EVALUATION OF PROPOSED LOW-BEAM HEADLIGHTING PATTERNS

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16. Abstract

This study evaluated several recent proposals for the low-beam headlighting pattern. The research consisted of (1) documenting the current U.S., European, and Japanese standards, (2) documenting the proposed low-beam patterns, (3) performing a comparative analysis of the proposed beam patterns, (4) developing a set of visual performance functions for low-beam headlamps, (5) defining the representative geometry for the visual performance functions, (6) setting criterion illuminance values for the visual performance functions based on available empirical data, and (7) evaluating the standards and proposals in relation to the criterion values by considering the worst allowed case.

The following are the main findings: (1) There is a lack of empirical evidence for evaluating the proposals on certain performance functions, including visual aim, effects of misaim, and homogeneity of the beam. (2) In terms of visibility, none of the proposals (nor existing standards) met our criterion of 33 lux for seeing low-contrast targets on the right side of the road, supporting the notion that we commonly overdrive our low beam headlamps. (3) Because the functional requirements of low beams are multifaceted and complex, it is not surprising that each proposal and standard has its advantages and disadvantages. (4) The relation between seeing illuminance and glare illuminance is likely to capture a substantial part of the functional requirements of low beams. (5) The proposal by Padmos and Alferdinck (explicitly designed to optimize European-type low beam) had the best mean ranking across the individual performance functions. The SAE proposal (based on the current U.S.-type beam, but implicitly designed to bridge the gap between the U.S. and European beams) had the second best mean ranking.

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INTRODUCTION

Over the years, different philosophies have emerged on the two sides of the Atlantic concerning the appropriate way to handle the conflict between visibility and glare with low-beam headlights. The European (ECE) approach differs from the U.S. (FMVSS) approach primarily in a greater emphasis on protecting oncoming drivers (as well as drivers ahead) from glare, the ease of aiming the headlamp visually (relying on perceptual judgment of the lamp aimer), and aesthetic and comfort aspects of the beam pattern when projected on the road surface. Consequently, the European low beam has (1) a well specified sharper transition (cutoff) between where the light is needed for visibility in front of the vehicle and where it might impinge on the eyes of oncoming drivers, (2) less light toward oncoming drivers, and (3) a wider, brighter, and more homogeneous foreground illumination. Each approach is superior to the other in certain traffic conditions (e.g., Rumar, Helmers and Thorell, 1973), but neither approach appears to be superior overall (Olson, 1977).

The lack of a demonstrated superiority of either approach has, over the years, softened the opposition from both camps towards international harmonization. A clear majority of manufacturers and scientists now favor flexibility and advocate scientific research into possible avenues for a compromise solution. The renewed support of international harmonization has already borne some fruit. For example, we have begun to understand the effects of prior headlighting experience and task difficulty on discomfort glare (Sivak, Olson, and Zeltner, 1989; Sivak, Flannagan, Ensing, and Simmons, 1991), the relationship between the sharpness of the cutoff and the reliability of vertical visual aim (Poynter, Plummer, and Donohue, 1989; Sivak, Flannagan, Chandra, and Gellatly, 1992), the required illumination above horizontal for assuring effectiveness of retroreflective traffic signs (Arens, 1987; Sivak, Gellatly, and Flannagan, 1991), and the complex interactions of light above and below the cutoff on the visibility of targets with and without retroreflectorization (Helmers, Fernlund, and Ytterbom, 1990). We have also seen a resurgence of interest in the old problem (Roper and Howard, 1938) of specifying the minimum illumination necessary for basic visual functions (Owens, Francis, and Leibowitz, 1989; Kosmatka, 1992a; Leibowitz and Owens, 1991).

In the current positive atmosphere towards international harmonization, the present research was designed to evaluate recent proposals that were made in the U.S., Europe, and Japan for improved low-beam headlighting. While some of these proposals were made explicitly as attempts at a harmonizable beam pattern (e.g., SAE, 1991), others were made within the general framework of either the European pattern (e.g., Padmos and Alferdinck, 1988) or the U.S. pattern (Bindels, 1984). Nevertheless, we decided to evaluate all recent English-language low-beam proposals that we were aware of as of January 1, 1992. The following proposals were evaluated: Bindels

(1984), Burgett, Matteson, Ulman, and Van Iderstine (1989), de Brabander (1990), Kosmatka (1988), Padmos and Alferdinck (1988), SAE (1991), Schmidt-Clausen (1985), Taniguchi, Kitagawa, and Jin (1989), and VEDILIS (1990).

APPROACH

This research involved the following phases:

(1) Document the current U.S. (FMVSS), European (ECE), and Japanese (JIS) standards, and the proposed standards in a common tabular format.

(2) Compare the existing and proposed standards in terms of illumination specified in different zones of the beam patterns (above horizontal, distant field, and foreground).

(3) Identify a set of 15 important visual performance functions (including seeing and glare) for low-beam headlamps.

(4) Define the relevant geometry relative to the visual performance functions.

(5) Set criterion values of illumination for each of the visual performance functions based on the available empirical data.

(6) Evaluate the existing and proposed standards relative to the criterion values by considering the worst-allowed-case approach. This approach involved using the minima specified by the standards and proposals for seeing functions, and the maxima for glare functions.

An evaluation of the standards using computer models such as CHESS (Bhise, Farber, and McMahan, 1976; Bhise, Farber, Saunby, Troell, Walunas, and Bernstein, 1977) was not possible. Such models require input of a detailed candela matrix to define the beam to be evaluated. The standards to be discussed in this report contain only a limited number of test points, lines, or zones. The great majority of the beam field is not explicitly controlled, and only *limits* (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 lamp to any particular candela matrix.

CURRENT STANDARDS IN THE U.S., EUROPE, AND JAPAN

The current U.S. (FMVSS), European (ECE), and Japanese (JIS) standards are summarized in Tables 1 through 3. The table also contains recent proposed modifications (NHTSA, 1991).

Table 1. The current U.S. photometric standard (FMVSS 108) for a 2-lamp system.

Test point	Minimum (cd)	Maximum (cd)
10U to 90U		125
1.5U, 1R to R		1,400
1.5U, 1R to 5R	450*	
1U, 1.5L to L		700
0.5U, 1.5L to L		1,000
0.5U, 1R to 3R	1,000*	2,700
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, 9R	1,000	
1.5D, 2R	15,000	
2D, 15L	850	
2D, 15R	850	
4D, 4R		12,500
Zone with corners: H, 8L; H, 8R; 4U, 8R; 4U, 8L	64*	
Zone with corners: H, 4L; H, 4R; 2U, 4R; 2U, 4L	135*	

* These values are from a proposed modification of the current U.S. standard (NHTSA, 1991).

Table 2. The current European standard (ECE Regulation R20).The original specifications of the test-point locations were converted from cm on a vertical surface at 25 m to the nearest quarter degree of visual coordinates of the visual field. Similarly, the original specifications of lux at 25 m were converted to cd (rounded to the nearest 5 cd).

Test Point or Region	Minimum (cd)	Maximum (cd)
0.5U, 3.5L (B50L)		250
0.5D, 3.5L (75L)		7,500
0.5D, 1.25R (75R)	7,500	
0.75D, 3.5L (50L)		9,375
0.75D, V (50V)	3,750	
0.75D, 1.75R (50R)	7,500	
1.75D, 9L (25L)	1,250	
1.75D, 9R (25R)	1,250	
Zone I (1.75D to D)		2 x the actual value of 0.75D, 1.75R
Zone III (above line H, 20L; H, V; 5.25U, 20R, or above line H, 20L; H, V; 0.5U, 0.5R; 0.5U, 20R)		440
Zone IV (corners: 0.75D, 5.25L; 0.75D, 5.25R; 1.75D, 5.25R; and 1.75D, 5.25L)	1,875	

Table 3. The current Japanese standard (JIS D5500B1-1984), converted to right-hand traffic.

Test Point or Region	Minimum (cd)	Maximum (cd)
10U to 90U		500
1.5U, 1R to R		1,500
1U, 1L to L		1,300
0.5U, 1L to L		1,700
0.5U, 1R to 3R		2,800
0.5D, 1L to L		3,300
0.5D, 2R	3,000	15,000
1D, 6L	600	
1.5D, 9L	800	
1.5D, 9R	800	
1.5D, 2R	7,000	
2D, 15L	400	
2D, 15R	400	
4D, 4R		12,500

PROPOSED LOW-BEAM STANDARDS

Bindels (1984)

Bindels' proposal attempted to improve the performance of the U.S. low beam while changing as few test points as possible. Bindels proposed to modify the U.S. standard (FMVSS 108, which in 1984 referenced the SAE Recommended Practice J579c) by changing only two test points: (1) increasing the maximum of 2,500 cd at 0.5D, 1.5L (the actual FMVSS specification is for 0.5D, 1.5L to L) to 5000 cd, or removing this maximum altogether, and (2) removing altogether the maximum of 20,000 cd at 0.5D, 1.5R. The proposed changes were intended to improve seeing distance, and, because the glare points were unchanged, no increase in glare was expected. Furthermore, according to Bindels, these two changes presented no problems given the state of the technology even in 1984.

Bindels' conclusion:
"This presentation has clearly demonstrated that for the purpose of improving the lower beam only a slight change would be needed in the actual SAE requirements. The improvement can be accomplished without any trade-off concept. By this we mean that the seeing distance can be improved without having to increase the glare values. On the contrary, this could be achieved even at reduced glare levels. This we would call a true advancement of safety regulations, utilizing the present day state of the art. The availability of the technology to improve on existing lower beam characteristics may certainly be beneficial to the promotion of the idea of harmonization" (p. 7).

By removing the maximum for a seeing point (0.5D, 1.5R) this proposal clearly opened the possibility of improved headlamp performance. However, as will be seen later, our approach was to use the *minima* allowed by the various specifications in our evaluations of how well they guaranteed seeing ability. For seeing, the minimum represents the worst case. (Analogously, we used the *maxima* allowed by the specifications for all glare considerations.) Because Bindels did not change the minimum specification for 0.5D, 1.5R, our evaluation of the seeing performance of lamps built to the modified specification proved to be identical to the unmodified FMVSS specification. The other modification proposed by Bindels increased the maximum for 0.5D, 1.5L to L. However, our evaluation did not use a test point in the vicinity of 0.5D, 1.5L to L. Consequently, it is not surprising that our evaluation of the current FMVSS specification with or without the Bindels' modification proved to be identical in all respects. Thus, in the discussion to follow, we will not evaluate Bindels' proposal. This decision has no implications for the potential improvements afforded by Bindels' modifications; it reflects our explicit strategy to evaluate the worst scenarios allowed by each specification.

Burgett et al. (1989)

This proposal embodies one drastic departure from all other proposals. Specifically, this headlamp standard is vehicle-based rather than headlamp-based. In theory, therefore, this standard can be met with any number of separate lamp units. Furthermore, if there are two or more units, their beam patterns do not need to be identical.

A computer model was used to estimate the lighting needs for visibility purposes (pedestrians, traffic signs, and lane delineation) and for glare protection (both direct and indirect via-rearview-mirror glare). This model uses elements of the CHESS Model (Bhise et al., 1976, 1977), which, in turn, is based on Blackwell's research on contrast sensitivity (Blackwell, 1952). Burgett et al. model the pedestrian as a 76 cm x 30 cm target on the right shoulder of the road and a reflectivity of 12%. Deceleration of 0.5 G is assumed, along with a driver reaction time of 1.42 s. Originally, a speed of 90 km/h was considered in some scenarios, but such speed led to impractically high luminous intensity requirements for the visibility of the road delineation and pedestrians. Consequently, the maximum speed considered was, apparently, 65 km/h.

The recommended standard, as applied to a two-lamp system, with a mounting height of 61 cm and a lamp-to-lamp separation of 122 cm, is shown in Table 4. (This table assumes that the left and right lamp contribute equally to each of the test points.) The angular coordinates were rounded to the nearest quarter degree, and the intensity specifications were rounded to the nearest 5 cd.

Burgett's et al. abstract:

"Nighttime accident data was studied to determine priorities for accident reduction through the use of improved vehicle roadway illumination. The relationship between the driver, vehicle, environment and target was then modeled, resulting in thousands of conflicting, yet high priority target points. Prioritized accident data and target similarity was then used to reduce the number of targets to a more manageable number for specification purposes. The resulting specification, based on safe driving needs during nighttime driving conditions, will be the basis for developing future lighting throughout the world" (p. 1).

