Evaluation of Headlamp Systems for Nighttime Safety: Their Relationship to Retroreflective Traffic Sign Performance

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Decisions regarding low-beam headlamp modeling are generally made following evaluation of pedestrian target visibility and glare to oncoming motorists. Retroreflective traffic control signs are parts of the model that have long been ignored, yet they are essential adjuncts to safety. The widespread use of retroreflective materials for information, regulation, and warning signs and their inclusion in many official standards suggested that the comparison of U.S. and Economic Commission for Europe (ECE) lower-beam headlamps should be made to reveal the consequences of further light reduction above the horizontal axis. Comparison of photometrics above the horizontal axis in the direction of commonly placed traffic signs for a variety of distances was used to determine the luminances for three types of material. The study permits comparisons among existing headlamp types and illustrates the significant deterioration in sign luminances that accompanies the use of ECE lower beam headlamps, or the alteration of U.S. lower beam photometrics to more closely correspond to those of ECE headlamps. The study permits some consideration of retroreflective material choice, depending on headlamp type, sign position, and sign luminance requirements.

Headlamps provide the primary source of illumination for the visual guidance of the motorist at night; therefore, the interrelationship of headlamps with such essential safety devices as retroreflective traffic control signs must be considered in system designs. In decisions regarding headlamp modeling, significant photometric alterations may be proposed after evaluation only of pedestrian target visibility and glare to oncoming motorists, whereas the effects of such alteration on the performance of retroreflective traffic control devices are too often ignored.

The use of retroreflective materials to enhance nighttime visibility of traffic control signs and other devices is sufficiently general to warrant the inclusion in various official standards of the requirement that signs that must be seen by the motorist at night must be either retroreflecting or illuminated. Retroreflectorization alone is quite sufficient for sign visibility under reasonably optimum conditions. These conditions include satisfactorily aligned and operating headlamps, minimal background illumination, and the use of retroreflective materials identified in such specifications as U.S. DOT FHWA FP–79, CIE Publication 39–2, ISO 3864, DIN 67520, BS 873, and others. But sign perception is also dependent on other external factors such as the complexity and luminance of the background surrounding the sign and the position of the sign relative to the general aim of the headlamps. Light output and distribution are therefore critical to sign performance; this is especially evident when light distribution varies widely from quadrant to quadrant, as is the case for U.S. and Economic Commission for Europe (ECE) standard lower beam headlamps. Alteration of headlamp output and beam pattern can seriously upset the compromise between acceptable glare levels to oncoming motorists and adequate performance of signs (such as those mounted overhead or on the left) that are in the lower illuminance areas of the pattern.

Previous studies by the authors have identified the luminance of conventional U.S. guide sign legends and backgrounds as well as the luminance enhancement from stream traffic and from rainfall. These assessments have used a mix of U.S. automobiles operating on low beams, which are used for most night driving and are the baseline lighting system for most retroreflective performance investigations.

The luminance requirements for sign legibility have been the subject of many investigations. A recent one is the review of 15 studies by Forbes *(1)*, titled *Acuity, Luminance and Contrast for Highway Sign Legibility.* This paper was followed by Sivak and Olson's *(2) Optimal and Replacement Luminances of Traffic Signs: A Review of Applied Legibility Research.* The latter work provides estimates of the coefficient of retroreflection required with U.S. and ECE low-beam headlamp systems to provide sign luminances to serve varying percentages of drivers at the design legibility distance. Sivak and Olson's *(2)* tables are included here (Tables 1 and 2), and emphasize the approximate two-to-one disparity between U.S. and ECE headlamp systems.

In Tables 1 and 2, the optimal values apply to white, yellow, and orange backgrounds of signs with black legends. (For fully reflectorized signs, the optimal legend-to-background contrast is 12:1.) The replacement values apply to white, yellow, and orange backgrounds of signs with black legends, and to legends of fully reflectorized signs with backgrounds up to 0.4 cd/m^2. The listed optimal and replacement values apply to generally ideal (i.e., dark) conditions.

This study provides a means of comparing the performance of U.S. and ECE low beams on current retroreflective materials with Sivak's *(2)* 75th-percentile value of 7.2 cd/m^2 as the criterion.

