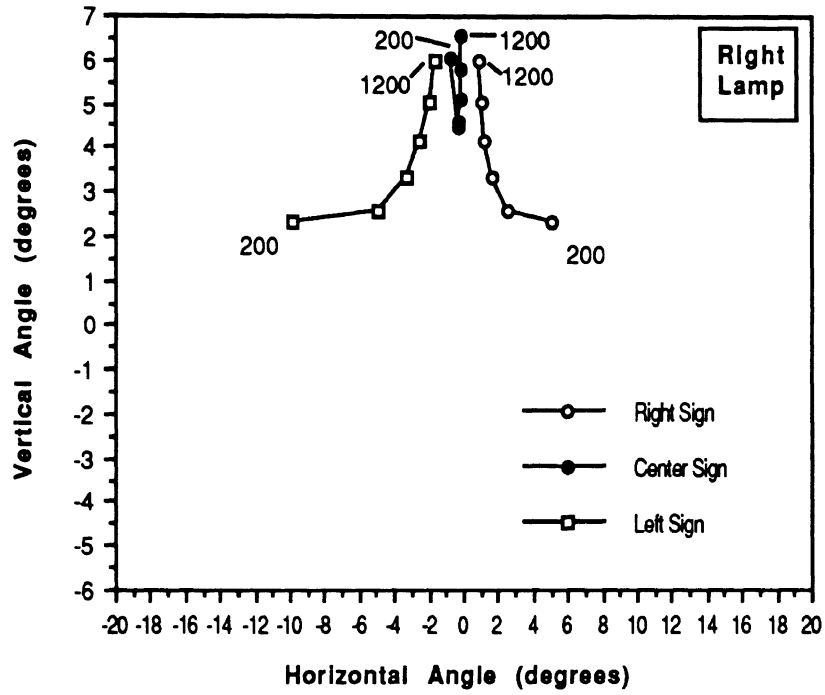


Figure 5. Relevant angles on a sag. (The numbers are distances in feet.)

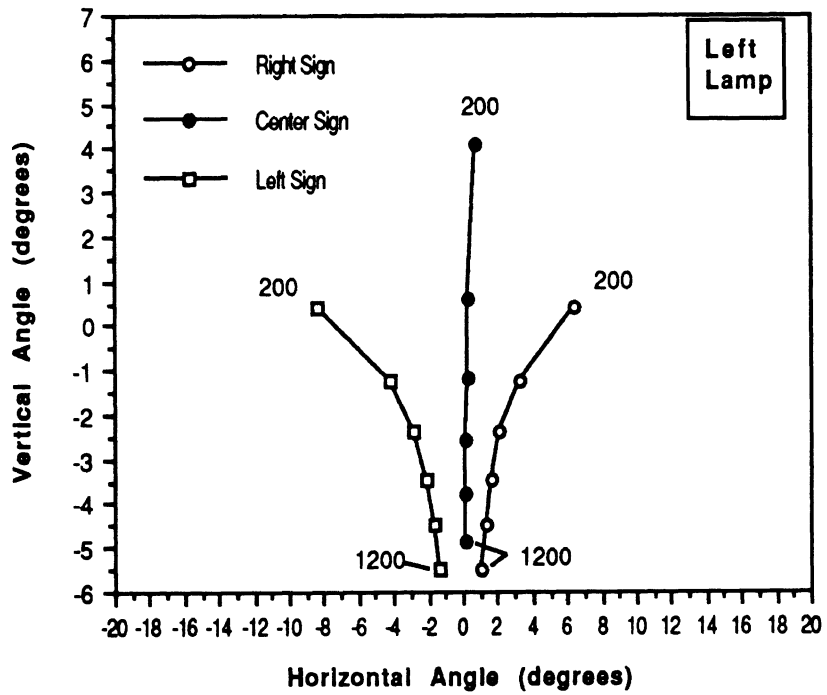
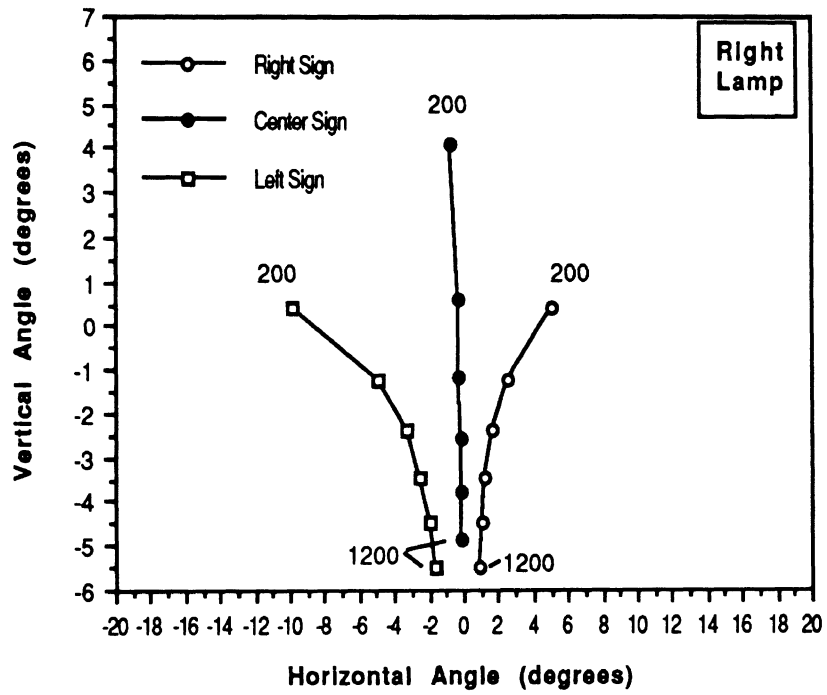


Figure 6. Relevant angles on a hill. (The numbers are distances in feet.)

The information in Figures 2 through 6 can be summarized as follows:

(1) Differences between the corresponding angles for the left and the right lamp are generally small. These differences are of consequence only for short distances (and, obviously, even then only for the horizontal angles).

