EVALUATION OF THE SAE J1735 DRAFT PROPOSAL FOR A HARMONIZED LOW-BEAM HEADLIGHTING PATTERN

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16. Abstract

This study evaluated the SAE J1735 Draft Proposal for a low-beam headlighting pattern in relation to the current standards in the U.S., Europe, and Japan. The approach consisted of the following steps: (1) identifying a set of 15 important visual performance functions (including seeing and glare) for low-beam headlamps; (2) defining the relevant geometry relative to the visual performance functions; (3) setting criterion values of illumination for each of the visual performance functions based on the available empirical data; and (4) evaluating the standards relative to the criterion values by considering the worst-allowed-case approach. This involved using the *minima* specified by the standards for seeing functions, and the *maxima* for glare functions.

The results indicate that the SAE J1735 Draft Proposal tended to require better performance than the current U.S., European, and Japanese standards.

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INTRODUCTION

In a previous study (Sivak, Helmers, Owens, and Flannagan, 1992) we evaluated several recent proposals for the low-beam headlighting pattern, along with the then current U.S., European, and Japanese standards. A later version of one of these proposals—the SAE J1735 Draft Proposal (a follow-up to the SAE Proposal 7A)—is currently being considered by international lighting experts for adoption as a harmonized beam pattern for use throughout the world. Consequently, the present study was designed to evaluate the SAE J1735 Draft Proposal in comparison with the current U.S., European, and Japanese standards. [The U.S. and European standards underwent some modifications since our previous study. Furthermore, Sivak et al. (1992) evaluated the proposed standards against the Japanese Industrial Standard (JIS, 1984); the present study used the Japanese governmental standard (JASIC, 1993).]

A major difference between the SAE J1735 Draft Proposal and its precursor—Proposal 7A (SAE, 1991)—is that the SAE J1735 Draft Proposal contains the four test points that were recommended by GTB (Groupe de Travail "Bruxelles 1952") for adoption as common test points worldwide. (These four test points, in turn, are based on the four test points recommended by Sivak and Flannagan, 1993.)

APPROACH

We used the same approach as in our previous study that evaluated several proposed and existing standards (Sivak et al., 1992). The approach consists of the following steps:

(1) Identifying a set of 15 important visual performance functions (including seeing and glare) for low-beam headlamps.
(2) Defining the relevant geometry relative to the visual performance functions.
(3) Setting criterion values of illumination for each of the visual performance functions based on the available empirical data.
(4) Evaluating the standards relative to the criterion values by considering the worst-allowed-case approach. This involves using the *minima* specified by the standards for seeing functions, and the *maxima* for glare functions.

As we have argued previously (Sivak et al., 1992), an evaluation of the standards using computer models such as CHESS (Bhise, Farber, and McMahan, 1976; Bhise, Farber, Saunby, Troell, Walunas, and Bernstein, 1977) is not feasible. Such models require input of a detailed candela matrix to define the beam to be evaluated. On the other hand, standards contain only a limited number of test points, lines, or zones. The great majority of the beam is not explicitly controlled, and only *limit*s (minimum and/or maximum), which fall short of specifying actual beam characteristics, are given for the points or regions of concern. Consequently, they do not constrain the beam to any particular candela matrix.

The present approach focuses on what is allowed by standards (and not on the performance of lamps that were manufactured to meet different standards). We believe that the present approach is the correct way to evaluate standards, particularly with respect to their harmonization potential, because harmonization raises the possibility that standards will be applied to technologies that have not traditionally been used in certain jurisdictions.

Because this approach is identical to that in Sivak et al. (1992), several sections from that study are incorporated in the present report. As in that report, our purpose is not to render a final definitive judgment about the relative merits of the various standards, but rather to provide an objective, systematic first step toward such a judgment.

THE PROPOSED AND EXISTING STANDARDS

We evaluated the SAE J1735 draft proposal in relation to the current standards in the U.S., Europe, and Japan. These four standards are summarized in Tables 1 through 4.

Table 1. The current U.S. standard (FMVSS, 1993) for a 2-lamp system.

Test point	Minimum (cd)	Maximum (cd)
10U to 90U		125
4U, 8L	64	
4U, 8R	64	
2U, 4L	135	
1.5U, 1R to R		1,400
1.5U, 1R to 3R	200	
1U, 1.5L to L		700
0.5U, 1.5L to L		1,000
0.5U, 1R to 3R	500	2,700
H, 8L	64	
H, 4L	135	
0.5D, 1.5L to L		3,000
0.5D, 1.5R	10,000	20,000
1D, 6L	1,000	
1.5D, 9L	1,000	
1.5D, 2R	15,000	
1.5D, 9R	1,000	
2D, 15L	850	
2D, 15R	850	
4D, 4R		12,500

Table 2. The current European standard (ECE, 1992). The original specifications of the test-point locations were converted from cm on a vertical surface at 25 m to angles. Similarly, the original specifications of illuminances at 25 m were converted to luminous intensities.