Table 4. Low-beam pattern proposed by Burgett et al. (1989). This table assumes a two-lamp system (a mounting height of 61 cm [24 in] and a lamp-to-lamp separation of 122 cm [48 in]), with the left and the right lamp contributing equally to each test point. The pairs of horizontal coordinates are for the left lamp and the right lamp, respectively.

Test Point (°)	Minimum (cd)	Maximum (cd)
1.75U, 1.5R/1.5L		380
1.75U, 0.5L/3.75L		420
1U, 3.75R/0.5R		600
0.75U, 4L/5.75L		445
0.75U, 7.5L/9.25L		480
0.5U, 2.75L/4L		950
8.75U, 0.75R/0.75L	20	
8.75U, 5.25R/3.75R	20	
6U, 2.5L/3.5L	50	
6U, 10R/9R	50	
4.5U, 8L/9L	85	
3.25U, 13.25L/13.75L	220	
3.25U, 0.25R/0.25L	230	
3.25U, 15.25R/14.75R	220	
2.25U, 13.75R/13.25R	230	
1.75U, 15.75L/16.25L	220	
1.75U, 18.75R/18.25R	220	
0.25U, 14.25L/14.75L	230	
0.25U, 12.75R/12.25R	230	
0.25D, 3R/1.75R	18,155	
0.75D, 6L/7.5L	16,260	
0.75D, 1.5L/2.75L	28,130	
1D, 1.75R/0.25L	6,985	
1D, 7.25R/5.5R	10,355	
1D, 4R/2R	4,105	
1.75D, 5.5L/9L	1,175	
1.75D, 1.75L/5.25L	1,255	
1.75D, 5.25R/1.75R	710	
1.75D, 9R/5.5R	785	
3.5D, 3.5R/3.5L		980 (the actual average of the preceding four points)

de Brabander (1990)

This article describes the current Belgian headlamp standard (NBN L 20-001). The main feature of this standard is that the emphasis is on minimum *ratios* between seeing illuminations and glare illuminations, as opposed to absolute minima and maxima of illumination.

This standard specifies the following (with the test-point locations converted from the tangent of the visual angle to visual angle):

(1) The maximum of either the U.S. hot spot (1.5D, 2R) or the line between ECE points 50R (0.75D, 1.75R) and 75R (0.5D, 1.25R) needs to be at least eight times the maximum in the left glare zone (above horizontal and to the left of 1.75L).
(2) The same maximum needs to be at least six times the maximum in the right glare zone (above the cutoff and to the right of H, 1.75L).
(3) The maximum straight ahead (line between 0.75D, V and 1.75D, V) needs to be at least 6.5 times the value at the main ECE glare direction B50L (0.5U, 3.5L).
(4) Line between 0.5D. 1.25R and 0.75D, 1.75R has a minimum of 3,750 cd.
(5) Left half of the ECE zone IV (with corners at 0.75D, V; 1.75D, V; 1.75D, 5.25L; and 0.75D, 5.25L) has a minimum of 750 cd.
(6) Right half of the ECE zone IV (with corners at 0.75D, V; 1.75D, V; 1.75D, 5.25R; and 0.75D, 5.25R) has a minimum of 1,250.

However, according to de Brabander, this standard is enforced by the Belgian motor vehicle inspection stations by performing only the following relative measurements:

(1) The maximum of 1.5D, 2R and 0.75D, 1.5R is compared with values at three locations at the bottom edge of the glare zone. This maximum needs to be at least four times the value at H, 1.75L, three times the value at H, V, and three times the value at 0.5U, 2.25R.
(2) The value at 1D, V needs to be at least four times the value at 0.5U, 3.5L.

de Brabander argues that this procedure also provides an excellent control of aiming in the case of a sharp cutoff, since the cutoff lies 0.5° below one test point (H, V) and 0.5° above another test point (1D, V).

de Brabander's conclusion:

"Within Belgium, very positive results have been achieved using only ratio requirements of the luminous intensities in the road illumination direction to those in the glare directions. In addition, the importance of these ratios for the visibility of targets has been emphasized by research on passing beams performed in Japan over a five year period between 1983-1988. In conclusion, the Belgian standard NBL L 20-001 should be strongly considered as a possible solution towards the international harmonization of passing beams" (p. 4).

Kosmatka (1988)

Kosmatka argues that the redefined low beam should meet the requirements of driving in city, rural, and undivided highway situations, while the redefined high beam should meet the requirements of divided highway driving. The proposed minima and maxima are based on current technology, using single-filament C8 sources. Kosmatka's proposal, along with the rationale, is summarized in Table 5.

Table 5. Low-beam pattern proposed by Kosmatka (1988). (The proposed test point 0.6D, 1.5R was rounded to 0.5D, 1.5R.)

Test Point or Region	Minimum (cd)	Maximum (cd)	Rationale
10U to 90U		90	Inclement glare
4U, 1R to R		300	Inclement glare
1.5U, 1.5R to R		700-1,000	Rearview mirror
1U, 1.5L to L		300-500	Opposing glare
0.5U, 1.5L to L		500-700	Opposing glare
0.5U, 1R to 3R		1,300-1,800	Rearview mirror
0.5D, 1.5R	8,000	20,000	Seeing light
1D, 6L	1,500		Lane delineation
1.5D, 2R	10,000	20,000	Seeing light
1.5D, 9R	1,500		Lane/berm light
1.5D, 9L	1,500		Left lane light
2D, 15R	1,000		Berm light
2D, 15L	1,000		Lane/berm light
2D, 20R	400		Berm light
2D, 20L	400		Berm light
4D, V		5,000	Foreground
4D, 4R		5,000	Foreground

Kosmatka's summary:

"Optimum photometric performance specifications must take into account not only the application, but to a certain measure, the headlamp system itself.

Present SAE tables J579c and J1383 probably represent the best compromise for dual filament C6 systems providing upper and lower beams.

In turnpike situations upper beam usage is limited.

The idealized lower beam for turnpike driving has needs diametrically opposed to that needed for lower speed driving where far reaching, down-the-road light is less important.

One way headlighting systems have been optimized has been by recognizing the 'high speed - opposing traffic' mode with intermediate or auxiliary beams.

Assuming that an optimized system must maintain a 'two beam' format (e.g. not 3-beam 2-3-3 or 2-3-4 format), the high beam pattern could be redefined as a controlled glare, 'intermediate' type of beam. The lower beam could be redefined with even lower glare, and less seeing light, similar to J579a or ECE regulations.

The superiority of any system could be evaluated by objective opposed seeing distance testing and subjective inclement weather evaluations and/or driving simulators such as CHESS" (p. 6).

Padmos and Alferdinck (1988)

This comprehensive report attempted to develop recommendations for a low-beam pattern within the constraints of the current ECE guidelines. It assumed that a minimum seeing distance of 110 m is needed for pedestrians, obstacles, and animals (at 80 km/h), 50-150 m for traffic signs, 75 m for bicycle reflectors, 30 m for cross streets, and 50-150 m for road delineation. Padmos and Alferdinck's proposal (with the test-point locations rounded to the nearest quarter degree of visual angle) is shown in Table 6.

Table 6. Low beam pattern proposed by Padmos and Alferdinck (1988).

Test Point or Region	Minimum (cd)	Maximum (cd)
7U, V	/40*	
0.5U, 3.5L (B50L)		250/500*
0.5D, 3.5L (75L)		7,000
0.5D, 1.25R (75R)	50,000	
0.75D, 3.5L (50L)		9,000
0.75D, V (50V)	20,000	
0.75D, 1.75R (50R)	20,000	
Zone Ia (corners: 4.25D, 15L; 4.25D, 15R; 8D, 15R; and 8D, 15L)	800	1/15 of 0.5D, 1.25R
Zone Ib (corners: 2.25D, 15L; 2.25D, 15R; 4.25D, 15R; and 4.25D, 15L)	2,000	1/5 of 0.5D, 1.25R
Zone IIa (corners: 0.5D, 15L; 0.5D, V; H, 0.5R; H, 15R; 1.75D, 15R; and 1.75D, 15L)	3,000	
Zone IIIa (corners: H, 1L; H, V; 0.5U, 0.5R; 0.5U, 2R; 2U, 2R; and 2U, 1L)	200/400*	400/1000*
Zone IIIb (corners: H, 15L; H, V; 0.5U, 0.5R; 0.5U, 15R; 4U, 15R; and 4U, 15L, except for Zone IIIa)		400/1,000*

* The values to the right of the slashes are from a later paper by the same authors (Alferdinck & Padmos, 1990). In the discussion to follow, only the values from the later paper are used.

Padmos and Alferdinck's' summary:

"A study of the literature from 1970 on the optimal luminous intensity distribution of the low beam, and trial runs with various car headlamps, were performed.

Calculations on basis of the literature resulted in light intensities required for seeing the various visual elements that are of importance for smooth and safe driving, taking into account the desired glare limitation and the homogeneity of the road illumination. During the trial runs, done with three types of headlamp, one with a conventional parabolic reflector, one with a homofocal ellipsoidal reflector, and one with a three-axis ellipsoidal reflector, the visibility of visual elements was appraised systematically.

The study resulted in recommendations for the light intensity distribution. These are more stringent than the European (ECE) guidelines. Differences are: a higher intensity and wider beam in the direction of the road at 25-75 m in front of the car; a stronger decrease of intensity closer to the car; a minimum intensity in a central area above the horizon. Moreover, a Z-shaped light-dark border is advocated.

From the literature study it was concluded that substantial improvements of the illuminating function of the low beam, while maintaining sufficient glare restriction, are not possible. Accordingly, from the trial runs only small functional differences between the headlamp types appeared. The headlamp type with the three-axis ellipsoidal reflector approaches most closely our recommendation.

A construction which enables maintaining the proper vertical aim of the headlamps during driving, is considered necessary in order to combine an optimal illumination function with glare restriction. Also, a wipe or spray installation on lantern's frontal lens is a useful device" (p. 5).

SAE (1991)

This proposal was developed by the Headlamp Beam Pattern Task Force of the SAE Lighting Committee. The latest version is designated Proposal 7A. A statement issued by the Task Force in the early phases of the deliberations stated that the following should be embodied in the eventual proposal:

- Consider the world environment.
- Both design and testing requirements are to be considered.
- The initial standard will be component based.
- Consideration is to be made for a vehicle-based standard.
- Standard should allow for symmetrical beam patterns even if standard is vehicle based.
- Signs should be considered.
- The beam pattern should have the flexibility such that higher output light sources can be accommodated.
- Compromises may be incorporated to account for weather conditions.

The proposed design guide is summarized in Table 7. In addition to the design guide, SAE has also proposed a set of conformance requirements (see Table 8). For the comparative analysis to follow, we used only the design guide.

Table 7. Low-beam design guide, proposed by SAE (1991).

Test Point or Region	Minimum (cd)	Maximum (cd)
1.5U, V to 3R	200	1,000
0.5U, 1.5L	300	800
0.5U, 1R to 2R	500	2,400
0.5D, 1.5R	8,000	
0.5D, 4R	5,000	
1D, 3.5L		9,000
1D, V	6,000	15,000
2D, 15L	1,000	
2D, 9L	1,250	
2D, 9R	1,250	
2D, 15R	1,000	
4D, 20L	300	
4D, 4R	0.5 x max in Zone I	12,500
4D, 20R	300	
Zone I (corners: 0.5D, 0.5R; 0.5D, 2.5R; 2D, 2.5R; 2D, 0.5R)	15,000	
Zone II (corners: 1D, 5L; 1D, 5R; 2D, 5R; 2D, 5L, except Zone I)	1,875	
Zone III (corners: 0.5U, 8L; 0.5U, 3L; 2U, V; 2U, 8R; 4U, 8R; and 4U, 8L)	80	750
Zone IV (4U to 10U, 15L to 15R)		525
Zone V (10U to 90U, 45L to 45R)		125 (438 within 2° conical angle)

Table 8. Low-beam conformance requirements, proposed by SAE (1991).

Test Point or Region	Minimum (cd)	Maximum (cd)
10U, V		125 (440 within 2° conical angle)
4U, 8L	65	900
2U, 1.5R	65	900
1.5U, 1.5R	150	1,300
0.5U, 1.5L	210	1,000
0.5U, 1.5R	400	3,000
1D, 5L	1,400	
2D, 15L	700	
2D, 15R	700	
Zone I (corners: 0.5D, 0.5R; 0.5D, 2.5R; 2D, 2.5R; 2D, 0.5R)	15,000 (at least at one point)	

Schmidt-Clausen (1985)

This paper describes a proposal for a European-type low-beam pattern, based on a projection system with an ellipsoidal reflector. According to Schmidt-Clausen, the advantages of this pattern are (1) no glare, (2) higher gradient in the cutoff area, and (3) greater lateral spread. This proposal is summarized in Table 9.