(2) Large positive vertical angles are required only for (a) center signs and (b) all signs on sags. All of the remaining vertical angles are less than  $1.5^\circ$ .

(3) Large positive or negative horizontal angles ( $>10^\circ$ ) are required only for signs on curves at large distances.

(4) All of the relevant angles above horizontal from Figures 2 through 6 are collected together in Figure 7. As can be seen from Figure 7, the locations of the traffic signs are generally within a region defined by two hyperbola-like functions.

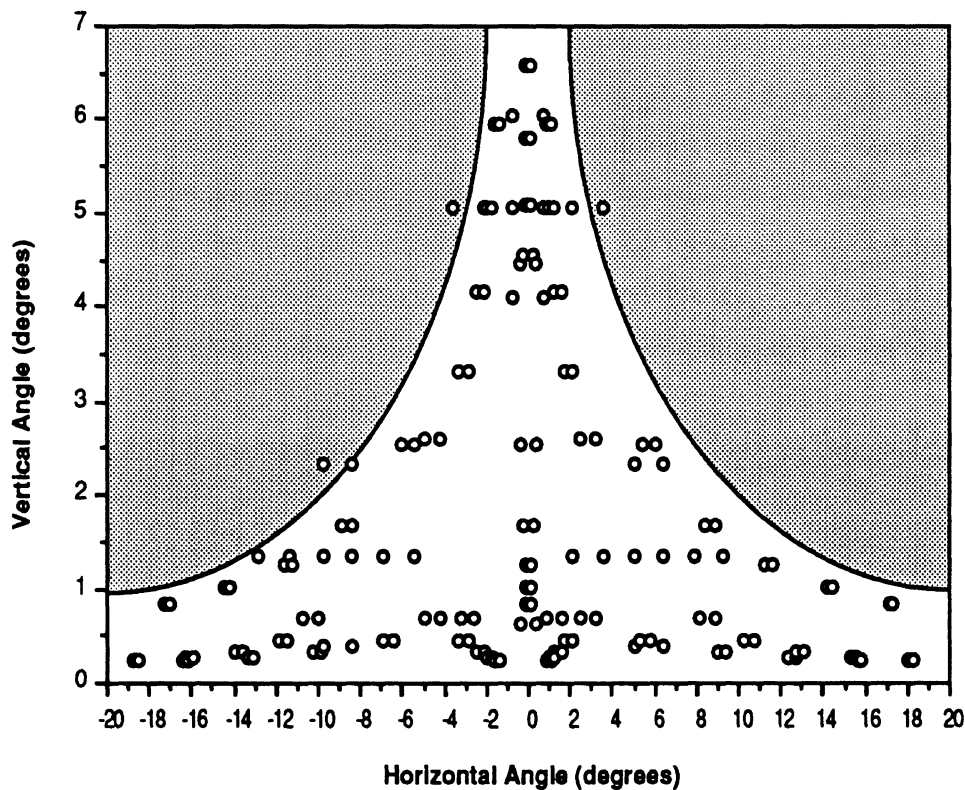


Figure 7. The relevant angles above horizontal. (The entries are all of the relevant angles above horizontal from Figures 2 through 6. For clarity, the vertical axis has been expanded in relation to the vertical axes in Figures 2 through 6.)

## MINIMUM SIGN LUMINANCE

Sivak and Olson (1985) reviewed applied research on sign legibility to obtain information on optimal and minimum desirable luminances of retroreflective traffic signs. The following seven experimental studies were reviewed: Allen and Straub (1955), Allen (1958), Allen, Smith, Janson, and Dyer (1967), Hills and Freeman (1970), Olson, Sivak, and Egan (1983), Richardson (1976), and Smyth (1947). The individual recommendations or findings were averaged into recommended values.

On the basis of the reviewed studies, Sivak and Olson (1985) concluded that "for signs that have light (white, yellow, and orange) backgrounds with black legends placed in low luminance surrounds, the optimal luminance of the background is approximately 75 cd/m<sup>2</sup>. For fully reflectorized signs, the optimal luminance of one component depends on the given luminance of the other component. The data suggest that for these signs the optimal legend to background contrast is about 12:1" (p. 56). Furthermore, "the reviewed legibility data suggest that the replacement [minimum] luminance value is 2.4 cd/m<sup>2</sup>. This applies to light legends with dark (green, blue, red, and brown) backgrounds of up to 0.4 cd/m<sup>2</sup>, and to light (white, yellow, and orange) backgrounds with black legends" (p. 56).

In conclusion, for the present purposes a conservative minimum luminance based on the review of Sivak and Olson (1985) is 75 cd/m<sup>2</sup>, while a liberal minimum is 2.4 cd/m<sup>2</sup>. The calculations to follow were based on 2.4 cd/m<sup>2</sup>.

## RELATIONSHIPS BETWEEN HEADLAMP INTENSITY AND SIGN LUMINANCE

The luminance of a retroreflective sign depends on (1) incident light and (2) retroreflective efficiency of the sign material. The amount of incident light for a given beam pattern, in turn, depends on the headlamp-to-sign distance and the position of the sign in the beam pattern. Retroreflective efficiency of a given sign material depends, in a complex manner, on the geometric relationships between the light source, sign, and the observer.

For the present purposes, the retroreflective efficiency can be characterized as the relationship between headlamp intensity and sign luminance. Woltman and Szczech (1989) developed the basic information necessary to derive this relationship. Their paper provides calculations of sign luminance for the three sign positions in Figure 1 and the five road profiles discussed above, using a standard (Westinghouse 6014) low-beam headlamp. The sign materials studied were the following three representative types of new white retroreflective materials: enclosed lens (with a coefficient of retroreflection of 120 cd/lux/m<sup>2</sup>), encapsulated lens (310 cd/lux/m<sup>2</sup>), and micro-prism (1100 cd/lux/m<sup>2</sup>).