Test Point or Region	Minimum (cd)	Maximum (cd)
4U, 8L	62	438
4U, V	62	438
4U, 8R	62	438
2U, 4L	125	438
2U, V	125	438
2U, 4R	125	438
H, 8L	65	438
H, 4L	125	438
0.6U, 3.4L (B50L)		250
0.6D, 3.4L (75L)		7,500
0.6D, 1.1R (75R)	7,500	
0.9D, 3.4L (50L)		9,375
0.9D, V (50V)	3,750	
0.9D, 1.7R (50R)	7,500	
1.7D, 9L (25L)	1,250	
1.7D, 9R (25R)	1,250	
Zone I (1.7D to D)		200% of the actual value at 0.9D, 1.7R
Zone III (above line H, 9L; H, V; 2.4U, 9R, or above line H, 9L; H, V; 0.6U, 0.6R; 0.6U, 9R)		438
Zone IV (corners: 0.9D, 5.1L; 0.9D, 5.1R; 1.7D, 5.1R; and 1.7D, 5.1L)	1,875	

Table 3. The current Japanese standard (JASIC, 1993), converted to right-hand traffic.

Test Point or Region	Minimum (cd)	Maximum (cd)
10U to 90U		125
1.5U, 1R to R		1,000
1U, 1L to L		700
0.5U, 1L to L		1,000
0.5U, 1R to 3R		2,700
0.5D, 1L to L		2,500
0.5D, 2R	6,000	20,000
1D, 6L	1,000	
1.5D, 9L	1,000	
1.5D, 2R	15,000	
1.5D, 9R	1,000	
2D, 15L	700	
2D, 15R	700	
4D, 4R		12,500

Table 4. The SAE J1735 Draft Proposal (SAE, 1994).

Test Point or Region	Minimum (cd)	Maximum (cd)
1.5U, V to 3R	200	1,000
0.5U, 1.5L	125	650
0.5U, 1R to 2R	500	2,400
0.5D, 4R	5,000	
0.6D, 1.3R	10,000	
0.9D, 3.5L	1,800	12,000
0.9D, V	4,500	
2D, 15L	1,000	
2D, 9L	1,250	
2D, 9R	1,250	
2D, 15R	1,000	
4D, 20L	300	
4D, 4R		50% of max in Zone I, but ≤ 12,500
4D, 20R	300	
Zone I (corners: 0.5D, 0.5R; 0.5D, 2.5R; 2D, 2.5R; 2D, 0.5R); tested at the maximum in the zone	15,000	
Zone II (corners: 1D, 5L; 1D, 5R; 2D, 5R; 2D, 5L, except Zone I); tested at the four corners	1,875	
Zone III (corners: 0.5U, 8L; 0.5U, 3L; 2U, V; 2U, 8R; 4U, 8R; and 4U, 8L); tested at the four extreme corners, and at the lower boundary line from 5L to 5R	80	650
Zone IV (4U to 10U, 15L to 15R); tested at 4U from 15L to 15R, and at V from 4U to 10U		525
Zone V (10U to 90U, 45L to 45R); tested at 45U from 45L to 45R, and at V from 10U to 90U		125 (438 within a 2° conical angle)

VISUAL PERFORMANCE FUNCTIONS OF LOW BEAMS

The visual performance functions that we considered important for low-beam headlamps in our previous evaluation of standards (Sivak et al., 1992) are listed below. They are grouped into functions dealing with illumination above horizontal, distant field, foreground, and overall considerations.

Above horizontal

- illumination of a traffic sign on the right shoulder
- illumination of an overhead traffic sign
- glare illumination towards oncoming traffic
- glare illumination towards traffic ahead via rearview mirrors
- illumination prone to scatter in adverse atmospheric conditions (fog, rain, and snow)

Distant field—between 1.75D and horizontal (more than 25 m in front of the vehicle)

- illumination directed towards targets on the right side of the road at intermediate distances
- illumination on hills
- illumination on sags

Foreground—below 1.75D (up to 25 m in front of the vehicle)

- illumination directed towards targets on the right side of the road at near distances
- homogeneity of the beam (aesthetic and comfort considerations)
- illumination prone to glare reflection from wet pavement

Overall

- lateral spread (lane keeping, and aesthetic and comfort considerations)
- relation between seeing illumination and glare illumination
- reliability of visual aiming
- effects of misaim

The following sections will (1) define the relevant geometry for the visual performance functions, (2) set criterion illuminance values for the visual performance functions based on available empirical data, and (3) evaluate the standards in relation to the performance criteria by considering the worst allowed case.

Several caveats are in order. First, to the extent that substantial variations exist in many relevant factors (such as road geometry, headlamp mounting height, and seated eye height), the proposed geometries cannot capture the full range of the properties of a given headlamp.

Second, the selected performance criteria of illumination are, obviously, subject to revision. Their place here is to provide some reasonable benchmarks for quantifying headlamp performance in terms of likely consequences for vehicle operators. Thus, these criteria may be improved through further research on human factors, and they may need revision to accommodate future changes in the driver-vehicle-highway environment.

Third, this research considered only automobiles. Other vehicles, such as trucks and buses were not considered. There are several visibility- and glare-related differences in the design of automobiles on one hand, and trucks and buses on the other hand (Sivak and Ensing, 1989). Of primary importance are differences in seated eye position of the driver and headlamp mounting height (Cobb, 1990), affecting the visibility of retroreflective traffic signs (Sivak, Flannagan, and Gellatly, 1991), visibility of other targets, and glare.