Table 9. Low-beam photometrics proposed by Schmidt-Clausen (1985).

Test Point or Region	Minimum (cd)	Maximum (cd)
0.5U, 3.5L (B50L)		250
0.5D, 3.5L (75L)	3,750	
0.5D, 1.25R (75R)	12,500	
0.75D, 3.5L (50L)	3,750	
0.75D, V (50V)	6,250	
1.75D, 15L	1,250	
1,75D, 10L	2,500	
1.75D, 10R	2,500	
1.75D, 15R	1,250	
Zone I (1.75D to D)		1.5 times the actual value of 0.75D, 1.75R
Zone III (above line H, 20L; H, V; 5.25U, 20R)		440
Zone IV (corners: 0.75D, 5.25L; 0.75D, 5.25R; 1.75D, 5.25R; and 1.75D, 5.25L)	3,750	
Zone A (corners: H, 8L; H, V; 2.25U, 8R; 4U, 8R; and 4U, 8L), except Zone B	60	440
Zone B (corners: H, 4L; H,V; 1U, 4R; 2U, 4R; and 2U, 4L)	125	440

Schmidt-Clausen's abstract:

"The recognition distance of a car-driver for objects on the street during night-time driving depends on several parameters. These parameters are, beside of others,

luminance of the object and the background
size and luminance factor of the object
adaptation level of the driver
recognition time for the object.

The influence of the parameter were investigated in dynamic tests. The headlamps used in the test were of the new type "elliptic reflector". During the test the headlamps were changed in

mounting height on the car
inclination of the headlamp

and in the light distribution by changing the amount of glare above the cut-off-line.
Out of this experiments minimum values of glare illuminance and illumination beyond horizontal line are derived" (p. i).

Taniguchi, Kitagawa, and Jin (1989)

Taniguchi et al. (1989) were concerned with (1) the visibility of small obstacles in the path of travel, (2) the visibility of pedestrians to the right (for ride-hand traffic), (3) the legibility of traffic signs, (4) the preview of the road geometry, and (5) the discomfort glare for the oncoming driver. They considered passenger cars travelling at 60 km/h (37 mph) on level, straight [except for item (4) above] two-lane roadway with dry asphalt pavement. The recommendations are based on both detection studies and subjective ratings. The visibility studies used small dark targets (20 cm x 20 cm, 5% reflectance), and targets simulating pedestrians (150 cm x 40 cm, 5% reflectance). Criterion detection distance for pedestrians was set at 44 m (assuming reaction time of 1.5 s, surface friction coefficient of 0.75, and deceleration of 7.4 m/s^2). The proposal by Taniguchi et al. (1989) is listed in Table 10.

Table 10. Low-beam pattern proposed by Taniguchi et al. (1989).

Test Point	Minimum (cd)	Maximum (cd)	Rationale
5U, V	75		Visibility of overhead signs
0.75U, 1R	300		Visibility of roadside traffic signs
0.5U, 3L		550	Glare for the oncoming driver
H, 2R	1,400		Pedestrians on the right
0.75D, 3L	2,000		Left-side road surface
0.75D, 0.5R	6,550		Obstacles ahead
0.75D, 2R	7,000		Right-side road surface
0.75D, 4R	5,350		Right-side road surface
1D, 6L	2,000		Left-side road surface
1.5D, 9L	2,000		Left-side road surface
1.5D, 11R	1,150		Right-side road surface

Excerpts from the conclusions by Taniguchi et al.

"This study aimed to establish the minimum passing beam photometric design guidelines that are regarded as necessary for safety of traffic environment in Japan. In this study we first set the visibility conditions, the travelling conditions, and the vehicle conditions that are the prerequisites for setting the photometric design guidelines, and then examined the light distribution of passing beams that satisfy these conditions by testing and research....

Among these points [the recommended test points in Table 10], we regard the 0.5U/3L, H/2R, and 0.75D/0.5R as the most important for safety.

To compare the points set by JARI [Japan Automobile Research Institute] with the points stipulated by the existing standards and regulations, 6 points are identical or approximate to JIS, 5 points to SAE Standard, and 6 points to ECE regulations. Regarding set luminous intensities, the point relating to the glare for the vehicles in the opposing traffic lanes is almost the same as the point stipulated by ECE Regulations. However, the luminous intensities are set lower than those stipulated in JIS and SAE standards. The points relating to the visibility of road surface below the horizontal line level have luminous intensities higher than those stipulated by JIS, SAE Standard, and ECE Regulations.

For some points, we are considering setting not only the minimum luminous intensity but also the maximum luminous intensity" (pp. 28 and 29).

VEDILIS (1990)

Table 11 describes the proposal that was made as part of the European project VEDILIS (Vehicle Discharge Light System) for a high-intensity discharge headlamp (D1). This proposal is, in several aspects, consistent with the current ECE Regulation 20. However, it includes higher intensities both above and below horizontal, lateral test points at near distances for a widened beam, and new maxima limits to minimize glare due to inclination changes of the vehicle or reflection from wet pavement. The measurements are to be done at 13.2 V. (However, the light output of high-intensity discharge headlamps is relatively independent of voltage.)

Table 11. Low beam photometrics proposed by VEDILIS (1990).

Test point or Region	Minimum (cd)	Maximum (cd)
Zone I (above line H, 20L; H, V; 0.5U, 0.5R; 0.5U, 2.25R; 2.5U, 20R)		810
0.75U, 5.25L to 5.25R	125	
0.5U, 3.5L (B50L)		500
H, V		810
0.5D, 3.5L (75L)		12,500
0.5D, 1.25R (75R)	10,000	
0.75D, 5.25L to 5.25R	3,750	
0.75D, 3.5L (50L)		18,750
0.75D, V (50V)	7,500	
0.75D, 1.75R (50R)	10,000	
1.75D, 9L (25L)	2,500	
1.75D, 3.75L to 1.5L		18,750
1.75D, 9R (25R)	2,500	
2.75D, 15L	1,250	
2.75D, 15R	1,250	
4.25D, 30L	310	
4.25D, 9.5L to 3.75L		12,500
4.25D, 30R	125	
Anywhere in the beam		43,750

COMPARATIVE SUMMARY OF THE EXISTING AND PROPOSED STANDARDS

Tables 12 through 17 present a comparative summary of the existing and proposed standards. A companion set of figures (Figures 1 through 6) illustrates the locations of the proposed test points/regions. Specifically, Tables 12 and 13 along with Figures 1 and 2 deal with light above horizontal, Tables 14 and 15 along with Figures 3 and 4 concern the distant field (between 25 m in front of the vehicle and horizontal), while Tables 16 and 17 along with Figures 5 and 6 deal with foreground illumination (up to 25 m in front of the vehicle).

The FMVSS and JIS standards are based on 12.8 V. On the other hand, the ECE standard requires that "during the checking of the headlight, the voltage at the terminals of the lamp must be regulated so as to obtain" (Section 6.1.3.) a consumption of about 55 W and light flux of 750 lumens. Consequently, no simple adjustment for the different testing procedures is possible. (The VEDILIS standard is based on 13.2 V, but the light output of high-intensity discharge headlamps is relatively independent of voltage.)

These tables and figures do not include the Belgian standard discussed by de Brabander (1990). The reason for this is that, according to de Brabander, this standard is enforced by performing only *relative* photometric measurements (see p. 12).

Light above horizontal—left

Table 12. Summary of test points/regions above horizontal and to the left of vertical (shown in Figure 1), and the corresponding candela values.

Test point/ region	Coordinates	Minimum (cd)	Maximum (cd)	Author(s)
a	1.75U, 15.75L	220		Burgett
b	0.25U, 14.25L	230		Burgett
c	3.25U, 13.25L	220		Burgett
d	4.5U, 8L	85		Burgett
e	0.75U, 7.5L		480	Burgett
f	0.75U, 4L		445	Burgett
g	0.5U, 3.5L		250	ECE
			500	Padmos
			500	VEDILIS
h	0.5U, 3L		550	Taniguchi
i	0.5U, 2.75L		950	Burgett
j	6U, 2.5L	50		Burgett
k	0.5U, 1.5L	300	800	SAE
l	1.75U, 0.5L		420	Burgett
m	H, V		810	VEDILIS
n	5U, V	75		Taniguchi
o	7U, V	40		Padmos
A	1U, 1.5L to L		700	FMVSS
			500	Kosmatka
B	1U, 1L to L		1,300	JIS
C	0.75U, 5.25L to V	125		VEDILIS
D	0.5U, 1.5L to L		1,000	FMVSS
			700	Kosmatka
E	0.5U, 1L to L		1,700	JIS
F	above horizontal		440	ECE
			440	Schmidt-C
			810	VEDILIS
G	zone with corners: H, 1L; H, V; 2U, V; 2U, 1L	400	1,000	Padmos
H	zone with corners: H, 15L; H, V; 4U, V; 4U, 15L, except zone G		1,000	Padmos
I	zone with corners: H, 4L; H, V; 2U, V; 2U, 4L	135		FMVSS
		125	440	Schmidt-C
J	zone with corners: H, 8L; H, V; 4U, V; 4U, 8L, except zone I	64		FMVSS
		60	440	Schmidt-C
K	10U to 90U		125	FMVSS
			500	JIS
			90	Kosmatka
L	zone with corners: 0.5U, 8L; 0.5U, 3L; 2U, V; 4U, V; 4U, 8L	80	750	SAE
M	zone with corners: 4U, 15L; 4U, V; 10U, V; 10U, 15L		525	SAE
Any point			43,750	VEDILIS

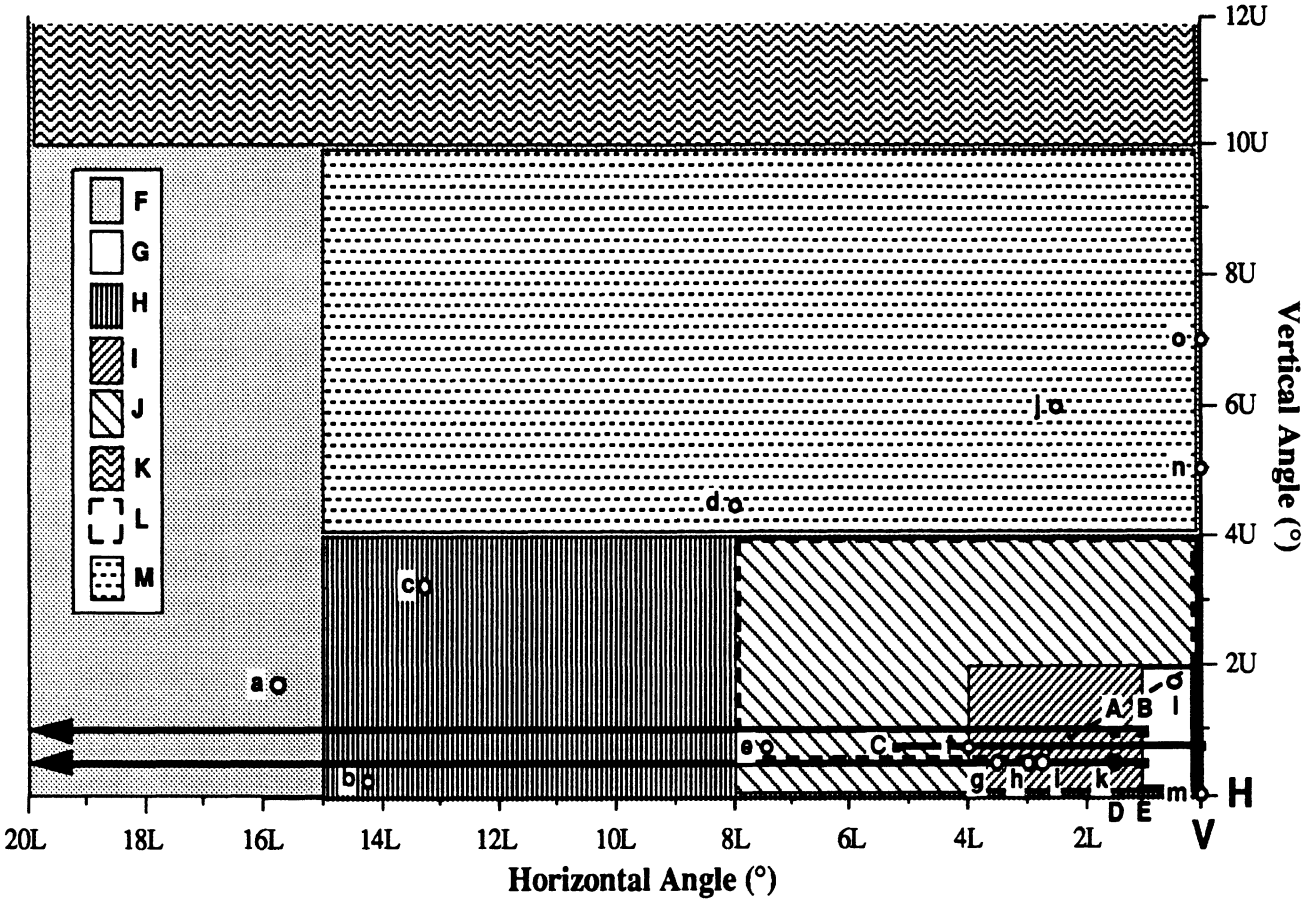

Figure 1. Summary of test points/regions above horizontal and to the left of vertical. The angular coordinates and the corresponding candela values are listed in Table 12.