While the paper of Woltman and Szczech (1989) did not contain the photometric information about this headlamp, that information was obtained from the authors. The intensity values for the headlamp beam in question were provided to us for angles from -20° to +20° horizontally and -4° to +6° vertically, in one-half degree steps. Interpolation was used to derive the intensity for the actual angles of interest.

The actual intensities (from the low beam in Woltman and Szczech's study) directed to the sign from the left and right headlamp were summed to derive the total actual intensity directed toward the sign. The required total intensity (to yield the required sign luminance of 2.4 cd/m<sup>2</sup>) was calculated as follows:

$$I_r = (L_r / L_a) \times I_a \quad \text{where}$$

$I_r$  = required total intensity (in cd) to yield sign luminance 2.4 cd/m<sup>2</sup>

$I_a$  = actual total intensity directed toward the sign in Woltman and Szczech (in cd)

$L_r$  = required sign luminance (2.4 cd/m<sup>2</sup>)

$L_a$  = actual sign luminance (in cd/m<sup>2</sup>) in Woltman and Szczech

The required total intensity was then divided equally between the left and right headlamp.

## DERIVATIONS OF REQUIRED INTENSITY

A sample of the results for the straight road profile is shown in Figure 8 for the two extreme distances (1200 and 200 feet), all three sign materials, and the two headlamps. The present study considered five road profiles, three sign positions, and six distances, yielding a potential set of 90 combinations of road profile, distance, and sign position. However, for all three sign positions at the three longest distances on the hill (nine combinations), the sign was obscured by the hill. Furthermore, for all three sign positions at the longest distance on the sag (three combinations) the angles exceeded the vertical range in which the headlamp intensity had been measured. Finally, the angles for five combinations of sign positions and distances on the hill were below horizontal. Therefore, information was obtained for 73 combinations of road profile, distance, and sign position, yielding a total of 438 data points for angles at or above horizontal ( $73 \times 3$  [sign materials]  $\times 2$  [headlamps]).



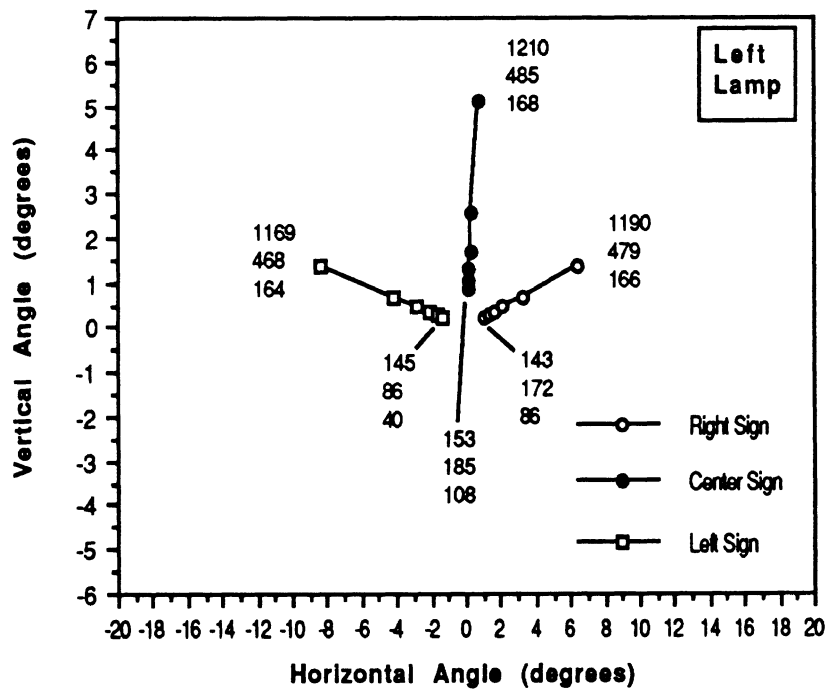
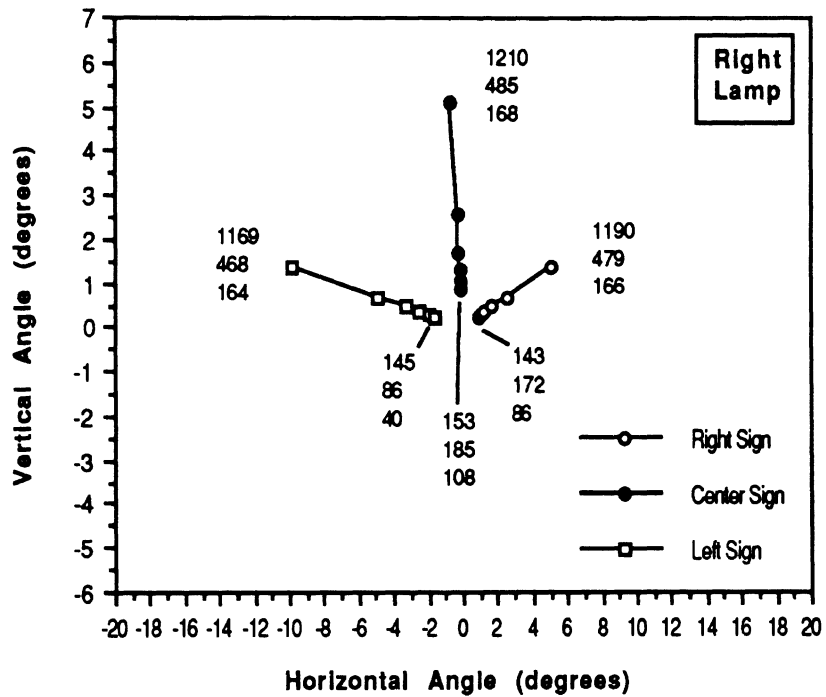


Figure 8. Required intensities (in cd) at the angles corresponding to the two extreme distances (1200 and 200 feet) on straight road. In each group of three, the numbers are (from top to bottom) for enclosed lens, encapsulated lens, and micro-prism.