Fourth, the headlamps are treated as being both mounted in the same physical location—in the center of the vehicle. This approximation disregards the differential contribution of light from two mounted headlamps towards a given point in space (cf. Burgett, Matteson, Ulman, and Van Iderstine, 1989). Any errors introduced by this assumption decrease as the relevant distance increases.

Fifth, the test points to be evaluated were not always addressed by every standard. In such instances, we had to rely on the nearest controlled test point. In most cases, the information that we used came from a controlled test point within ±0.75° of the desired test point. This approach is justified given the current variability of aims for on-the-road vehicles, with the standard deviations of 0.8° for horizontal aims and 0.9° for vertical aims (Olson, 1985). Furthermore, where there was an option of two approximately equidistant controlled points, we used the one nearer to the desired point vertically, because, in general, gradients are steeper vertically than horizontally. (The specific controlled test point that we relied on is always identified in the comparisons that follow.)

Sixth, many real-world conditions that lead to decrements in visual performance were not included in the present analysis. These conditions include dirty or scratched headlamps (Cox, 1968), dirt on retroreflective targets (Anderson and Carlson, 1966), atmospheric attenuation, voltage drop, as well as changes in vision of older drivers (Sivak, Olson, and Pastalan, 1981).

Seventh, the actual illumination directed towards a given point in space is not prescribed by the examined standards, which present only minima or maxima, and therefore an actual beam pattern cannot be described. (In the few cases of simultaneous minima and maxima for a given test point, the ranges are still quite substantial.) Thus, our analysis necessarily evaluated the worst case allowed by a given standard. Consequently, we used the specified *minima* in our visibility evaluations, and the *maxima* in glare evaluations. (More specifically, the present analysis evaluated the worst case allowed by the standards, but under relatively optimal driver and environmental conditions—see the preceding point.)

Illumination of a traffic sign on the right shoulder (0.5U, 2.25R)

Geometry. The illumination directed towards a shoulder-mounted traffic sign was evaluated by assuming the following geometry on a two-lane roadway:

- Longitudinal separation between the sign and the headlamps: 150 m. This value was selected because it represents a reasonable sign-legibility distance (Sivak, Flannagan, and Gellatly, 1991).
- Lateral separation between the sign and the headlamps: 6.15 m. This is based on a lane width of 3.7 m, and a lateral separation of the sign from the edge of the roadway of 4.3 m (Woltman and Szczech, 1989).
- Vertical separation between the sign and the headlamps: 1.5 m. This is based on a headlamp mounting height of 0.6 m (Cobb, 1990), and a sign mounting height of 2.1 m (Woltman and Szczech, 1989).

The angle corresponding to the preceding geometry is 0.5U, 2.25R.

Criterion illuminance. The criterion traffic-sign-illuminance value was set at 0.02 lux based on the following considerations:

- The observation angle for the given geometry is 0.31°.
- The coefficient of retroreflection of the sign material is 150 cd/lux/m^2 at an observation angle of 0.2°. A typical value for a white, encapsulated, sign material is 300 cd/lux/m^2; a realistic in-use value is 50% of the new value (Alferdinck, 1984).
- Assuming the relative reflectance of sign material at 0.2° is set equal to 1, then the relative reflectance at 0.31° is 0.777 (interpolated from the data in Sivak, Flannagan, and Gellatly, 1991 on the effect of the observation angle on the relative reflectance).
- The computed coefficient of retroreflection of the sign material for an observation angle of 0.31° is 116 cd/lux/m^2 (150 x 0.777).
- The desired minimum luminance of the sign material is 2.4 cd/m^2. This value was recommended by Sivak and Olson (1985) and Jenkins and Gennaoui (1992) as a *minimum (replacement)* value of sign materials, based on a literature review of available studies on the effects of sign luminance on their legibility. (In comparison, the *optimal* luminance was found by Sivak and Olson to be 75 cd/m^2.)
- To obtain sign luminance of 2.4 cd/m^2 using a sign material with a coefficient of retroreflection of 116 cd/lux/m^2, the illuminance must be 0.02 lux (2.4/116).

Findings. Table 5 ranks all standards in terms of the decreasing combined luminous intensity from both lamps directed towards 0.5U, 2.25R. This table also lists the nearest controlled test point for each standard (column 4), the difference between the logarithms of the intensity in question and the highest intensity in this direction from all standards (column 5), the resultant illuminance at the sign (column 6), and the difference between the logarithms of the illuminance in question and the criterion illuminance of 0.02 lux (column 7). Two standards exceeded this performance criterion.

Table 5. Illumination of a traffic sign on the right shoulder. The relevant angle (0.5U, 2.25R) corresponds to the following assumed separations between the headlamps and the sign: lateral 6.15 m, vertical 1.5 m, and longitudinal 150 m. The criterion illuminance value was set at 0.02 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 150 m	Δlog lux from 0.02
1.5	SAE	1,000	0.5U, 2R	0	.044	+.34
1.5	U.S.	1,000	0.5U, 2.25R	0	.044	+.34
3.5	Europe	?	no nearby minimum	N.A.	N.A.	N.A.
3.5	Japan	?	no nearby minimum	N.A.	N.A.	N.A.