DESIGN OF EXPERIMENT

The performance of retroreflective signs was carefully compared with that of U.S. and ECE (European H4) headlamps,

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TABLE 1 COEFFICIENTS OF RETROREFLECTION FOR OPTIMAL AND REPLACEMENT SIGN LUMINANCES FOR U.S. LOW-BEAM HEADLAMP SYSTEMS

Level	Sign Luminance (cd/m2)	Coefficients of Retroreflection, cd/lx/m2			
		Left Shoulder	Overhead	Right Shoulder	Shoulder Guide
Optimal	75	2,806	3,547	736	856
Replacement					
85th percentile	16.8	630	798	168	189
75th percentile	7.2	270	342	72	81
50th percentile	2.4	90	114	24	27

TABLE 2 COEFFICIENTS OF RETROREFLECTION FOR OPTIMAL AND REPLACEMENT SIGN LUMINANCES FOR ECE LOW-BEAM HEADLAMP SYSTEMS

Level	Sign Luminance (cd/m2)	Coefficients of Retroreflection, cd/lx/m2			
		Left Shoulder	Overhead	Right Shoulder	Shoulder Guide
Optimal	75	4,644	7,252	2,436	1,113
Replacement					
85th percentile	16.8	1,043	1,624	546	252
75th percentile	7.2	447	696	234	108
50th percentile	2.4	149	232	78	36

particularly in sign placement areas where the ECE low-beam photometrics were significantly lower than those of U.S. low beam headlamps. Thus, in addition to the usual measurements on the right shoulder, the overhead and left-shoulder locations were included (Figure 1). Sign luminance profiles over a variety of distances were fairly well established for circa 1975 U.S. headlamps for the center, overhead, and right-shoulder locations. Correlative and new information was needed at similar distances for the left side, for overheads over the left lane for U.S. low-beam headlamps, and for all locations with ECE low-beam headlamps.

TABLE 3 WHITE AND GREEN RETROREFLECTIVE SIGNING MATERIALS BY TYPE AND COEFFICIENT OF RETROREFLECTION

Material	Reflective Sheeting Type	Color	Coefficient of Retroreflection (cd/lx/m2) at 0.2° Observation and −4° Entrance Angles
A	Enclosed lens	White	80
		Green	9
B	Encapsulated lens	White	250
		Green	45
C	Cube corner	White	1,000
		Green	150

The authors' previous efforts in determining retroreflective sign luminance used carefully photometered signs, and in many cases carefully characterized retroreflective samples, as measured from the driver's eye position in a standard-sized passenger car. The measurements were taken of samples in typical sign positions from distances corresponding to those of the longest of decision sight distance models to relatively short sign-reading distances. Headlamps used either were typical of new-vehicle equipment or were supplied from equipment manufacturers following photometric testing. Aim was adjusted to correspond to SAE recommendations usually using the aiming screen method of SAE J 599 *(3)*. Level tangent sections of roadway were used. A full description of the methods is contained in three papers by Youngblood and Woltman *(4–6)*.

Despite careful attention to the details, luminance measurements for a specific distance and material type may differ by 100 percent or more. The disparities are largely due to differences in headlamp output and headlamp aim. One has only to view the rapidly changing contours of an isocandela diagram to appreciate the critical nature of headlamp aim. Additionally, test points for headlamps permit quite wide latitude in output.

For these reasons, it is desirable to use a careful comparison of typical headlamps representative of the lower-beam output

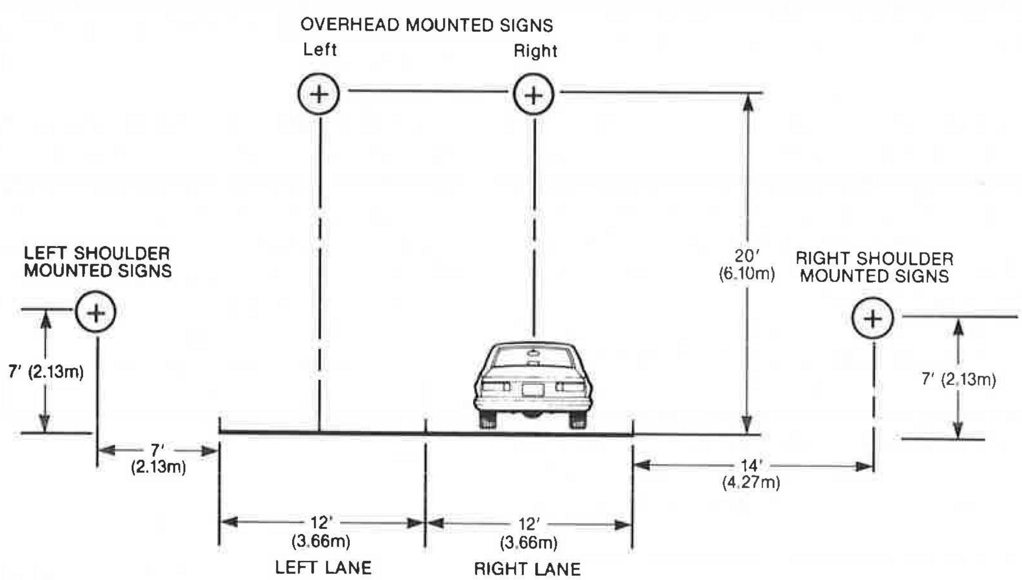

FIGURE 1 Sign positions.

at half-degree increments across that portion of the field appropriate to the sign position and distance. If all other factors (distances, retroreflective materials, sign offsets, etc.) remain constant, this method is a more appropriate means of comparing U.S. and ECE lower beams as they affect sign luminance.