In order to produce a single set of requirements that would insure adequate luminance in all the situations considered, the *required* intensity values for the five road profiles, three sign positions, six distances, and two headlamps formed the basic information for the derivation of the *summary* intensity values. This derivation involved the following steps:

(1) Each angular coordinate was rounded to the nearest one-half degree.

(2) Each point in this half-a-degree-grid space would then correspond to either zero, one, or more than one required intensities. The number of the required intensities per given point in space was equal to the number of combinations of the road profile, sign position, distance, and headlamp (left or right) that yielded the given point.

(3) For the points in space with no required intensity value, no summary intensity value was derived. If only one required value was available, the summary intensity was set to the required intensity. If more than one required intensity value was available, the summary intensity was set to equal the maximum of the corresponding required values.

The summary intensity values required to yield sign luminance of  $2.4 \text{ cd/m}^2$  are presented in Figures 9 through 17 for each of the three sign materials, with each of these figures including information for a given horizontal segment of the headlamp beam. These figures also contain comparisons with the actual intensities from the low-beam headlamp used by Woltman and Szczech (1989). The summary intensity values to yield sign luminance of  $75 \text{ cd/m}^2$  are not presented, but can be obtained by multiplying the top three values in each cell in Figures 9 through 17 by 31.2 (75 divided by 2.4).

There are two aspects of the information in Figures 9 through 17 that need clarification. First of all, in each cell the summary intensity is usually highest for enclosed lens, followed by encapsulated lens, and micro-prism. However, because of the unique retroreflective properties of these materials as a function of the relevant angles involved (Woltman and Szczech, 1989), there are several reversals. Second, certain adjacent entries (differing only by one-half degree) for the same sign material are substantially different. This is a consequence of the fact that any two adjacent cells might be based on different combinations of distances, road profiles, and sign positions.

6.0									
5.5									
5.0									
4.5									
4.0									
3.5									
3.0									
2.5									
2.0									
1.5									
1.0					1583 576 307 (261)	1583 576 307 (266)			
0.5							1126 420 * 170 * (452)	1126 420 * 170 * (458)	
0.0		1608 593 300 * (440)	1608 593 300 * (445)				1839 677 333 * (488)	1839 677 333 * (493)	
	-20.0	-19.5	-19.0	-18.5	-18.0	-17.5	-17.0	-16.5	-16.0

Figure 9. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between -20° and -16°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

6.0									
5.5									
5.0									
4.5									
4.0									
3.5									
3.0									
2.5									
2.0									
1.5					155 *			819	
					106 *			311	
					54 *			115 *	
					(231)			(291)	
1.0		1196	1196						
		442	442						
		207 *	207 *						
		(316)	(322)						
0.5			728	1238	1238		450	450	
			284 *	461 *	461 *		192 *	192 *	
			96 *	183 *	183 *		61 *	61 *	
			(442)	(518)	(524)		(415)	(425)	
0.0									
	-15.5	-15.0	-14.5	-14.0	-13.5	-13.0	-12.5	-12.0	-11.5

Figure 10. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between -15.5° and -11.5°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

6.0									
5.5									
5.0									
4.5									
4.0									
3.5									
3.0									
2.5		139 * 96 * 43 * (170)			139 * 96 * 43 * (187)				
2.0									
1.5		145 * 86 * 40 * (278)		466 191 * 57 * (224)	466 191 * 57 * (230)			144 * 82 * 41 * (310)	
1.0									
0.5	241 * 110 * 33 * (397)	762 294 * 102 * (533)			133 * 70 * 32 * (515)			447 * 183 * 59 * (515)	
0.0									
	-11.0	-10.5	-10.0	-9.5	-9.0	-8.5	-8.0	-7.5	-7.0
	<b>Horizontal Angle (degrees)</b>								

Figure 11. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between -11° and -7°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

6.0									
5.5									
5.0						149 171 80 * (106)			
4.5									
4.0								692 261 86 * (167)	
3.5						457 180 * 58 * (186)	457 180 * 58 *		
3.0									
2.5		274 125 * 38 * (201)	274 125 * 38 *	270 123 * 39 *		270 123 * 39 *			
2.0									
1.5			144 * 82 * 41 * (305)						
1.0									
0.5	447 * 183 * 59 * (519)		267 * 113 * 33 * (458)		267 * 113 * 33 *	423 * 159 * 58 * (578)	423 * 159 * 58 *	629 * 243 * 88 * (667)	
0.0									
	-6.5	-6.0	-5.5	-5.0	-4.5	-4.0	-3.5	-3.0	-2.5

Figure 12. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between -6.5° and -2.5°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

Vertical Angle (degrees)	6.0			167 226 130 (126)	1010 383 122 * (160)	167 226 130 (100)				
	5.5									
	5.0	976 376 122 * (155)	976 376 122 * (146)		153 * 185 108 * (161)	724 272 87 * (194)	153 185 108 * (120)	1169 461 143 (133)	1169 461 143 (140)	169 * 220 127 * (170)
	4.5				309 149 * 56 * (222)	492 189 * 62 * (222)	309 149 * 56 * (177)			
	4.0	692 261 86 * (178)			151 * 163 * 88 * (225)		151 * 163 * 88 * (202)		874 332 104 * (235)	
	3.5								479 180 * 58 * (317)	479 180 * 58 * (322)
	3.0									
	2.5				270 * 121 * 42 * (343)		270 * 121 * 42 * (347)			
	2.0									
	1.5					642 * 247 * 83 * (691)				202 * 244 * 123 * (810)
	1.0					898 353 * 119 * (863)				
	0.5	876 345 * 121 * (766)	876 345 * 121 * (811)		239 * 100 * 31 * (1038)	1210 485 * 168 * (1038)	239 * 100 * 31 * (1504)	892 * 352 * 118 * (3405)	892 * 352 * 118 * (3680)	426 * 162 * 52 * (2624)
	0.0		1169 468 * 164 * (903)					1190 * 479 * 166 * (3736)		
		-2.0	-1.5	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0

Figure 13. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between -2° and +2°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

6.0								
5.5								
5.0			169 220 127 * (159)					
4.5								
4.0								
3.5								
3.0								
2.5	268 * 117 * 44 * (477)	268 * 117 * 44 * (468)			92 * 111 * 56 * (372)	305 * 127 * 51 * (337)	305 * 127 * 51 * (331)	92 * 111 * 56 * (360)
2.0								
1.5			202 * 244 * 123 * (798)		143 * 172 * 86 * (605)			143 * 172 * 86 * (527)
1.0								
0.5	257 * 110 * 39 * (1736)	257 * 110 * 39 * (1601)			378 * 456 * 229 * (1801)	467 * 166 * 54 * (1517)	467 * 166 * 54 * (1302)	378 * 456 * 229 * (1200)
0.0								
	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
	Horizontal Angle (degrees)							

Figure 14. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between +2.5° and +6.5°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).