Illumination of an overhead traffic sign (2U, V)

Geometry. The illumination directed towards an overhead traffic sign was evaluated by considering the following geometry on a two-lane roadway:

- Longitudinal separation between the sign and the headlamps: 150 m.
- Lateral separation between the sign and the headlamps: 0 m.
- Vertical separation between the sign and the headlamps: 5.5 m. This is based on a headlamp mounting height of 0.6 m (Cobb, 1990), and a sign mounting height of 6.1 m (Woltman and Szczech, 1989).

The angle corresponding to the preceding geometry is 2U, V.

Criterion illuminance. The criterion traffic-sign illuminance was set at 0.02 lux based on the same considerations as in the preceding section dealing with traffic signs on the right shoulder. (The observation angles are very similar, 0.33° for the overhead sign and 0.31° for the shoulder sign.)

Findings. Table 6 ranks all standards in terms of the decreasing combined luminous intensity from both lamps directed towards 2U, V. This table also lists the nearest controlled test point (column 4), the difference between the logarithm of the intensity in question and the highest intensity in this direction from all standards (column 5), the resultant illuminance at the sign (column 6), and the difference between the logarithm of the illuminance in question and the target illuminance of 0.02 lux (column 7). None of the standards met this performance criterion.

Table 6. Illumination of an overhead traffic sign. The relevant angle (2U, V) corresponds to the following assumed separations between the headlamps and the sign: lateral 0 m, vertical 5.5 m, and longitudinal 150 m. The criterion illuminance value was set at 0.02 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 150 m	Δlog lux from 0.02
1.5	SAE	400	1.5U, V	0	.018	-.05
1.5	U.S.	400	1.5U, 1R	0	.018	-.05
3	Europe	250	2U, V	-.2	.011	-.26
4	Japan	?	no nearby minimum	N.A.	N.A.	N.A.

Glare illumination towards oncoming traffic (0.5U, 3.5L)

Geometry. The glare illumination directed towards an oncoming driver was evaluated by assuming the following geometry on a two-lane roadway:

- Longitudinal separation between the oncoming driver and the headlamps: 50 m.
- Lateral separation between the oncoming driver and the headlamps: 3 m.
- Vertical separation between the eyes of the oncoming driver and the headlamps: 0.5 m. This is based on a headlamp mounting height of 0.6 m (Cobb, 1990), and a driver eye height of 1.1 m (Cobb, 1990).

The angle corresponding to the preceding geometry is 0.5U, 3.5L.

Criterion illuminance. The criterion illuminance value was set at 0.7 lux based on the following considerations:

- In a typical nighttime situation, discomfort glare reaches the value 4 on the de Boer scale (de Boer, 1967) at approximately -0.25 log lux or 0.56 lux at the eye (Schmidt-Clausen and Bindels, 1974; Olson and Sivak, 1984a). (The de Boer scale is a nine-point scale with adjectives for odd points only. "Disturbing" corresponds to 3, and "just acceptable" corresponds to 5.)
- The transmittance of the windshield is assumed to be 0.85, which is typical of untinted glass at rake angle of about 45°.
- To achieve the illuminance at the driver's eyes of 0.56 lux after the light passes through the windshield, the illuminance at the surface of the windshield needs to be 0.7 lux (0.56/0.85).

Findings. Table 7 ranks all standards in terms of the increasing combined luminous intensity from both lamps directed towards 0.5U, 3.5L. This table also lists the nearest controlled test point (column 4), the difference between the logarithm of the intensity in question and the lowest intensity (in this direction) from all standards (column 5), the resultant illuminance at 150 m (column 6), and the difference between the logarithm of the illuminance in question and the criterion illuminance of 0.7 lux (column 7). Two standards exceeded this criterion.

Table 7. Glare illumination towards an oncoming driver. The relevant angle (0.5U, 3.5L) corresponds to the following assumed separations between the eyes of an oncoming driver and the headlamps: lateral 3 m, vertical 0.5 m, and longitudinal 50 m. The criterion illuminance value was set at 0.7 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 50 m	Δlog lux from 0.7*
1	Europe	500	0.6U, 3.4L	0	.20	-.54
2	SAE	1,300	0.5U, 3L	+.41	.52	-.13
3.5	Japan	2,000	0.5U, 3.5L	+.60	.80	+.06
3.5	U.S.	2,000	0.5U, 3.5L	+.60	.80	+.06

*Negative values are desirable, indicating values lower than the maximum criterion illuminance at the eye.

Glare illumination towards traffic ahead via exterior rearview mirrors (1.25U, 8.25R)

Geometry. The glare illumination directed towards a driver ahead via the left exterior rearview mirror was evaluated by assuming the following geometry on a four-lane roadway:

- Longitudinal separation between the mirror and the headlamps of the glare car: 15 m.
- Lateral separation between the mirror and the glare headlamps in the left adjacent lane: 2.2 m.
- Vertical separation between the mirror and the glare headlamps: 0.3 m.

The angle corresponding to the preceding geometry is 1.25U, 8.25R.

Criterion illuminance. The criterion illuminance was set at 11 lux based on the data of Olson and Sivak (1984b), which showed that, given the geometry of interest, a value of 4 on the de Boer discomfort scale is reached at illuminance of approximately 7.5 lux. When corrections for mirror reflectivity (.80) and windshield transmittance (.85) are applied, the target illuminance becomes 11 lux (7.5/(.85 x .80)). (The target illuminance here is substantially greater than in the oncoming-glare situation discussed in the preceding section. The primary factor responsible for this discrepancy is the increased glare angle in the present situation; the secondary factor is the loss of light due to the reflectivity of the mirror.)