The procedure used in this study is the modeling of sign luminance using a procedure first detailed by Elstad et al. *(7)*. The model uses the carefully detailed headlamp outputs in a matrix encompassing all directions of interest for sign positions at any distance. The values derived for sign luminance involve complex geometric and retroreflective response relationships; nevertheless, correspondence with the previously cited field studies is within the extreme measurements and permits comparisons of resultant sign luminances by headlamp type with greater reliability and precision.

SIGNING MATERIALS

The signing materials studied are representative of new white and green retroreflective materials used for traffic control signs; copy and background for overhead and shoulder-mounted guide signs. Luminances of other colors and their ratios to white generally fall within the following limits: yellow = 0.67 to 0.74, orange = 0.33 to 0.42, red = 0.17 to 0.23, blue = 0.07 to 0.09.

The materials studied are described in Table 3. The coefficients of retroreflection, which are essential for sign luminance computations, were determined according to ASTM method E810 *(8)*.

RESULTS

The results are presented in Table 4 for white retroreflective sheetings and in Table 5 for green retroreflective sheetings.

The two headlamp systems are compared for white materials for the left side, left overhead, right overhead, and right side. The luminances for the two headlamp systems are compared with Sivak's *(2)* 75th-percentile value of 7.2 cd/m2 (Table 1). This criterion does not include a margin of safety to permit further diminution due to such factors as dirt, natural weathering, or substitution of colors having lower reflectances.

Left Shoulder

At 1,200 ft (366 m), there is a difference of a factor of 2.3 for the brighter U.S. low-beam headlamps compared with the ECE low-beam headlamps. At 400 ft (124 m), the distance of maximum luminance, the difference is less, a factor of 1.4. Material B produces 75th-percentile luminances of 7.2 cd/m2 for U.S. headlamps only. Material C would be required for ECE lamps for similar performance.

Left Side Overhead

At 1,200 ft (366 m), the difference is a factor of 2.5 for the brighter U.S. low-beam headlamps compared with the ECE low-beam headlamps. At 400 ft (124 m) the difference is a factor of 1.4.

TABLE 4 RETROREFLECTIVE SIGN LUMINANCE FOR U.S. AND ECE LOW-BEAM HEADLAMPS—WHITE COLOR LUMINANCE (cd/m2)

	Distance, ft (m)					
Material	1,200 (366)	1,000 (305)	800 (244)	600 (183)	400 (122)	200 (61)
Left-Side Shoulder-Mounted						
A						
U.S.	1.2	1.5	1.8	2.2	3.0	3.2
ECE	0.52	0.69	0.95	1.4	2.1	2.6
B						
U.S.	4.3	5.2	6.5	8.0	9.4	8.4
ECE	1.9	2.5	3.5	4.9	6.7	6.7
C						
U.S.	10.8	11.8	13.2	15.1	12.7	1.6
ECE	4.7	5.6	7.0	9.2	9.0	1.3
Left-Side Overhead						
A						
U.S.	1.04	1.18	1.3	1.4	1.6	1.3
ECE	0.41	0.51	0.63	0.82	1.15	1.07
B						
U.S.	3.7	4.3	4.9	5.2	5.2	1.8
ECE	1.5	1.9	2.4	3.0	3.7	1.5
C						
U.S.	9.2	9.5	9.4	8.4	4.8	0.95
ECE	3.6	4.1	4.5	4.8	3.4	0.77
Right-Side Overhead						
A						
U.S.	1.3	1.5	1.6	1.7	2.0	1.5
ECE	0.14	0.51	0.64	0.82	1.1	1.1
B						
U.S.	4.7	5.4	6.1	6.3	6.6	2.0
ECE	1.5	1.9	2.4	3.0	3.4	1.4
C						
U.S.	11.7	11.9	11.6	9.6	5.3	0.95
ECE	3.6	4.1	4.4	4.5	2.8	0.73
Right-Side Shoulder-Mounted						
A						
U.S.	4.9	6.4	8.1	9.8	10.5	6.5
ECE	1.2	1.7	2.7	4.6	6.2	3.7
B						
U.S.	17.3	23.0	30.1	36.9	35.3	8.2
ECE	4.1	6.1	9.9	17.2	21.1	4.7
C						
U.S.	43.9	51.9	58.1	56.6	28.9	3.5
ECE	10.6	14.3	20.3	28.5	17.6	2.0

Only Material C produces at least 7.2 cd/m2 luminance and only with U.S. lamps.