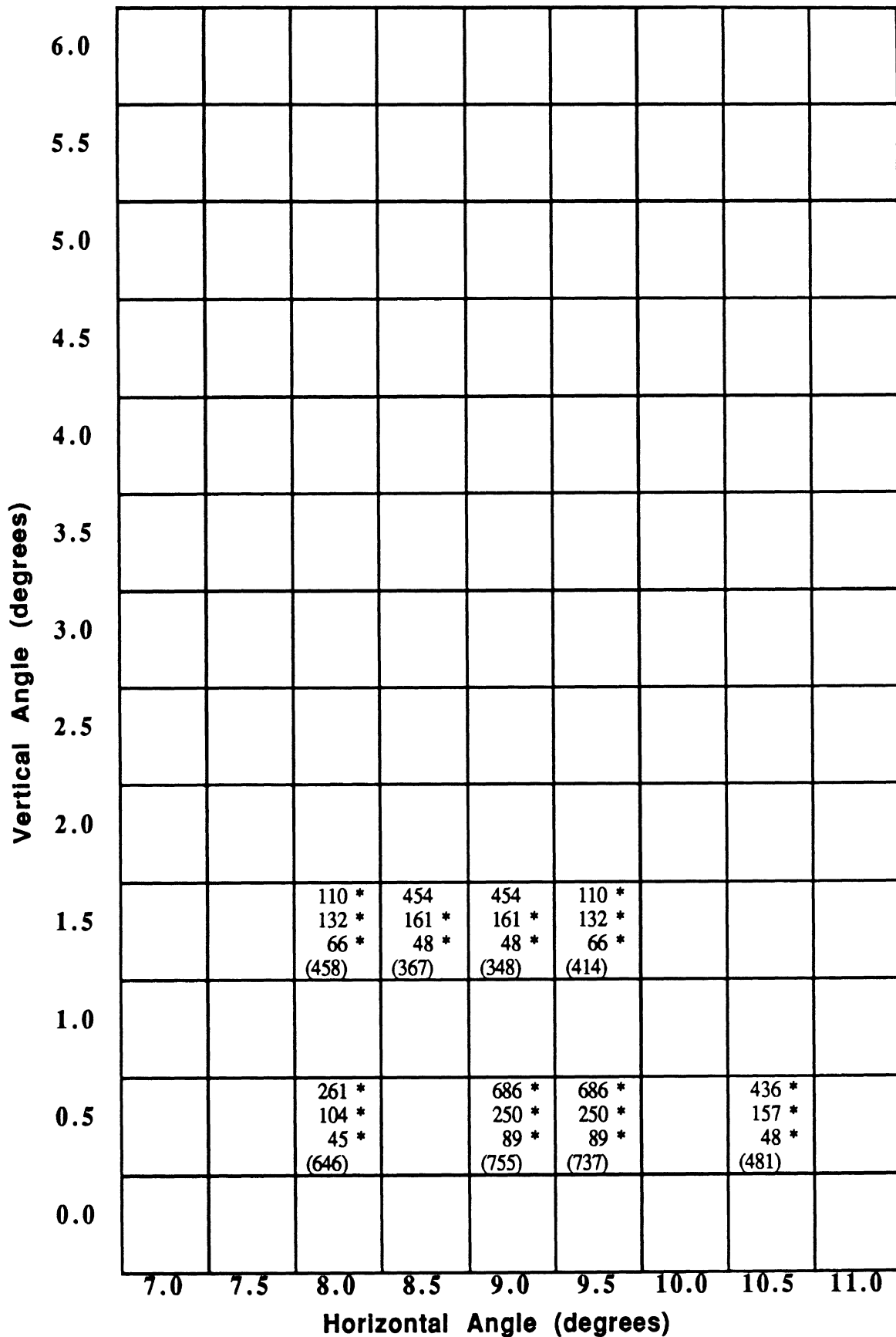


Figure 15. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between +7° and +11°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

6.0									
5.5									
5.0									
4.5									
4.0									
3.5									
3.0									
2.5									
2.0									
1.5	705 259 * 75 * (338)								
1.0					1013 381 148 * (362)	1013 381 148 * (356)			
0.5		997 373 * 165 * (562)	669 253 * 68 * (480)				1052 408 * 118 * (457)		
0.0							1407 532 272 * (485)		
	11.5	12.0	12.5	13.0	13.5	14.0	14.5	15.0	15.5

Figure 16. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between +11.5° and +15.5°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