Findings. Table 8 ranks all standards in terms of the increasing combined luminous intensity from both lamps directed towards 1.25U, 8.25R. This table also lists the nearest controlled test point (column 4), the difference between the logarithm of the intensity in question and the lowest intensity in this direction from all standards (column 5), the resultant illuminance at 15 m (column 6), and the difference between the logarithm of the illuminance in question and the criterion illuminance of 11 lux (column 7). Three standards exceeded this performance criterion.

Table 8. Glare illumination towards traffic ahead via exterior left rearview mirror. The relevant angle (1.25U, 8.25R) corresponds to the following assumed separations between the mirror and the glare headlamps: lateral 2.2 m, vertical 0.3 m, and longitudinal 15 m. The criterion illuminance value was set at 11 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 15 m	Δlog lux from 11*
1	Europe**	876	1.25U, 8.25R	0	3.89	-.45
2	SAE	1,300	2U, 8R	+.17	5.78	-.28
3	Japan	2,000	1.5U, 8.25R	+.36	8.89	-.09
4	U.S.	2,800	1.5U, 8.25R	+.50	12.44	+.05

*Negative values are desirable, indicating values lower than the maximum criterion illuminance at the eye.

**The European specifications allow two different types of the cutoff to the right of vertical (see Table 2). The point under discussion (1.25U, 8.25R) is controlled for the horizontal cutoff option. For the 15° inclining cutoff option, this point is in an uncontrolled zone, and thus the European specification would be ranked 4.

Illumination prone to scatter in adverse atmospheric conditions (fog, rain, and snow) (10U, V)

Geometry. One aspect of the performance under adverse atmospheric conditions was evaluated by considering the amount of illumination directed towards 10U, V. The logic here is that a good beam pattern minimizes the amount of light scatter due to adverse atmospheric conditions (such as fog, rain, and snow) by minimizing the illumination directed toward areas where no targets or signs are likely. The selected vertical angle (10U) corresponds to an overhead sign (6.1 m above the roadway) at 34 m, too short a distance to be of likely importance for sign detection or legibility.

Criterion illuminance. There is insufficient empirical data to set a criterion value.

Findings. Table 9 ranks all standards in terms of the increasing combined luminous intensity from both lamps directed towards 10U, V. This table also lists the nearest controlled test point (column 4), and the difference between the logarithm of the intensity in question and the highest intensity (in this direction) from all standards (column 5).[1]

Table 9. Illumination prone to scatter in adverse atmospheric conditions (10U, V).

1	2	3	4	5
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best
2	Japan	250	10U, V	0
2	SAE	250	10U, V	0
2	U.S.	250	10U, V	0
4	Europe	876	10U, V	+.54

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[1] The lamps currently manufactured to meet the European standard produce less light above horizontal than do lamps manufactured to meet the U.S. standard (Sivak, Flannagan, and Sato, 1993). However, as indicated in the introduction, the present study evaluates what is *allowed* under a given standard. In that respect, the European standard allows more light at 10U and above than does the U.S. standard.

Illumination directed towards targets on the right side of the road at intermediate distances (0.5D, 1.25R)

Geometry. The illumination provided for detecting targets on the right side of the lane of travel at intermediate distances was evaluated by assuming the following geometry:

- Longitudinal separation between the target and the headlamps: 75 m.
- Lateral separation between the target and the headlamps: 1.6 m.
- Vertical separation between the target and the headlamps (i.e., headlamp mounting height): 0.6 m.

The angle that corresponds to the preceding geometry is 0.5D, 1.25R.

Criterion illuminance. The criterion illuminance was set at 33 lux to permit visual performance that is midway between capabilities in daylight and moonlight. This illuminance is equivalent to the mid-point of log ambient illumination during civil twilight, which occurs when the sun is less than 6° below the horizon and covers levels ranging from 330 to 3 lux (Leibowitz, 1987). Over this range, visual recognition performance falls from near-optimal levels in daylight to near-minimal levels in moonlight. Assuming the criterion illumination and a reflectance of 10%, object luminance is 1 cd/m^2. At this level, visual acuity is about 50% and peak contrast sensitivity is about 33% of photopic values (Owens, Francis, and Leibowitz, 1989). Historically, the dark boundary of civil twilight (3 lux) has been used widely as a benchmark for setting the limit of useful visual recognition. The 3 lux criterion may be a useful value for activities that are not visually challenging, such as farming or sailing, but is inappropriately low for visual demanding tasks, such as driving (Leibowitz and Owens, 1991). The criterion of 33 lux is not out of line with other current estimates of necessary illumination for perceiving unexpected low-contrast targets. For example, Kosmatka's (1992a) calculations for a 7% reflectance target indicate that the illuminance needs to be 32 lux (341,000 cd at 104 m), while Fisher's (1970) analysis (also for a 7% reflectance target), leads to 91 lux (1,200,000 cd at 115 m). Padmos and Alferdinck (1988) accept Fisher's intensity requirement of 1,200,000 cd, but use a distance of 110 m, for target illuminance of 99 lux.