Light above horizontal—right

Table 13. Summary of test points/regions above horizontal and to the right of vertical (shown in Figure 2), and the corresponding candela values.

Test point/ region	Coordinates	Minimum (cd)	Maximum (cd)	Author(s)
a	3.25U, 0.25R	230		Burgett
b	8.75U, 0.75R	20		Burgett
c	0.75U, 1R	300		Taniguchi
d	1.75U, 1.5R		380	Burgett
e	H, 2R	1,400		Taniguchi
f	1U, 3.75R		600	Burgett
g	8.75U, 5.25R	20		Burgett
h	6U, 10R	50		Burgett
i	0.25U, 12.75R	230		Burgett
j	2.25U, 13.75R	230		Burgett
k	3.25U, 15.25R	220		Burgett
l	1.75U, 18.75R	220		Burgett
A	4U, 1R to R		300	Kosmatka
B	1.5U, 1R to R		1,400	FMVSS
			1,500	JIS
C	1.5U, 1R to 5R	450		FMVSS
D	1.5U, 1.5R to R		1,000	Kosmatka
E	1.5U, V to 3R	200	1,000	SAE
F	0.75U, V to 5.25R	125		VEDILIS
G	0.5U, 1R to 3R	1,000	2,700	FMVSS
			2,800	JIS
			1,800	Kosmatka
H	0.5U, 1R to 2R	500	2,400	SAE
I	10U to 90U		125	FMVSS
			500	JIS
			90	Kosmatka
			125	SAE
J	above line H, V; 5.25U, 20R		440	ECE*
			440	Schmidt-C
			810	VEDILIS**
K	zone with corners: H, V; 0.5U, 0.5R; 0.5U, 2R; 2U, 2R; 2U, V	400	1,000	Padmos
L	zone with corners: H, V; 0.5U, 0.5R; 0.5U, 15R; 4U, 15R; 4U, V; except zone K		1,000	Padmos
M	zone with corners: H, V; 1U, 4R; 2U, 4R; 2U, V	125	440	Schmidt-C
N	zone with corners: H, V; 2.25U, 8R, 4U, 8R; 4U, V; except zone M	60	440	Schmidt-C
O	zone with corners: H, V; H, 4R; 2U, 4R; 2U, V	135		FMVSS
P	zone with corners: H, V; H, 8R; 4U, 8R; 4U, V except zone O	64		FMVSS
Q	zone with corners: 4U, V; 4U, 15R; 10U, 15R; 10U, V		525	SAE
R	zone with corners: 2U, V; 2U, 8R; 4U, 8R; 4U,V	80	750	SAE
Any point			43,750	VEDILIS

*Second alternative: above line H, V; 0.5U, 0.5R, 0.5U, 20R

**The actual specifications: above line H,V; 0.5U, 0.5R; 0.5U, 2R; 5.5U, 20R

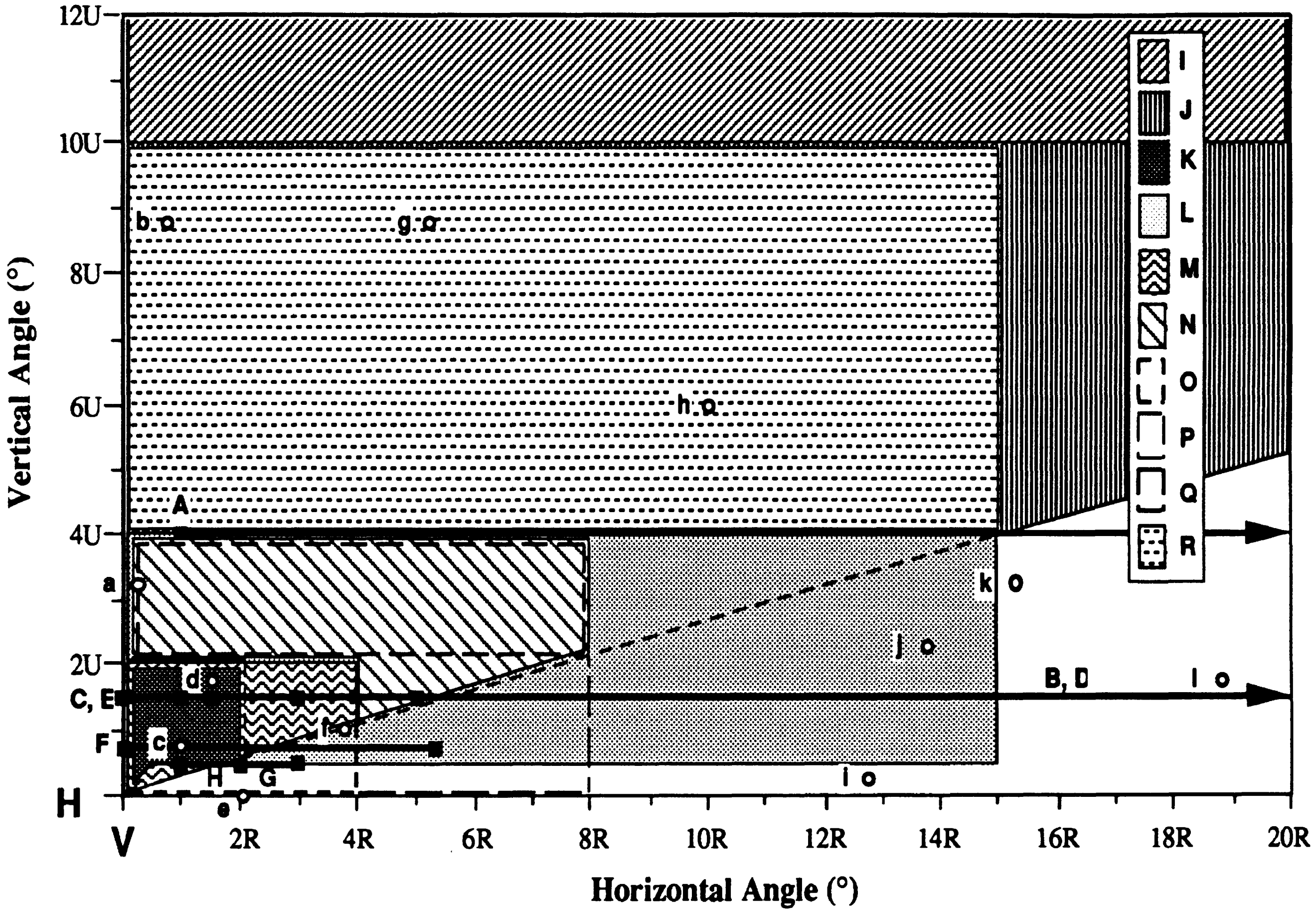

Figure 2. Summary of test points/regions above horizontal and to the right of vertical. The angular coordinates and the corresponding candela values are listed in Table 13.

Distant field—left

Table 14. Summary of test points/regions in the distant field and to the left of vertical (shown in Figure 3), and the corresponding candela values.

Test point/ region	Coordinates	Minimum (cd)	Maximum (cd)	Author(s)
a	1.5D, 9L	1,000		FMVSS
		800		JIS
		1,500		Kosmatka
		2,000		Taniguchi
b	1D, 6L	1,000		FMVSS
		600		JIS
		1,500		Kosmatka
		2,000		Taniguchi
c	0.75D, 6L	16,260		Burgett
d	1D, 3.5L		9,000	SAE
e	1D, V	6,000	15,000	SAE
f	0.75D, 3.5L		9,375	ECE
			9,000	Padmos
		3,750		Schmidt-C
			18,750	VEDILIS
g	0.5D, 3.5L		7,500	ECE
			7,000	Padmos
		3,750		Schmidt-C
			12,500	VEDILIS
h	0.75D, 3L	2,000		Taniguchi
i	0.75D, 1.5L	28,130		Burgett
j	0.75D, V	3,750		ECE
		20,000		Padmos
		6,250		Schmidt-C
		7,500		VEDILIS
A	0.75D, 5.25L to V	3,750		VEDILIS
B	0.5D, 1.5L to L		3,000	FMVSS
C	0.5D, 1L to L		3,300	JIS
D	zone with corners: 0.75D, 5.25L; 0.75D, V; 1.75D, V; 1.75D, 5.25L	1,875		ECE
		3,750		Schmidt-C
E	zone with corners: 0.5D, 15L; 0.5D, V; 1.75D, V; 1.75D, 15L	3,000		Padmos
F	zone with corners: 1D, 5L; 1D, V; 1.75D, V; 1.75D, 5L	1,875		SAE
Any point			43,750	VEDILIS

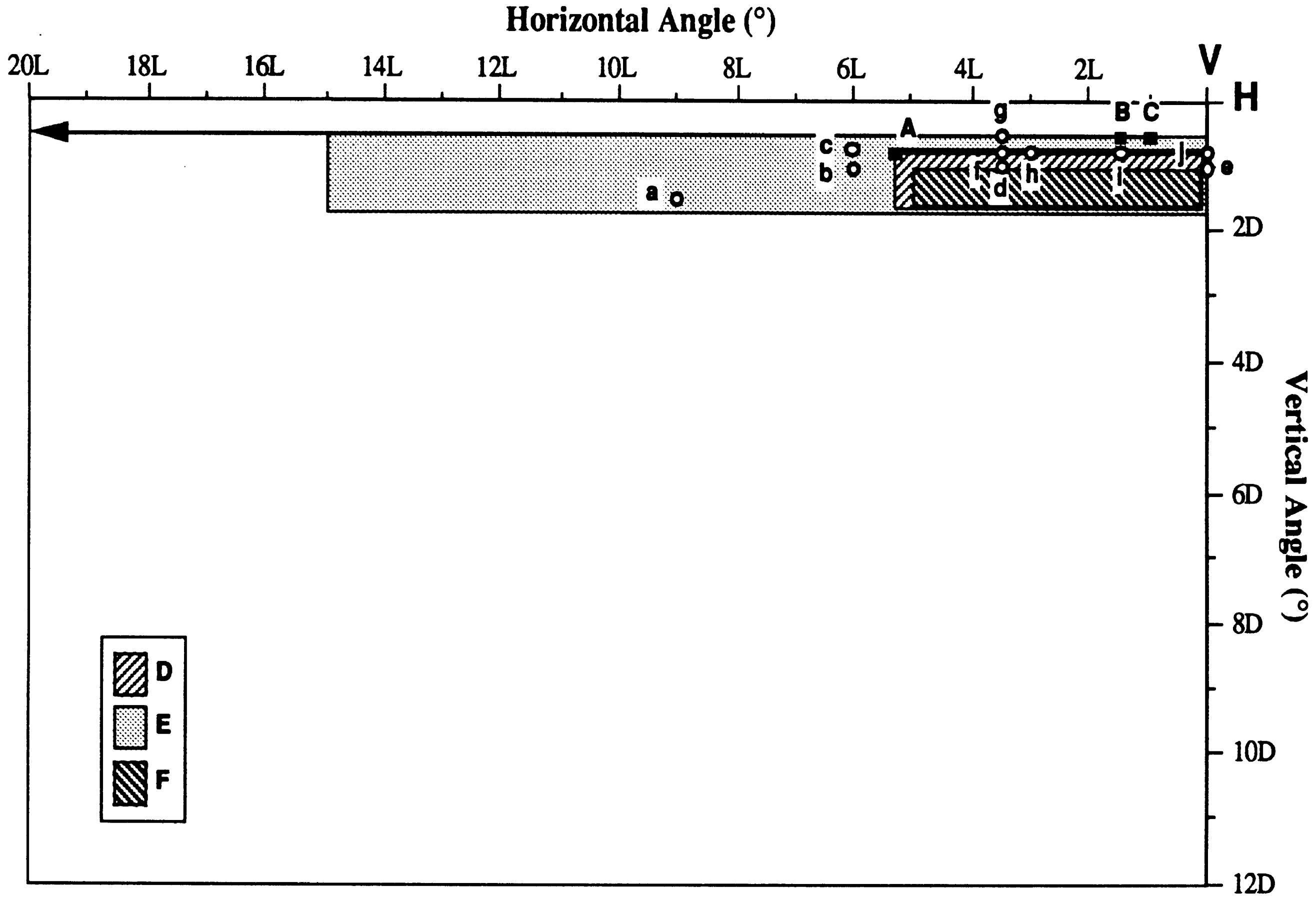

Figure 3. Summary of test points/regions in the distant field and to the left of vertical. The angular coordinates and the corresponding candela values are listed in Table 14.