Right Side Overhead

At 1,200 ft (366 m) the difference is a factor of 3.2 between the brighter U.S. headlamps and the ECE headlamps. At 400 ft (124 m), the difference is a factor of 2.1. Only Material C produces 7.2 cd/m2 luminance and only with U.S. headlamps.

Right Shoulder

At 1,200 ft (366 m), the difference is a factor of 4.1 for the brighter U.S. headlamps compared with the ECE headlamps.

TABLE 5 RETROREFLECTIVE SIGN LUMINANCE FOR U.S. AND ECE LOW-BEAM HEADLAMPS—GREEN COLOR LUMINANCE (cd/m2)

Material	Distance, ft (m) 1,200 (366)	1,000 (305)	800 (244)	600 (183)	400 (122)	200 (61)
Left-Side Shoulder-Mounted						
A						
U.S.	0.14	0.16	0.20	0.25	0.34	0.36
ECE	0.06	0.08	0.11	0.15	0.24	0.29
B						
U.S.	0.65	0.80	0.99	1.22	1.43	1.28
ECE	0.29	0.38	0.53	0.75	1.02	1.03
C						
U.S.	1.6	1.8	2.0	2.3	1.9	0.24
ECE	0.70	0.84	1.1	1.4	1.4	0.19
Left-Side Overhead						
A						
U.S.	0.12	0.13	0.15	0.16	0.18	0.14
ECE	0.05	0.06	0.07	0.09	0.13	0.12
B						
U.S.	0.57	0.65	0.74	0.79	0.80	0.28
ECE	0.22	0.28	0.36	0.46	0.56	0.32
C						
U.S.	1.4	1.4	1.4	1.3	0.72	0.14
ECE	0.54	0.61	0.67	0.71	0.50	0.11
Right-Side Overhead						
A						
U.S.	0.15	0.17	0.18	0.19	0.23	0.17
ECE	0.05	0.06	0.07	0.09	0.12	0.12
B						
U.S.	0.72	0.82	0.93	0.94	1.00	0.30
ECE	0.22	0.28	0.36	0.46	0.52	0.21
C						
U.S.	1.8	1.8	1.7	1.4	0.80	0.14
ECE	0.54	0.61	0.66	0.68	0.41	0.11
Right-Side Shoulder-Mounted						
A						
U.S.	0.55	0.72	0.91	1.1	1.2	0.73
ECE	0.13	0.19	0.30	0.52	0.69	0.41
B						
U.S.	2.6	3.5	4.6	5.6	5.4	1.3
ECE	0.63	0.93	1.5	2.6	3.2	0.71
C						
U.S.	6.6	7.8	8.7	8.5	4.3	0.52
ECE	1.6	2.1	3.1	4.3	2.6	0.30

At 400 ft (124 m), the difference is a factor of 1.7. With U.S. headlamps, Material A provides at least 7.2 cd/m2 luminance. With ECE headlamps, Material B or C is required to provide 7.2 cd/m2 luminance.

Table 5 presents sign luminances for various materials of green color used for backgrounds of information signs. Work by Youngblood and Woltman *(4)* suggests that a minimum value of 0.7 cd/m2 is required for color identification. This value is approximately one-tenth the legend luminance of 7.2 cd/m2 suggested by Sivak *(2)* for white. This value also produces a satisfactory contrast ratio between legend and sign background. Table 5 thus provides a means of selecting materials meeting either a 0.7-cd/m2 luminance level or a desired contrast ratio, depending on the headlamp used.

CONCLUSIONS

The significant differences revealed in sign luminance for the two headlamp systems have resulted in approximately one-half to one-quarter of the illumination above the horizontal axis for European low-beam headlamps compared to U.S. low-beam headlamps. The study permits comparisons between existing headlamp types and illustrates the significant deterioration in sign luminance that accompanies the use of European lower beams, and the consequences of the alteration of U.S. lower-beam photometrics to more closely correspond to ECE headlamps. The study permits some consideration of retroreflective material choice depending on headlamp type, sign position, and sign luminance requirements.

Headlamps provide the primary source of illumination for the visual guidance of the motorist at night and the luminance of essential traffic control signs. The lower beams represent compromises—the reduction of glare to oncoming motorists and of backscatter from fog have been gained at the expense of the performance of retroreflective traffic control signs. The system design must accommodate both.

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