Findings. Table 10 ranks all standards in terms of the decreasing combined luminous intensity from both lamps directed towards 0.5D, 1.25R. This table also lists the nearest controlled test point (column 4), the difference between the logarithm of the intensity in question and the highest intensity (in this direction) from all standards (column 5), the resultant illuminance at 75 m (column 6), and the difference between the logarithm of the illuminance in question and the criterion illuminance of 33 lux (column 7). None of the standards met this performance criterion.

Table 10. Illumination directed towards targets on the right side of the road at 75 m (0.5D, 1.25R). The criterion illuminance was set at 33 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 75 m	Δlog lux from 33
1.5	SAE	20,000	0.6D, 1.3R	0	3.56	-.97
1.5	U.S.	20,000	0.5D, 1.5R	0	3.56	-.97
3	Europe	15,000	0.6D, 1.1R	-.12	2.67	-1.09
4	Japan	12,000	0.5D, 2R	-.22	2.13	-1.19

Illumination on hills (1.25D, 2R)

Geometry. Driving on hills was evaluated by considering the illumination directed towards right side delineation using the following geometry:

- Longitudinal separation between the delineation and the headlamps: 50 m.
- Lateral separation between the delineation and the headlamps: 1.85 m.
- Radius of curvature: 3,000 m.
- Headlamp mounting height: 0.6 m.

The angle corresponding to the preceding geometry is 1.25D, 2R.

Criterion illuminance. The criterion illuminance was set at 6.4 lux based of the following considerations:

- Specific luminance of the road delineation: 0.1 cd/lux/m^2.
- Road delineation with specific luminance of 0.1 cd/lux/m^2 was found by Helmers and Lundquist (1991) to be visible at about 50 m.
- The headlamps used by Helmers and Lundquist are similar to the low-beam headlamp documented in Helmers and Rumar (1975). Using the isocandela diagram in Helmers and Rumar (1975), we estimated that each lamp directed approximately 8,000 cd towards the delineation at 50 m, for the resulting illuminance of 6.4 lux (16,000/50^2).

Findings. Table 11 ranks all standards in terms of the decreasing combined luminous intensity from both lamps directed towards 1.25D, 2R. This table also lists the nearest controlled test point (column 4), the difference between the logarithms of the intensity in question and the highest intensity in this direction from all standards (column 5), the resultant illuminance at 50 m (column 6), and the difference between the logarithms of the illuminance in question and the criterion illuminance of 6.4 lux (column 7). Three standards met or exceeded this performance criterion.

Table 11. Illumination directed towards delineation at the right road edge at 50 m on a hill (1.25D, 2R). The criterion illuminance was set at 6.4 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 50 m	Δlog lux from 6.4
2	Japan	30,000	1.5D, 2R	0	12.00	+.27
2	SAE	30,000	*	0	12.00	+.27
2	U.S.	30,000	1.5D, 2R	0	12.00	+.27
4	Europe	15,000	0.9D, 1.7R	-.30	6.00	-.03

*The minimum of 15,000 cd per lamp has to be met at least at one point in Zone 1 (corners: 0.5D, 0.5R; 0.5D, 2.5R; 2D, 2.5R; 2D, 0.5R).

Illumination on sags (0.25D, 2R)

Geometry. Driving on sags was evaluated by considering the illumination directed towards right side delineation using the following geometry:

- Longitudinal separation between the delineation and the headlamps: 50 m.
- Lateral separation between the delineation and the headlamps: 1.85 m.
- Radius of curvature: 3,000 m.
- Headlamp mounting height: 0.6 m.

The angle that corresponds to the preceding geometry is 0.25D, 2R. (For a level road, this angle corresponds to a longitudinal separation of 138 m between the delineation and the headlamps.)

Criterion illuminance. The criterion illuminance was set at the same level (6.4 lux) as in the above analysis for delineation on a hill.

Findings. Table 12 ranks all standards in terms of the decreasing combined luminous intensity from both lamps directed towards 0.25D, 2R. This table also lists the nearest controlled test point (column 4), the difference between the logarithms of the intensity in question and the highest intensity in this direction from all standards (column 5), the resultant illuminance at 50 m (column 6), and the difference between the logarithms of the illuminance in question and the criterion illuminance of 6.4 lux (column 7). Two standards met or exceeded this performance criterion.

Table 12. Illumination directed towards delineation at the right road edge at 50 m on a sag (0.25D, 2R). The criterion illuminance was set at 6.4 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 50 m	Δlog lux from 6.4
1.5	SAE	20,000	0.6D, 1.3R	0	8.00	+.10
1.5	U.S.	20,000	0.5D, 1.5R	0	8.00	+.10
3	Europe	15,000	0.6D, 1.1R	-.12	6.00	-.03
4	Japan	12,000	0.5D, 2R	-.22	4.80	-.12

Illumination directed towards targets on the right side of the road at near distances (1.25D, 3.75R)

Geometry. The illumination directed towards targets on the right side of the lane of travel at near distances was evaluated by considering the following geometry:

- Longitudinal separation between the target and the headlamps: 25 m.
- Lateral separation between the target and the headlamps: 1.6 m.
- Vertical separation between the target and the headlamps (i.e., headlamp mounting height): 0.6 m.