Distant field—right

Table 15. Summary of test points/regions in the distant field and to the right of vertical (shown in Figure 4), and the corresponding candela values.

Test point/ region	Coordinates	Minimum (cd)	Maximum (cd)	Author(s)
a	0.75D, 0.5R	6,550		Taniguchi
b	0.5D, 1.25R	7,500		ECE
		50,000		Padmos
		12,500		Schmidt-C
		10,000		VEDILIS
c	0.5D, 1.5R	10,000	20,000	FMVSS
		8,000	20,000	Kosmatka
		8,000		SAE
d	0.5D, 4R	5,000		SAE
e	1D, 1.75R	6,985		Burgett
f	0.75D, 1.75R	7,500		ECE
		20,000		Padmos
		10,000		VEDILIS
g	1.5D, 2R	15,000		FMVSS
		7,000		JIS
		10,000	20,000	Kosmatka
h	0.75D, 2R	7,000		Taniguchi
i	0.5D, 2R	3,000	15,000	JIS
j	0.25D, 3R	18,155		Burgett
k	1D, 4R	4,105		Burgett
l	0.75D, 4R	5,350		Taniguchi
m	1D, 7.25R	10,355		Burgett
n	1.5D, 9R	1,000		FMVSS
		800		JIS
		1,500		Kosmatka
o	1.5D, 11R	1,150		Taniguchi
A	0.75D, V to 5.25R	3,750		VEDILIS
B	zone with corners: 0.75D, V; 0.75D, 5.25R; 1.75D, 5.25R; 1.75D, V	1,875		ECE
		3,750		Schmidt-C
C	zone with corners: 0.5D, V; H, 0.5R; H, 15R; 1.75D, 15R; 1.75D, V	3,000		Padmos
D	zone with corners: 0.5D, 0.5R; 0.5D, 2.5R; 1.75D, 2.5R; 1.75D, 0.5R	15,000		SAE
E	zone with corners: 1D, V; 1D, 0.5R; 1.75D, 0.5R; 1.75D, V	1,875		SAE
F	zone with corners: 1D, 2.5R; 1D, 5R; 1.75D, 5R; 1.75D, 2.5R	1,875		SAE
Any point			43,750	VEDILIS

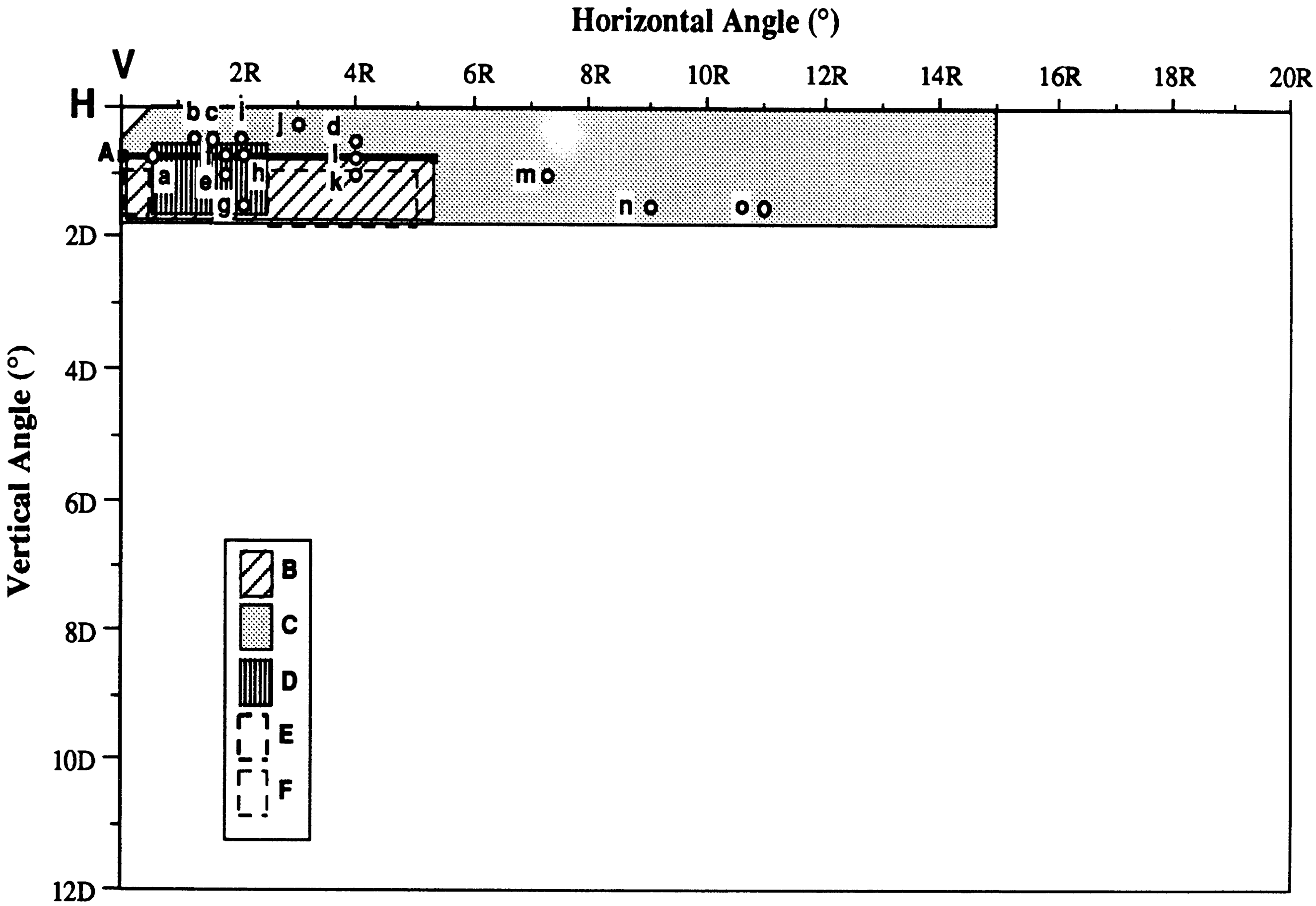

Figure 4. Summary of test points/regions in the distant field and to the right of vertical. The angular coordinates and the corresponding candela values are listed in Table 15.

Foreground illumination—l

Table 16. Summary of test points/regions in the foreground and to the left of vertical (shown in Figure 5), and the corresponding candela values.

Test point/ region	Coordinates	Minimum (cd)	Maximum (cd)	Author(s)
a	4.25D, 30L	310		VEDILIS
b	4D, 20L	300		SAE
c	2D, 20L	400		Kosmatka
d	2.75D, 15L	1,250		VEDILIS
e	2D, 15L	850		FMVSS
		400		JIS
		1,000		Kosmatka
		1,000		SAE
f	2D, 9L	1,250		SAE
g	1.75D, 15L	1,250		Schmidt-C
h	1.75D, 10L	2,500		Schmidt-C
i	1.75D, 9L	1,250		ECE
		2,500		VEDILIS
j	1.75D, 5.5L	1,175		Burgett
k	1.75D, 1.75L	1,255		Burgett
l	4D, V		5,000	Kosmatka
A	4.25D, 9.5L to 3.75L		12,500	VEDILIS
B	1.75D, 3.75L to 1.5L		18,750	VEDILIS
C	zone with corners: 2.25D, 15L; 2.25D, V; 4.25D, V; 4.25D, 15L	2,000	10,000	Padmos
D	zone with corners: 4.25D, 15L; 4.25D, V; 8D, V; 8D, 15L	800	3,335	Padmos
E	below 1.75D		*	ECE
			**	Schmidt-C
F	zone with corners: 1.75D, 5L; 1.75D, V; 2D, V; 2D, 5L	1,875		SAE
Any point			43,750	VEDILIS

* 2 times the actual value of 0.75D, 1.75R
** 1.5 times the actual value of 0.75D, 1.75R

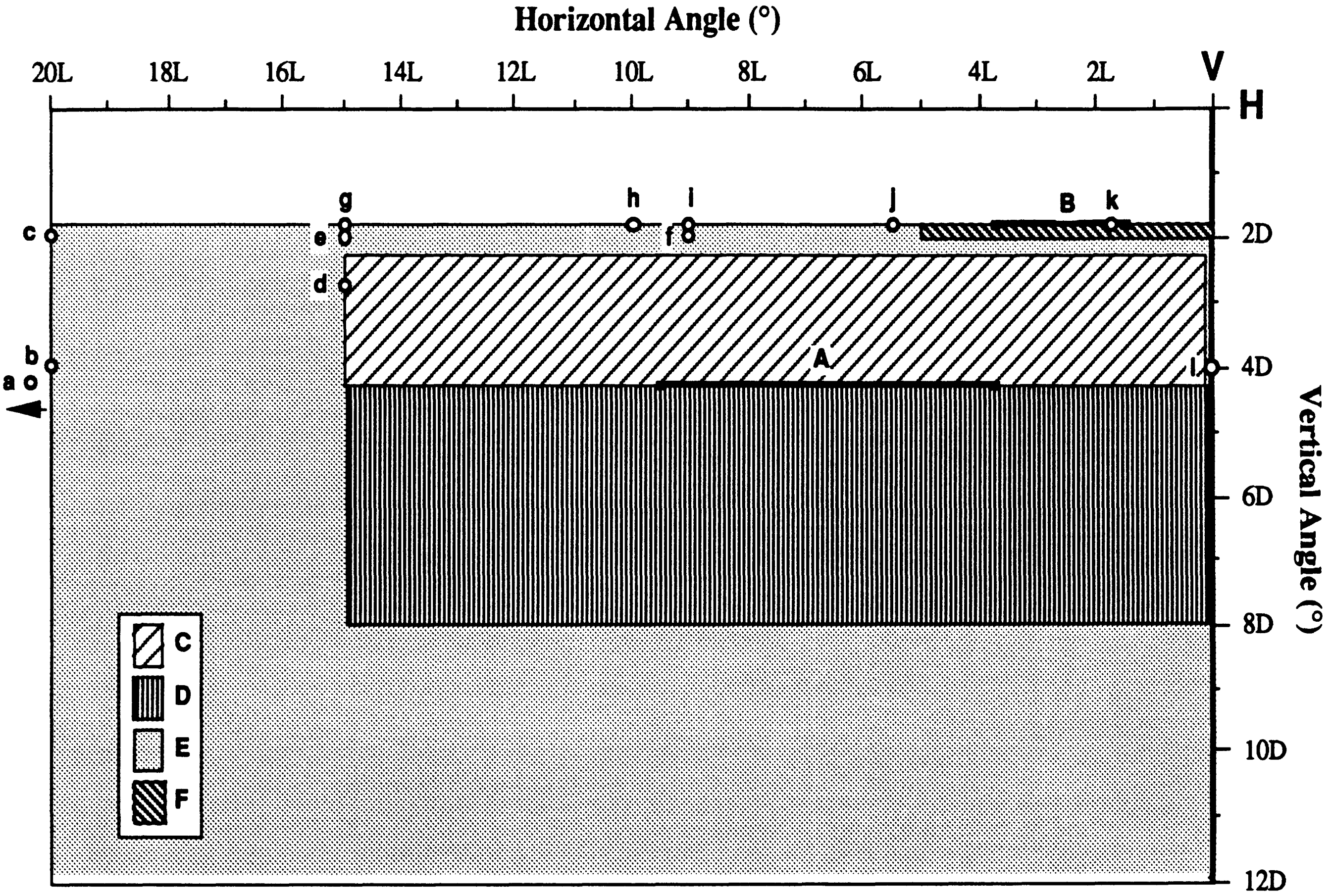

Figure 5. Summary of test points/regions in the foreground and to the left of vertical. The angular coordinates and the corresponding candela values are listed in Table 16.