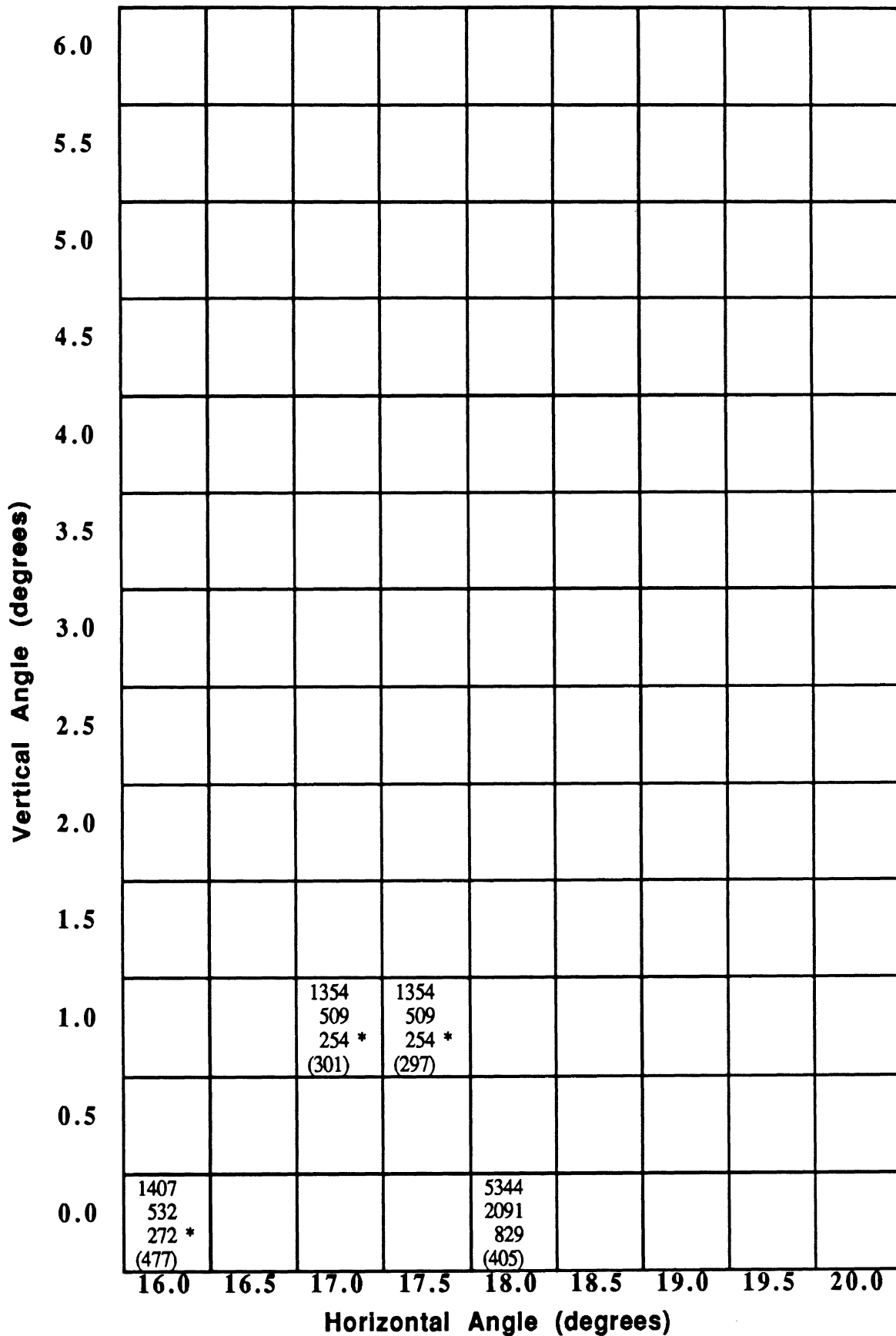


Figure 17. Summary intensity values (in cd) yielding luminance of 2.4 cd/m<sup>2</sup> for the horizontal segment between +16° and +20°. The first three entries in each cell are for (top to bottom) enclosed lens, encapsulated lens, and micro-prism. An asterisk indicates that the summary intensity value is less than the actual value (in parentheses) from the headlamp used by Woltman and Szczech (1989).

## UNDERLYING ASSUMPTIONS

### **Selected values of critical parameters**

The present study was designed to provide a method for determining minimum levels of low-beam illumination above horizontal, as well as initial guidance concerning actual values. In order to perform the needed calculations, assumptions had to be made concerning the values of several parameters which, in turn, critically influence the headlamp beam recommendations. The selected road profiles, sign positions, and headlamp-to-sign distances all affect the relevant angles. The selected sign-luminance levels and headlamp-to-sign distances affect the desired headlamp intensity. Each of these parameters is discussed below.

**Road profiles.** Five different road profiles for a two-lane roadway were considered: straight approach, right and left curves with 2,000-ft radii, and a sag and a hill with 6,000-ft radii. These particular geometries were selected because they were included in the study by Woltman and Szczech (1989) that contained the critical sign luminance information. (Woltman and Szczech did not deal with curves of significantly smaller radii because of the limitations of the headlamp beam matrix used for the calculations.)

The selected road geometries affect the angular locations of signs. For example, decreasing the radius of a curve would increase the horizontal angles, but would not affect the vertical angles. On the other hand, decreasing the radius of a sag would increase the vertical angles, but would not affect the horizontal angles.

**Sign positions.** Three sign positions were considered: right and left shoulder, and center--all with a specific lateral offset and mounting height (see Figure 1). These are the same three positions considered by Woltman and Szczech. On two-lane highways, the right-shoulder position is commonly used, for example, for regulatory signs, the center position for route-guidance signs mounted on overpasses, and the left-shoulder position for No Passing Zone signs. Again, selecting other positions would have resulted in a different set of angles. Specifically, increasing the mounting height would have increased the vertical angles, while widening the lateral separation between the vehicle and the sign would have increased the horizontal angles.

**Headlamp-to-sign distance.** Six distances were included in the present calculations, ranging from 1200 to 200 feet. Again, these are the distances for which Woltman and Szczech provided luminance information.

One way of determining the distance at which sign luminance is important is to use the approach of Perchonok and Pollack (1981) for estimating minimum

detection distances. Their estimation was based on an explicit assumption of serial processing stages that include detection, recognition, decision, response, and maneuver. Perchonok and Pollack provided guidelines (in terms of time and distance given certain speed) for each individual stage. Using this information, a total minimum distance can be computed for a given sign that is being approached at a given speed. Since not all signs require the involvement of all stages, different minimum distances are obtained when considering different signs approached at the same speed. For example, a STOP sign requires the involvement of all stages, including response and maneuver (applying the brakes and coming to a full stop). On the other hand, a STOP AHEAD sign does not require any explicit response and maneuver before reaching the sign.