The angle that corresponds to the preceding geometry is 1.25D, 3.75R.

Criterion illuminance. The criterion illuminance was set at the same level (33 lux) as in the above analysis for a target at 75 m.

Findings. Table 13 ranks all standards in terms of the decreasing combined luminous intensity from both lamps directed towards 1.25D, 3.75R. This table also lists the nearest controlled test point (column 4), the difference between the logarithm of the intensity in question and the highest intensity (in this direction) from all standards (column 5), the resultant illuminance at 25 m (column 6), and the difference between the logarithm of the illuminance in question and the target illuminance of 33 lux (column 7). None of the standards met this performance criterion level.

Table 13. Illumination directed towards targets on the right side of the road at 25 m (1.25D, 3.75R). The criterion illuminance was set at 33 lux.

1	2	3	4	5	6	7
Rank	Standard	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 25 m	Δlog lux from 33
1	SAE	10,000	0.5D, 4R	0	16.00	-.31
2	Europe	3,750	1.25D, 3.75R	-.43	6.00	-.74
3.5	Japan	?	no nearby test point	N.A.	N.A.	N.A.
3.5	U.S.	?	no nearby test point	N.A.	N.A.	N.A.

Homogeneity of the beam (a comparison of 1.25D, 3.75R and 1.25D, V)

We planned to evaluate the homogeneity of the beam by comparing the illumination directed towards two foreground test points, one on the right side and one straight ahead. The selected test points were 1.25D, 3.75R and 1.25D, V. To perform the evaluation, we needed both the minima and maxima in this region of the beam, so that we could estimate the likely illumination. In the standards under review, that was not the case. Thus, homogeneity is simply not addressed by the standards and, therefore, cannot be evaluated.

Illumination prone to reflected glare from wet pavement (2D, 3.5L)

Geometry. One aspect of visual performance in adverse weather was evaluated by considering the amount of illumination reflected from the wet pavement in the direction of an oncoming driver in the adjacent lane at the distance of 50 m (i.e., the illumination *reflected* from the pavement towards the same point as the *direct* illumination considered on pp. 12 and 13). The direct glare was evaluated for 0.5U, 3.5L. The calculated direction for the light to be reflected towards 0.5U, 3.5L at 50 m is 2D, 3.5L. This calculation assumes longitudinal separation between the oncoming driver and the headlamps of 50 m, lateral separation between the driver and the headlamps of 3 m, mounting height of headlamps of 0.6 m, and driver eye height of 1.1 m.

Criterion illuminance. The proportion of light reflected in the direction of interest depends on the type of the road surface and the extent to which the standing water fills the depressions in the road surface. Because the proportion of reflected light varies quite substantially with these two factors, no criterion illuminance was set.

Findings. None of the standards have a maximum near 2D, 3.5L. Consequently, we were not able to evaluate the standards on this function.

Lateral spread

The extent of the lateral spread of illumination (important for visual performance on sharp horizontal curves and at intersections) was evaluated by examining the widest controlled test points. Table 14 ranks all standards in terms of the decreasing lateral angle of the most extreme controlled test points. Within proposals with equivalent width of the coverage, the proposals are ranked in the decreasing order of the specified minimum luminous intensity.

Table 14. The extent of lateral spread.

1	2	3	4
Rank	Standard	Widest controlled point(s)	cd (both lamps)
1	SAE	20L/20R (4D)	600
2	U.S.	15L/15R (2D)	1,700
3	Japan	15L/15R (2D)	1,400
4	Europe	9L/9R (1.7D)	2,500

Relation between seeing illumination and direct glare illumination (a comparison of 0.5D, 1.25R and 0.5U, 3.5L)

The relation between seeing illumination and direct glare illumination was evaluated by computing the ratio between illumination at 0.5D, 1.25R and 0.5U, 3.5L. Table 15 ranks all standards in terms of the decreasing ratio of luminous intensity directed towards 0.5D, 1.25R and 0.5U, 3.5L (column 3). It also lists the differences in logarithms between these two luminous intensities (column 5) and the difference between the logarithm of the ratio in question and the highest ratio from all standards (column 6). From the standpoint of visibility, the highest ratios are most desirable because they indicate high visibility with low glare to oncoming drivers.

Table 15. Ratio of seeing illumination (0.5D, 1.25R) and glare illumination (0.5U, 3.5L).

1	2	3	4	5	6
Rank	Standard	Ratio	Nearest controlled points	Δlog cd	Δlog ratio from the best
1	Europe	30.0:1	see Tables 10 and 7	1.48	0
2	SAE	15.4:1	see Tables 10 and 7	1.19	-.29
3	U.S.	10.0:1	see Tables 10 and 7	1.00	-.48
4	Japan	6.0:1	see Tables 10 and 7	0.78	-.70

Reliability of visual aiming

Vertical aiming is of primary concern here. The evidence indicates that reliability of vertical visual aiming is affected by the luminous-intensity contrast between vertically adjacent parts of the beam (Poynter, Plummer, and Donohue, 1989; Sivak, Flannagan, Chandra, and Gellatly, 1992). Contrast in these two studies was computed in steps of 0.1° from available candela matrices. However, such a computation of contrast is not possible for the standards under consideration because of the limited number of test point/regions.