Foreground illumination—right

Table 17. Summary of test points/regions in the foreground and to the right of vertical (shown in Figure 6), and the corresponding candela values.

Test point/ region	Coordinates	Minimum (cd)	Maximum (cd)	Author(s)
a	3.5D, 3.5R		980	Burgett
b	4D, 4R		12,500	FMVSS
			12,500	JIS
			5,000	Kosmatka
		*	12,500	SAE
c	4D, 20R	300		SAE
d	1.75D, 5.25R	710		Burgett
e	1.75D, 9R	1,250		ECE
		785		Burgett
		2,500		VEDILIS
f	1.75D, 10R	2,500		Schmidt-C
g	2.75D, 15R	1,250		VEDILIS
h	2D, 9R	1,250		SAE
i	2D, 15R	850		FMVSS
		400		JIS
		1,000		Kosmatka
		1,000		SAE
j	1.75D, 15R	1,250		Schmidt-C
k	2D, 20R	400		Kosmatka
l	4.25D, 30R	125		VEDILIS
A	zone with corners: 2.25D, V; 4.25D, V; 4.25D, 15R; 2.25D, 15R	2,000	10,000	Padmos
B	zone with corners: 4.25D, V; 8D, V; 8D, 15R; 4.25D, 15R	800	3,335	Padmos
C	zone with corners: 1.75D, 0.5R; 1.75D, 2.5R; 2D, 2.5R; 2D, 0.5R	15,000		SAE
D	below 1.75D		**	ECE
			***	Schmidt-C
E	zone with corners: 1.75D, V; 1.75D, 0.5R; 2D, 0.5R; 2D, V	1,875		SAE
F	zone with corners: 1.75D, 2.5R; 1.75D, 5R; 2D, 5R; 2D, 2.5R	1,875		SAE
Any point			43,750	VEDILIS

*0.5 times the maximum in zone with corners: 0.5D, 0.5R; 0.5D, 2.5R; 2D, 2.5R; 2D, 0.5R
**2 times the actual value of 0.75D, 1.75R
***1.5 times the actual value of 0.75D, 1.75R

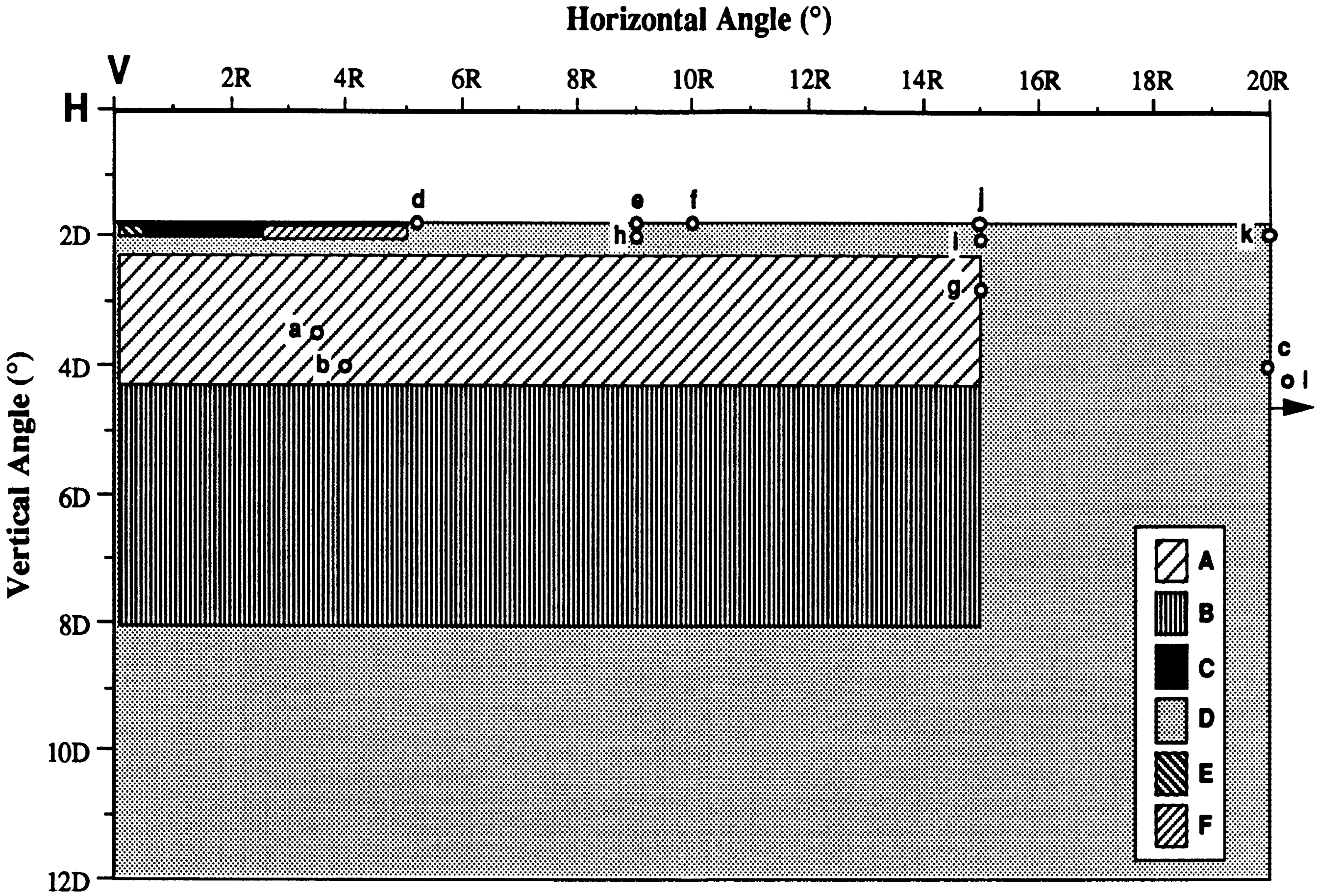

Figure 6. Summary of test points/regions in the foreground and to the right of vertical. The angular coordinates and the corresponding candela values are listed in Table 17.

VISUAL PERFORMANCE FUNCTIONS OF LOW BEAMS

The visual performance functions that we considered important for low-beam headlamps 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 and proposals 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 geometry 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 (except in the case of the vehicle performance standard by Burgett et al.). This approximation disregards the differential contribution of light from two mounted headlamps towards a given point in space. Any errors introduced by this assumption decrease as the relevant distance increases.

Fifth, the 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 ±0.5° of the desired test point. This approach is justified given the current variability of aims for on-the-road vehicles (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 are 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 *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 18 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). Five of the 10 standards met or exceeded this performance criterion.

Table 18. 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	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 150 m	Δlog lux from 0.02*
1	FMVSS	2,000	0.5U, 2.25R	0	.089	+.65
2	SAE	1,000	0.5U, 2R	-.30	.044	+.35
3	Padmos	800	0.5U, 2R	-.40	.036	+.25
4	Taniguchi	600	0.75U, 1R**	-.52	.027	+.12
5	Burgett	460	3.25U, 0.25R/0.25L	-.64	.020	+.01
6.5	Schmidt-C	250	0.5U, 2.25R	-.90	.011	-.26
6.5	VEDILIS	250	0.75U, 2.25R	-.90	.011	-.26
9	ECE	?	no nearby minimum	N.A.	N.A.	N.A.
9	JIS	?	no nearby minimum	N.A.	N.A.	N.A.
9	Kosmatka	?	no nearby minimum	N.A.	N.A.	N.A.

*The differences in log lux values (column 7) were calculated using the candela values in column 3 (not the rounded lux values in column 6).

**There is a somewhat closer controlled test point (H, 2R). We did not use this test point, because the difference between it and the desired point (0.5U, 2.25R) is primarily in the vertical direction. (Near horizontal larger differences in luminous intensity are more likely in the vertical than in the horizontal directions.)

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 19 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). Four of the 10 standards met or exceeded this performance criterion.

Table 19. 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 Rank	2 Author(s)	3 cd (both lamps)	4 Nearest controlled point	5 Δlog cd from the best	6 lux @ 150 m	7 Δlog lux from 0.02
1	FMVSS	900	1.5U, 1R	0	.040	+.30
2	Padmos	800	2U, V	-.05	.036	+.25
3	Taniguchi	600	0.75U, 1R	-.18	.027	+.12
4	Burgett	460	3.25U, 0.25R/0.25L	-.29	.020	+.01
5	SAE	400	1.5U, V	-.35	.018	-.05
6.5	Schmidt-C	250	2U, V	-.56	.011	-.26
6.5	VEDILIS	250	0.75U, V	-.56	.011	-.26
9	ECE	?	no nearby minimum	N.A.	N.A.	N.A.
9	JIS	?	no nearby minimum	N.A.	N.A.	N.A.
9	Kosmatka	?	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. This angle is identical to the main European glare direction (B50L).

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 transmissivity 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 20 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). Seven of the 10 standards met or exceeded this criterion.

Table 20. 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	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 50 m	Δlog lux from 0.7*
1.5	ECE	500	0.5U, 3.5L	0	.20	-.54
1.5	Schmidt-C	500	0.5U, 3.5L	0	.20	-.54
3.5	Padmos	1,000	0.5U, 3.5L	+.30	.40	-.24
3.5	VEDILIS	1,000	0.5U, 3.5L	+.30	.40	-.24
5	Taniguchi	1,100	0.5U, 3L	+.34	.44	-.20
6	Kosmatka	1,400	0.5U, 3.5L	+.45	.56	-.10
7	SAE	1,500	0.5U, 3.5L	+.48	.60	-.07
8	Burgett	1,900	0.5U,2.75L/4L	+.58	.76	+.04
9	FMVSS	2,000	0.5U, 3.5L	+.60	.80	+.06
10	JIS	3,400	0.5U, 3.5L	+.83	1.36	+.29

*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 two-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 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, 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 transmissivity (.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 non-100% reflectivity of the mirror.)

Findings. Table 21 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). Four of the 10 standards met or exceeded this performance criterion.

Table 21. 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	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 15 m	Δlog lux from 11*
1	ECE**	880	1.25U, 8.25R	0	3.9	-.45
2	SAE	1,500	1.25U, 8R	+.23	6.7	-.22
3.5	Kosmatka	2,000	1.5U, 8.25R	+.36	8.9	-.09
3.5	Padmos	2,000	1.25U, 8.25R	+.36	8.9	-.09
5	FMVSS	2,800	1.5U, 8.25R	+.50	12.4	+.05
6	JIS	3,000	1.5U, 8.25R	+.53	13.3	+.08
8.5	Burgett	?	no nearby test point	N.A.	N.A.	N.A.
8.5	Schmidt-C	?	no nearby test point	N.A.	N.A.	N.A.
8.5	Taniguchi	?	no nearby test point	N.A.	N.A.	N.A.
8.5	VEDILIS	?	no nearby test point	N.A.	N.A.	N.A.

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

**The ECE 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 ECE specification would be ranked on the bottom along with the four other proposals for which there is no nearby controlled test point.

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 importance for sign detection or legibility.

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

Findings. Table 22 ranks all standard 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).

Table 22. Illumination prone to scatter in adverse atmospheric conditions (10U, V).

1	2	3	4	5
Rank	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best
1	Kosmatka	180	10U, V	0
2.5	FMVSS	250	10U, V	+.14
2.5	SAE	250	10U, V	+.14
4.5	ECE	880	10U, V	+.69
4.5	Schmidt-C	880	10U, V	+.69
6	JIS	1,000	10U, V	+.74
7	VEDILIS	1,620	10U, V	+.95
9	Burgett	?	no nearby maximum	N.A.
9	Padmos	?	no nearby maximum	N.A.
9	Taniguchi	?	no nearby maximum	N.A.

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. This angle is identical to the ECE test point 75R.

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 bound 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 23 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 10 standards met this performance criterion; the strongest (Padmos and Alferdinck) at 17.78 lux falls 0.27 log units short of the criterion level.