Let us consider an example--a sign that requires the involvement of all stages (such as a STOP sign). The minimum detection distances (using the approach and values provided by Perchonok and Pollack) would range from 1157 feet at 60 mph to 290 feet at 30 mph. Furthermore, after the sign becomes visible, it needs to remain visible for a finite period of time--at least during the detection and recognition stages. According to Perchonok and Pollack, the corresponding values for the combination of detection and recognition are 365 feet at 60 mph and 103 feet at 30 mph. Consequently, the 1157 and 290 feet should form the upper bounds, with the lower bounds being 792 (1157 minus 365) and 187 (290 minus 103).

The numbers that were derived in the above example range from 1157 to 187. These numbers should be taken as an illustration of the wide range of distances needed, depending on the type of sign, speed, and environment. Consequently, the present calculations were performed for the entire range that was used by Woltman and Szczech (1200 to 200 feet).

**Sign color.** The sign color studied in this report was white. However, for any given type of sign material, white signs are the most efficient retroreflectors. Woltman and Szczech (1989) provide the following information concerning the luminance of other colors (with white being 100%): yellow, 61-76%; orange, 33-42%; red, 17-30%; green, 13-19%; and blue, 7-10%. Consequently, the present calculations apply only to white sign materials. Any extension to other colors would require correction for these color effects.

**Sign luminance.** The calculations in this report were based on the required sign luminance of 2.4 cd/m<sup>2</sup>. As indicated above, 2.4 cd/m<sup>2</sup> was considered by Sivak and Olson (1985) as a minimum sign luminance, with an optimum of 75 cd/m<sup>2</sup>. Furthermore, as pointed out by Sivak and Olson, considerations of detrimental factors, such as dirt on signs and on headlamps

would argue for even higher design luminance. Consequently, the present calculations should be viewed as providing only bare minima for sign legibility. On the other hand, the need to provide illumination for retroreflective traffic signs is frequently in conflict with the desire to protect oncoming drivers from excessive glare. Consequently, glare considerations would eventually have to be included in the derivation of intensity recommendations.

The current calculations of required intensity, which were made for sign luminance of 2.4 cd/m<sup>2</sup>, can easily be extended to any other level of luminance. To obtain the required intensity assuming sign luminance of L cd/m<sup>2</sup>, the obtained intensity values for 2.4 cd/m<sup>2</sup> need to be multiplied by the ratio of L to 2.4.

**Left vs. right headlamp**

The intensity contributions of the left and right lamp to a given point in space are generally not the same, because a given point in space corresponds to different (horizontal) angles in relation to the axes of the two lamps. The differential contribution of the two lamps was retained in the calculations of the *actual* total intensity directed to the sign in the Woltman and Szczech calculations. However, to arrive at the *required* component intensity from the left and right lamp, the total required intensity was divided by two. This implicitly assumes that the angular differences (and thus the differences in intensity contributions) for the two lamps are small. This assumption was confirmed by the analysis of the actual intensity ratios from the two headlamps for the tested points in space (see Table 1).

Table 1.

Frequency distribution of the intensity ratios from the two headlamps for the tested points in space.

<b>Intensity Ratio (less intense / more intense)</b>	<b>Frequency</b>
.901 - 1.00	59
.801 - .899	8
.701 - .799	4
.601 - .699	2

## IMPLICATIONS FOR STANDARDS

One of the goals of this research was to develop initial guidance concerning relevant angles and corresponding minimum intensity levels. The relevant angles above horizontal, given the geometries studied, are summarized in Figure 7. Conversely, the corresponding headlamp intensity values that would yield a given sign luminance value are presented in Figures 9 through 17 for three types of sign material. Is the information in Figures 7 and 9 through 17 sufficient for generating a set of recommended modifications to the existing low-beam standard? The answer is "no." The reasons for this will be evident in the following two illustrative examples of approaches to modification of the current standards. The first example deals with addition of minima to the current test regions above horizontal; the second example with addition of new test regions for minima only.

### Example 1: Addition of minima to current test regions

The current low-beam standard includes five regions above horizontal. In all five instances, only maxima are specified. Consequently, the least drastic modifications to the existing standard would involve an addition of minima for these five regions. Based on the information in Figures 9 through 17 for sign luminance of 2.4 cd/m<sup>2</sup>, such *potential* minima are indicated in Table 2 for four regions that contained the evaluated signs. These minima were obtained from Figures 9 through 17 by taking the approximate maximum value in the corresponding regions. (In Table 2 and in the text to follow, U stands for a positive vertical angle, R for a positive horizontal angle, and L for a negative horizontal angle.)

Table 2.

Potential minimum intensity values for existing test regions.  
(U stands for a positive vertical angle, R a positive horizontal angle,  
and L a negative horizontal angle.)

Test Region (degrees)	Current Maximum (cd)	Potential Minimum (cd)		
		Enclosed Lens	Encapsulated Lens	Micro- prism
10U to 90U	125	--	--	--
1U, 1.5L to L	700	1600	600	300
0.5U, 1.5L to L	1000	1250	500	200
1.5U, 1R to R	1400	700	250	125
0.5U, 1R to 3R	2700	900	350	125

Table 2 illustrates four of the issues that need to be resolved before minima can be proposed for a standard

Issue 1: *Should the minima be tied to the existing test regions for maxima?* Is there an advantage in minimizing the total number of test regions (points)? Or is there an advantage, from the manufacturing point of view, in separating regions requiring maxima and minima?

Issue 2: *What sign material should the standard be based on?* The present computations were made for each of three types of sign materials. The required intensity depends on the assumed type, and currently all three are in use.

Issue 3: *How do we reconcile sign needs with glare-protection needs?* Two of the potential minima in Table 1 are *greater* than the existing maxima.