In the absence of actual contrast measures, we estimated the gradient by using the method proposed by Kosmatka (1992b), which involves the following steps (see Table 16): (1) Select a point to the right of vertical and below horizontal that involves a minimum and is within 1° of horizontal. (2) Select a point to the right of vertical and above horizontal that involves a maximum, is within 1° of horizontal, and is at the same lateral position as the previously considered minimum. (3) Compute the ratio of these two values. Raise this ratio to the power that is the inverse of the number of 0.1° steps that separate the two points in columns 3 and 4. Subtract 1.00 and multiply by 100. This yields the percent by which candela values change over each 0.1° step, assuming that the gradient is constant in terms of percent change over the entire interval (i.e., assuming that log candela values change linearly with angle). The results of these calculations are shown in Table 16. The computed gradients ranged from 37% to about 8%.

Adverse effects of misaim

Of primary concern here are the potential adverse effects of vertical misaim: misdirecting seeing illumination to glare zones, and restricted glare illumination to seeing zones. As a first approximation, the effect of vertical misaim is likely to be *inversely* proportional to the steepness of the vertical gradient. Consequently, the *inverse* of the ranking in Table 16 represents our best prediction concerning the effects of misaim.

Table 16. Gradient to the right of vertical.

1	2	3	4	5	6	7
Rank	Standard	Minimum cd below horizontal for one lamp (controlled point)	Maximum cd above horizontal for one lamp (controlled point)	Vertical distance (°) between points in 3 and 4	Ratio of columns 3 and 4	Gradient (%)
1	Europe*	7,500 (0.6D, 1.1R)	438 (0.3U, 1.1R)	.9	17.1	37
2.5	SAE	10,000 (0.6D, 1.3R)	2,400 (0.5U, 1.3R)	1.1	4.2	14
2.5	U.S.	10,000 (0.5D, 1.5R)	2,700 (0.5U, 1.5R)	1.0	3.7	14
4	Japan	6,000 (0.5D, 2R)	2,700 (0.5U, 2R)	1.0	2.2	8

*The European standard allows two different types of cutoff (see p. 6). The calculations in this table are for the continuously inclining cutoff; for the horizontal cutoff, the resulting gradient is 27%.

DISCUSSION

There are three main problems in coming up with a single overall figure of merit. First, the visual performance functions are not equally important from the safety point of view. For example, strong arguments could be made that visibility and direct glare should be weighted more heavily than the other functions such as indirect glare via rearview mirrors (because of the existence of dual-position and variable-reflectance mirrors) and homogeneity of the beam (because it deals mostly with considerations of aesthetics and comfort). There is no general consensus, however, about the appropriate weights for all the different functions addressed here. Second, performance on certain visual performance functions could not be evaluated for some lamp standards under review. This happened because the selected critical points did not always coincide with or fall near to test points in the standards. Furthermore, in some instances where there was a coincidence of test points, the required minimum luminous intensity (for seeing considerations), or the required maximum luminous intensity (for glare considerations), was not included in the standards. Third, because of the lack of relevant empirical data, for several functions we were unable to determine criterion illuminance values against which to evaluate the standards.

In spite of the above limitations, we tried to integrate and summarize in Table 17 the rankings for the individual visual performance functions from Tables 5 through 16. (The inverse of the ranking of the reliability of visual aiming [Table 17] was used to estimate effects of misaim.) Table 17 also presents the mean rankings for all visual performance functions.

Table 17. Rankings of the standards on the individual visual performance functions in Tables 5 through 16.

	Standard			
Visual performance function	SAE	U.S.	Europe	Japan
Right traffic signs (Table 5)	1.5	1.5	3.5	3.5
Overhead traffic signs (Table 6)	1.5	1.5	3	4
Direct glare (Table 7)	2	3.5	1	3.5
Rearview-mirror glare (Table 8)	2	4	1	3
Fog, rain, and snow scatter (Table 9)	2	2	4	2
Intermediate-distance targets (Table 10)	1.5	1.5	3	4
Illumination on hills (Table 11)	2	2	4	2
Illumination on sags (Table 12)	1.5	1.5	3	4
Near-distance targets (Table 13)	1	3.5	2	3.5
Lateral spread (Table 14)	1	2	4	3
Seeing-to-glare ratio (Table 15)	2	3	1	4
Reliability of visual aiming (Table 16)	2.5	2.5	1	4
Effects of misaim (Table 16)	2.5	2.5	4	1
Mean ranking	**1.77**	**2.38**	**2.65**	**3.19**

CONCLUSIONS

This study evaluated SAE J1735 Draft Proposal for a low-beam headlighting pattern in relation to the current standards in the U.S., Europe, and Japan. The approach consisted of the following steps: (1) identifying a set of 15 important visual performance functions (including seeing and glare) for low-beam headlamps; (2) defining the relevant geometry relative to the visual performance functions; (3) setting criterion values of illumination for each of the visual performance functions based on the available empirical data; and (4) evaluating the standards relative to the criterion values by considering the worst-allowed-case approach. This involved using the *minima* specified by the standards and proposals for seeing functions, and the *maxima* for glare functions.

The results indicate that the SAE J1735 Draft Proposal tended to require better performance than the current U.S., European, and Japanese standards.

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