Table 23. 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	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 75 m	Δlog lux from 33
1	Padmos	100,000	0.5D, 1.25R	0	17.78	-.27
2	Burgett	36,310	0.25D, 3R/1.75R	-.44	6.46	-.71
3	Schmidt-C	25,000	0.5D, 1.25R	-.60	4.44	-.87
4.5	FMVSS	20,000	0.5D, 1.5R	-.70	3.56	-.97
4.5	VEDILIS	20,000	0.5D, 1.25R	-.70	3.56	-.97
6.5	Kosmatka	16,000	0.5D, 1.5R	-.80	2.84	-1.06
6.5	SAE	16,000	0.5D, 1.5R	-.80	2.84	-1.06
8	ECE	15,000	0.5D, 1.25R	-.82	2.67	-1.09
9	Taniguchi	14,000	0.75D, 2R	-.85	2.49	-1.12
10	JIS	6,000	0.5D, 2R	-1.22	1.07	-1.49

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 iso-candela 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 24 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). Five of the 10 standards met or exceeded this performance criterion.

Table 24. 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	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 50 m	Δlog lux from 6.4
1	Padmos	40,000	0.75D, 1.75R	0	16.00	+.40
2.5	FMVSS	30,000	1.5D, 2R	-.12	12.00	+.27
2.5	SAE	30,000	1.25D, 2R*	-.12	12.00	+.27
4.5	Kosmatka	20,000	1.5D, 2R	-.30	8.00	+.10
4.5	VEDILIS	20,000	0.75D, 1.75R	-.30	8.00	+.10
6	ECE	15,000	0.75D, 1.75R	-.43	6.00	-.03
7.5	JIS	14,000	1.5D, 2R	-.46	5.60	-.06
7.5	Taniguchi	14,000	0.75D, 2R	-.46	5.60	-.06
9	Burgett	8,210	1D, 4R/2R	-.69	3.28	-.29
10	Schmidt-C	7,500	1.25D, 2R	-.73	3.00	-.33

*The SAE design guide indicates that the maximum in Zone I (with corners 0.5D, 0.5R; 0.5D, 2.5R; 2D, 2.5R; 2D, 0.5R) shall met or exceed 15,000 cd.

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 at the same level–6.4 lux–as in the above analysis for delineation on a hill.

Findings. Table 25 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). Four of the 10 standards met or exceeded this performance criterion.

Table 25. 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	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 50 m	Δlog lux from 6.4
1	Burgett	36,310	0.25D, 3R/1.75R	0	14.52	+.36
2	SAE*	30,000	0.5D, 2R	-.08	12.00	+.27
3	FMVSS	20,000	0.5D, 1.5R	-.26	8.00	+.10
4	Kosmatka	16,000	0.5D, 1.5R	-.36	6.40	0
5	Schmidt-C	7,500	0.75D, 2R	-.68	3.00	-.33
6.5	JIS	6,000	0.5D, 2R	-.78	2.40	-.43
6.5	Padmos	6,000	0.25D, 2R	-.78	2.40	-.43
8	ECE	3,750	0.75D, 2R	-.99	1.50	-.63
9	Taniguchi	2,800	H, 2R	-1.11	1.12	-.76
10	VEDILIS	?	no nearby test point	N.A.	N.A.	N.A.

*The SAE design guide indicates that the maximum in Zone I (with corners 0.5D, 0.5R; 0.5D, 2.5R; 2D, 2.5R; 2D, 0.5R) shall met or exceed 15,000 cd.

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 at the same level–33 lux–as in the above analysis for a target at 75 m.

Findings. Table 26 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 10 standards met this performance criterion level; the strongest (Taniguchi et al.) at 17.12 lux falls 0.29 log units short of the criterion.

Table 26. 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	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best	lux @ 25 m	Δlog lux from 33
1	Taniguchi	10,700	0.75D, 4R	0	17.12	-.29
2.5	Schmidt-C	7,500	1.25D, 3.75R	-.15	12.00	-.44
2.5	VEDILIS	7,500	0.75D, 3.75R	-.15	12.00	-.44
4	Padmos	6,000	1.25D, 3.75R	-.25	9.60	-.54
5.5	SAE	3,750	1.25D, 3.75R	-.46	6.00	-.74
5.5	ECE	3,750	1.25D, 3.75R	-.46	6.00	-.74
7	Burgett	1,420	1.75D, 5.25R/1.75R	-.88	2.27	-1.16
9	FMVSS	?	no nearby test point	N.A.	N.A.	N.A.
9	JIS	?	no nearby test point	N.A.	N.A.	N.A.
9	Kosmatka	?	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, so that we could estimate the likely illumination. In the standards under review, however, 1.25D, 3.75R was controlled only by specifying minima, and 1.25D, V was not controlled by any of the standards. 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. 48 and 49). 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. Table 27 ranks all standards in terms of the increasing combined luminous intensity from both lamps directed towards 2.25D, 2L. 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).

Table 27. Illumination prone to be reflected from wet pavement towards an oncoming driver (2D, 3.5L).

1	2	3	4	5
Rank	Author(s)	cd (both lamps)	Nearest controlled point	Δlog cd from the best
1	Padmos*	20,000	2.25D, 3.5L	0
2	ECE**	30,000	2D, 3.5L	+.18
3	VEDILIS	37,500	1.75D, 3.5L	+.27
7	FMVSS	?	no nearby test point	N.A.
7	JIS	?	no nearby test point	N.A.
7	Burgett	?	no nearby maximum	N.A.
7	Kosmatka	?	no nearby test point	N.A.
7	SAE	?	no nearby maximum	N.A.
7	Schmidt-C***	?	no nearby maximum	N.A.
7	Taniguchi	?	no nearby test point	N.A.

*Padmos and Alferdinck call for zone Ib (with corners 2.25D, 15L; 2.25D, 15R; 4.24D, 15R; and 4.25D, 15L to have a maximum that is one fifth of the actual value at 0.5D, 1.25R, which, in turn, has a minimum of 50,000 cd per lamp.

**The ECE specification calls for zone I (1.75D to D) to have a maximum equal to twice the actual value of 0.75D, 1.75R, which, in turn, is controlled only by specifying a minimum (7,500 cd per lamp).

***The proposal by Schmidt-Clausen calls for zone I (1.75D to D) to have a maximum that is equal to 1.5 times the actual value of 0.75D, 1.75R. However, 0.75D, 1.75R is not explicitly controlled.

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 28 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 minima.

Table 28. The extent of lateral spread.

1	2	3	4
Rank	Author(s)	Widest controlled point(s)	cd (both lamps)
1	VEDILIS	30L (4.25D)	620
		30R(4.25D)	250
2	Kosmatka	20L/20R(2D)	800
3	SAE	20L/20R(4D)	600
4	Padmos	15L(0.5D - 1.75D)	6,000
		15R(H - 1.75D)	6,000
5	Schmidt-C	15L/15R(1.75D)	2,500
6	FMVSS	15L/15R(1.75D)	1,700
7	JIS	15L/15R(2D)	800
8	Taniguchi	9L(1.5D)	4,000
		11R(1.5D)	2,300
9	ECE	9L/9R(1.75D)	2,500
10	Burgett	5.5L/9L(1.75D)	2,350
		9R/5.5R(1.75D)	1,570

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 29 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). The variation of seeing-to-glare ratios covers a range of 55.6:1 or 1.75 log units. From the standpoint of visibility, the highest ratios are most desirable because they indicate high visibility with low glare to oncoming drivers.

Table 29. Ratio of seeing illumination (0.5D, 1.25R) and glare illumination (0.5U, 3.5L).

1	2	3	4	5	6
Rank	Author(s)	Ratio	Nearest controlled points	Δlog cd	Δlog ratio from the best
1	Padmos	100.0:1	see Tables 22 and 19	2.00	0
2	Schmidt-C	50.0:1	see Tables 22 and 19	1.70	-.30
3	ECE	30.0:1	see Tables 22 and 19	1.48	-.52
4	VEDILIS	20.0:1	see Tables 22 and 19	1.30	-.70
5	Burgett	19.1:1	see Tables 22 and 19	1.28	-.72
6	Taniguchi	12.7:1	see Tables 22 and 19	1.10	-.90
7	Kosmatka	11.4:1	see Tables 22 and 19	1.06	-.94
8	SAE	10.7:1	see Tables 22 and 19	1.03	-.97
9	FMVSS	10.0:1	see Tables 22 and 19	1.00	-1.00
*	de Brabander	8.0:1	**	0.90	-1.10
10	JIS	1.8:1	see Tables 22 and 19	0.26	-1.74

*Because of the nature of the Belgian standard that is described by de Brabander, we could not included it in any of the previous ranking tables. For consistency, therefore, we have decided not to assign it an explicit rank in this table either.

**The Belgian standard that is described by de Brabander specifies that the maximum of either the U.S. hot spot (1.5D, 2R) or the line between ECE points 50R (0.75D, 1.75R) and 75R (0,5D, 1.25R) needs to be at least eight times the maximum in the left glare zone (above horizontal and to the left of 1.75L).

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: (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 30. The computed gradients ranged from 56% to about 1%.

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 ratio of seeing illumination to glare illumination. Consequently, the *inverse* of the ranking in Table 30 represents our best prediction concerning the effects of misaim.

Table 30. Gradient to the right of vertical.

1	2	3	4	5	6	7
Rank	Author(s)	Minimum cd below horizontal (controlled point)	Maximum cd above horizontal (controlled point)	Vertical distance (°) between points in 3 and 4	Ratio of columns 3 and 4	Gradient (%)
1	Schmidt-Clausen	12,500 (0.5D, 1.25R)	440 (0.25U, 1.25R)	.75	28.4	56
2	Padmos	50,000 (0.5D, 1.25R)	1,000 (0.5U, 1.25R)	1.00	50.0	48
3	ECE*	7,500 (0.5D, 1.25R)	440 (0.25U, 1.25R)	.75	17.0	46
4	Burgett	18,155 (0.25D, 3R/1.75R)	600 (1U, 3.75R/0.5R)	1.25	30.3	31
5	VEDILIS	10,000 (0.5D, 1.25R)	810 (0.5U, 1.25R)	1.00	12.3	29
6	Kosmatka	8,000 (0.5D, 1.5R)	1,800 (0.5U, 1.5R)	1.00	4.4	16
7	FMVSS	10,000 (0.5D, 1.5R)	2,700 (0.5U, 1.5R)	1.00	3.7	14
8	SAE	8,000 (0.5D, 1.5R)	2,400 (0.5U, 1.25R)	1.00	3.3	13
9	JIS	3,000 (0.5D, 2R)	2,800 (0.5U, 2R)	1.00	1.1	1
10	Taniguchi	7,000 (0.75D, 2R)	**	?	?	?

*ECE allows two different types of cutoff (see p. 6). The present calculations in this table are for the continuously inclining cutoff; for the horizontal cutoff, the resulting gradient is 40%.

**Taniguchi does not specify maxima for any points above horizontal and to the right of vertical.

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-prism and electrochromic 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 required maximum (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. These functions include light scatter in adverse weather (fog, rain, and snow), light reflected from wet pavement, relation between seeing and glare illuminance, lateral spread, visual aim, effects of misaim, and homogeneity of the beam.

Because a single comparative summary of the performance of the various standards cannot be fully justified on objective research and unquestionable functional weightings, we present four different approaches to characterize the strengths and weaknesses of the different standards: (1) performance scaled relative to criteria for each of the identified visual performance functions, (2) performance scaled relative to the best of the standards under review for each individual visual performance function, (3) ordinal rankings of the standards on each of the identified visual performance functions, and (4) comparison of the standards solely with regard to seeing versus glare performance.

Performance relative to criteria for each visual performance function

Figure 7 presents a profile of each of the standards on the visual performance functions for which we were able to determine criterion values. It presents the results of our analysis on a log scale depicting the scores of each standard relative to eight of the 15 visual performance functions. The performance criteria for each function are set at zero; positive scores indicate that the standard exceeds or "outperforms" the relevant criterion (below the maximum for glare; above the minimum for visibility). The values in Figure 7 are based on entries in Tables 17 through 28, with the sign reversed for glare functions so that for *all* scores a positive difference in Figure 7 implies that the given standard performs better than the criterion value.