Issue 4: *What are the reasonable differences or ratios between minima and maxima for the same test regions?* For example, the potential minimum of 600 cd for encapsulated lens at  $1^\circ$  U,  $1.5^\circ$  L to L may be too close to the corresponding maximum of 700 cd to allow a realistic design window. But how about the minimum of 300 cd for micro-prism for the same region?

#### **Example 2: Addition of new test regions**

The existing test regions above horizontal cover only a small fraction of the angles where traffic signs might be present. As can be seen from Figure 7, the locations above horizontal of traffic signs will be within a region defined by two hyperbola-like functions. The actual shape of the relevant region depends on the viewing distance, sign position, and road profile (see the discussion below). With that critical proviso, based on the conditions considered in the present study, additional test points specifying minimum intensity would be most desirable in the following two areas: a triangular region defined by  $2.5^\circ$  U,  $8^\circ$  R;  $2.5^\circ$  U,  $8^\circ$  L; and  $6.5^\circ$  U, V; and  $0.5^\circ$  U,  $3^\circ$  R to R. A graphical representation of both the existing test regions (with the exception of  $10^\circ$  U to  $90^\circ$  U) and the additional regions in need of coverage are shown in Figure 18.



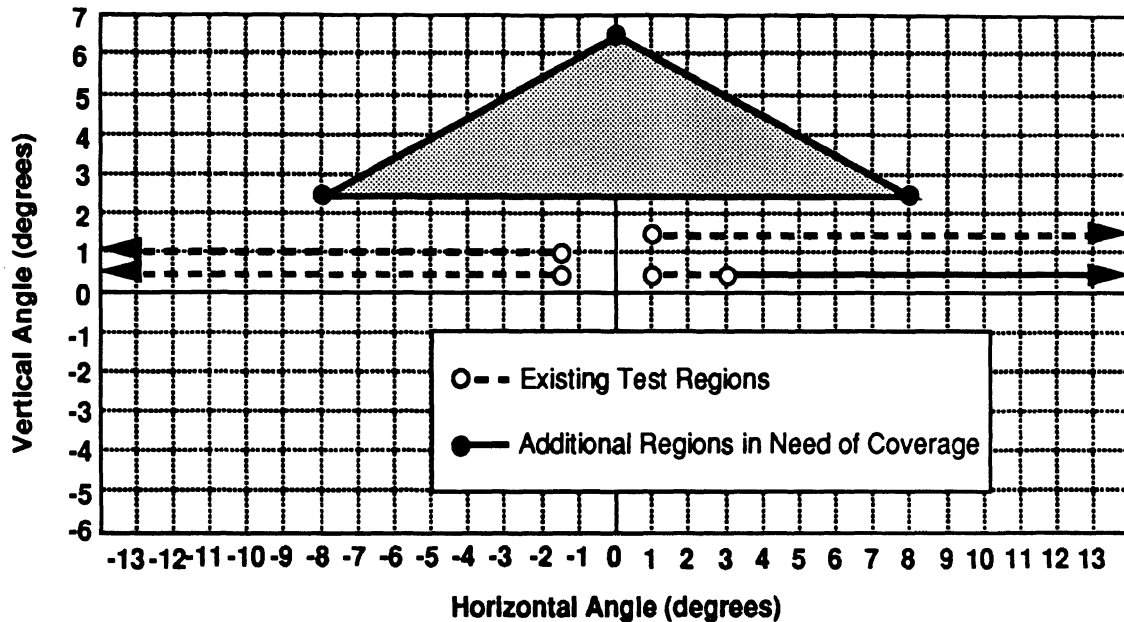


Figure 18. Existing test regions above horizontal and additional areas in need of coverage. (Existing test regions below horizontal are not shown.)

This example illustrates the following unresolved issues:

Issue 5: *Is there a need for the new test regions to have maxima (in addition to minima) for glare protection?*

Issue 6: *From the compliance point of view, are two-dimensional test regions, rather than test points or lines, feasible? Can a triangular region, such as the one in Figure 18, be part of an actual standard?*

Issue 7: *How near need the adjacent regions be to assure sufficient overall coverage? For example, if there is a test region at 1° U, L to R, would this assure a certain intensity level for points at 2° U or only at 1.5° U?*

Issue 8: *How near need the adjacent test points be within a given region to assure sufficient within-region coverage? For example, is it sufficient if they are spaced two degrees apart? Or do they need to be spaced one-half degree apart? (Issues 7 and 8 are interrelated; the answers to them depend on manufacturing tolerances.)*

## CONCLUDING COMMENTS

This study had two goals. First, to develop a method for determining minimum levels of low-beam illumination above horizontal for legibility of retroreflective traffic signs. Second, to provide initial guidance concerning actual critical angles and corresponding intensity values.

The developed method involves determining (1) relevant angles above horizontal, (2) desirable sign luminance, and (3) relationship between headlamp intensity and sign luminance for the relevant angles and different types of sign materials. Using this method, relevant angles and corresponding required intensity to achieve a given sign luminance were derived.

The present calculations are tentative for several reasons. First, this study considered only a limited number of road profiles, sign positions, and headlamp-to-sign distances. As discussed above, the actual values of these parameters are critical in the derivation of the relevant angles and required intensity. Second, each combination of the tested parameter values was weighted equally. Third, legibility was the only sign characteristic considered; conspicuity was not dealt with. Fourth, the present computations were made for three types of sign materials (enclosed lens, encapsulated lens, and micro-prism). The required intensity depends on the assumed type of sign material, and currently all three materials are in use. Fifth, the calculations were based on new white sign materials. However, relative to white other colors would be less efficient retroreflectors. Also, all materials lose retroreflective efficiency with age.

Following the derivation of relevant angles and corresponding required intensities, two approaches for amending the current low-beam standard were discussed: adding minima to test regions that currently deal only with maxima, and adding new test regions for minima only. Implementation of either (or both) of these approaches requires resolution of several important issues, including reconciliation of sign needs with glare-reduction needs, and manufacturing tolerances.

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