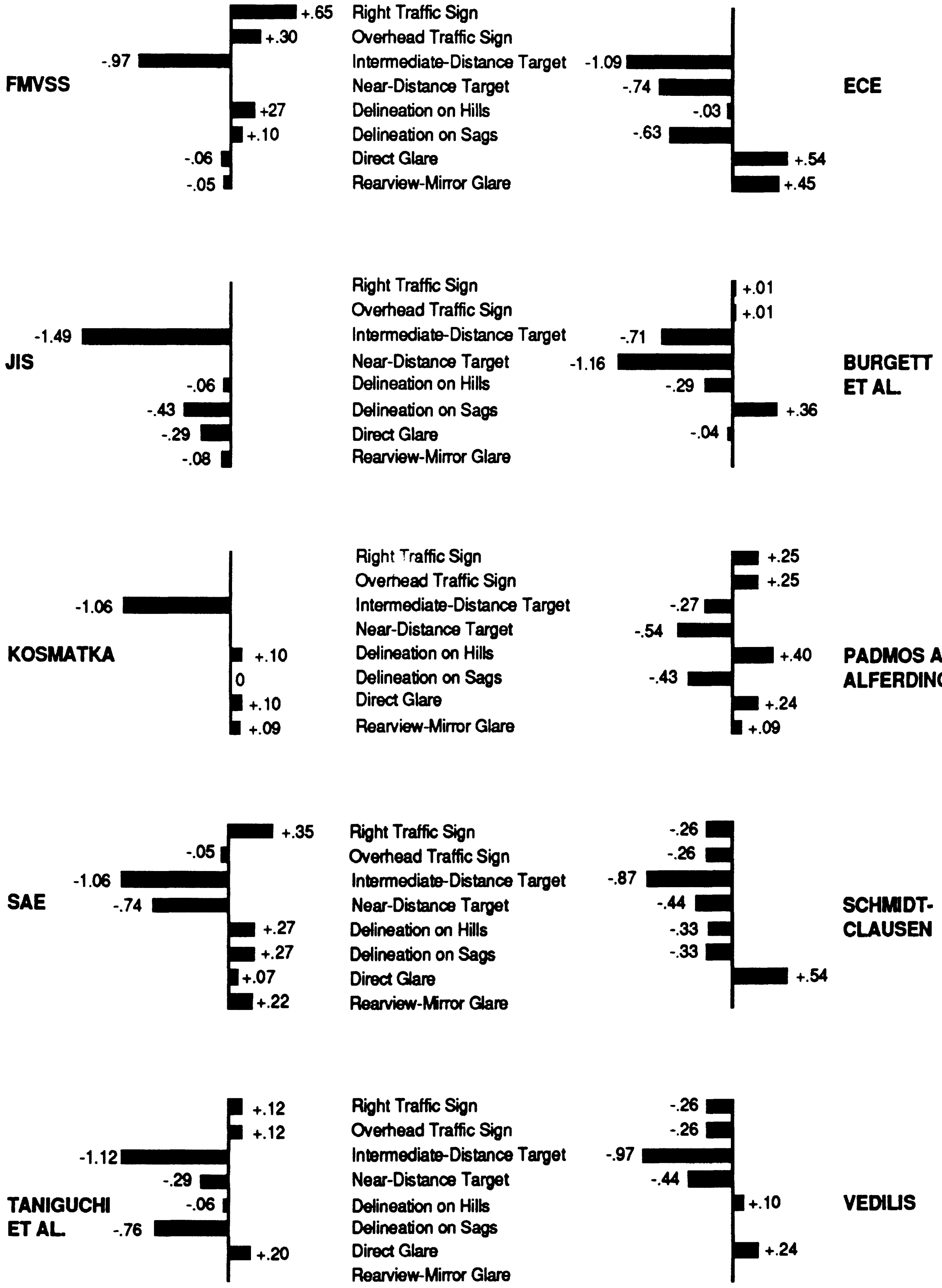

Figure 7. Log differences between the criterion illuminances and the corresponding minima or maxima in the different standards. No entry indicates that the standard did not include a relevant limitation.

The main feature of the data in Figure 7 is that none of the standards met the criterion values for seeing low-contrast targets at either 75 m or 25 m. For the distance of 75 m, the proposal by Padmos and Alferdinck comes closest, while for the distance of 25 m, it is the proposal by Taniguchi et al. Furthermore, the situation for longer target distances, such as 100 m, is even worse. This is the case because (a) no more light is called for by any of the standards for test points near 0.25D, 1R (corresponding to right-side target at 100 m) than for 0.5D, 1.25R (corresponding to right-side target at 75 m), and (b) as the distance increases, a given luminous intensity results in less illuminance impinging on the target. To the extent that at current legal speeds 75 m is too short a distance either to stop (Olson, Cleveland, Fancher, Kostyniuk, and Schneider, 1984) or to maneuver (Padmos and Alferdinck, 1988) to avoid an unexpected low-contrast obstacle, the actual state of affairs is worse than the present analysis suggests.

For more than 50 years, traffic safety specialists have lamented the fact that motorists routinely "overdrive" their low-beam headlights at night (Roper and Howard, 1938; Johansson and Rumar, 1968; Olson and Sivak, 1983; Leibowitz, Owens, and Tyrrell, 1992). For example, Johansson and Rumar (1968) estimated that the maximum safe speeds are between 25km/h and 50 km/h (depending on conditions), while Leibowitz et al. (1992) estimated the maximum safe speed to be 32 km/h. It seems unlikely that any industrialized society is prepared to limit nighttime traffic speeds so drastically.

Padmos and Alferdinck (1988) summarized the situation well by stating that "without permanent road lighting a pedestrian on the road is not sufficiently visible to a motorist [using low beams], unless the pedestrian wears retroreflectors of sufficient quality" (p. 16). Another possibility would be to raise the maximum standards as far as practicable in the region of interest. The tradeoff between seeing distance and glare is an unavoidable concern here. As shown in Tables 19 and 22, the standards under review take a wide range of positions with respect to this tradeoff. While none of the standards met the criterion illuminance for seeing, several called for less illumination than the criterion illuminance for discomfort glare.

The present study did not aim to derive new guidelines or standards, and it avoided technical aspects of headlight design. Nevertheless, it seems appropriate to point out that limitations of visibility, of varying degrees of seriousness, are inherent in all standards under review, and to recommend that this problem merits high priority for discussion as we approach global harmonization of headlight design.

Performance relative to the best of the considered standards on each individual visual performance functions

Figure 8 compares the illuminances of all standards for 10 of the 15 visual performance functions. In this case, each score is scaled relative to the "best" standard reviewed. The "best" of the examined standards is set at zero in Figure 8. It was defined as that standards that had the greatest maximum for a seeing function, and the lowest minimum for a glare function. Because the analysis in Figure 8 is independent of the criterion values at the selected test points, this analysis includes two more functions than shown in Figure 7, fog, rain, and snow scatter, and wet-road reflection. Specifically, Figure 8 includes three functions (fog, rain, and snow scatter, wet-road reflection, and seeing/glare ratio) that were not included in Figure 7 because of the lack of empirical support for criterion values. There are no positive entries in Figure 8 because "best" equals zero. For seeing functions, a negative entry indicates that the standard in question allows a lower minimum than the best standard; conversely, for glare functions, a negative entry indicates that the standard in question allows a higher maximum than the best standard.

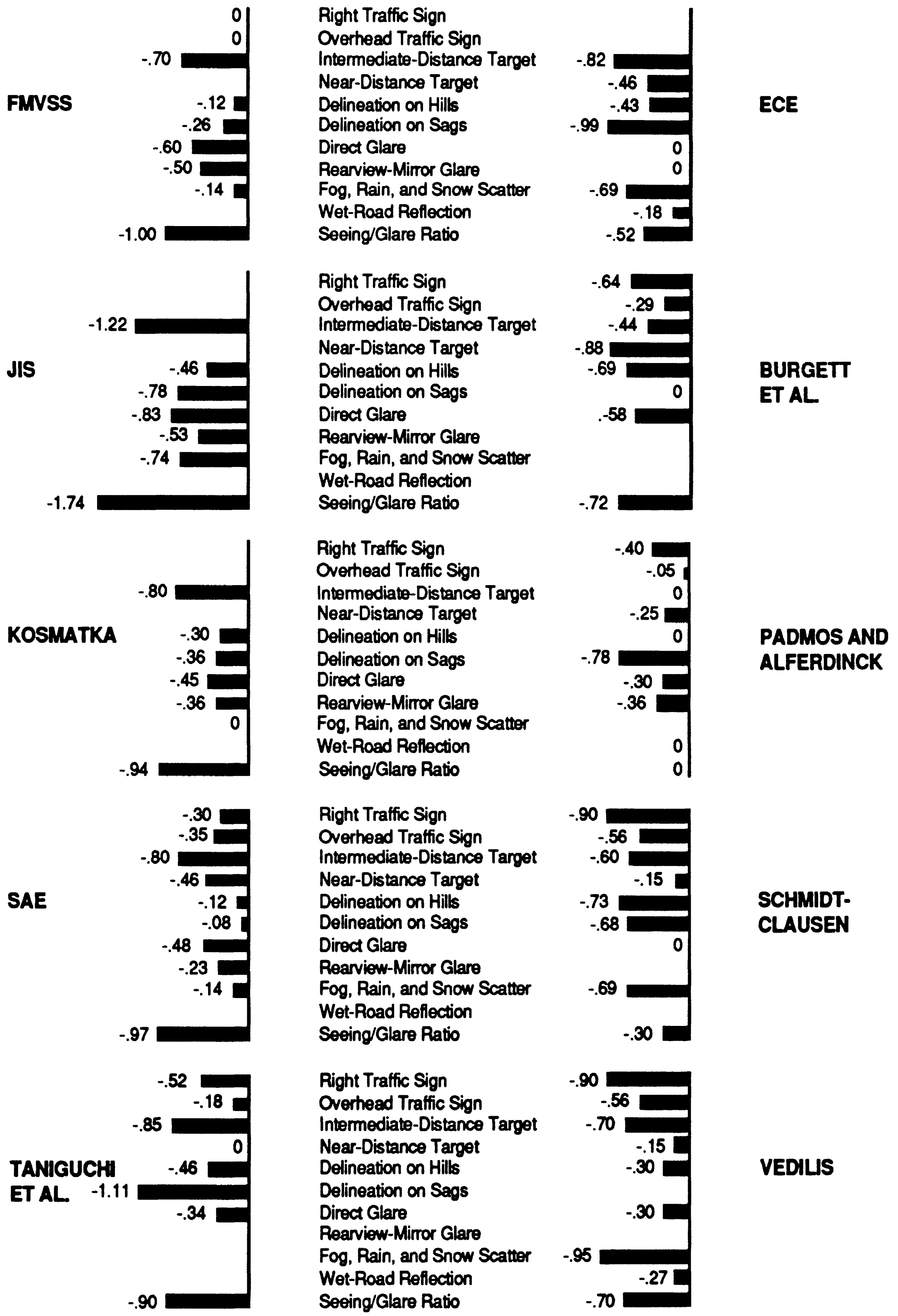

Figure 8. Log differences between the illuminances provided by the best standards and the corresponding minima or maxima in the different standards. No entry indicates that the standard did not include a relevant limitation.

Table 31 lists, for each visual performance function, the best standard and (if available) the log range across all considered standards. The information in Table 31 indicates that all but two standards (SAE and Taniguchi) scored highest on at least one visual performance function. Padmos and Alferdinck's standard scored highest on most functions—four.

Table 31. Best standards and ranges of log illuminance for each visual performance function.

Function	Best standard	Range of log illuminances for all standards
Intermediate-distance targets	Padmos and Alferdinck	1.22
Near-distance targets	Taniguchi	.87
Delineation on hills	Padmos and Alferdinck	.73
Delineation on sags	Burgett	1.12
Lateral spread	VEDILIS	?
Right traffic sign	FMVSS	.91
Overhead traffic sign	FMVSS	.56
Direct glare	ECE and Schmidt-Clausen	.83
Rearview-mirror glare	ECE	.53
Fog, rain, and snow scatter	Kosmatka	.95
Wet-road reflection	Padmos and Alferdinck	.27
Seeing vs. glare ratio	Padmos and Alferdinck	1.74
Reliability of visual aim	Schmidt-Clausen	?
Effects of misaim	Taniguchi	?

The choice of the standards might be especially important for a function with a wide range of illuminances across different standards. From this point of view, the proposal by Padmos and Alferdinck scored highest on the function with the greatest range of illuminance values across the considered standards—seeing/glare ratio. (The ranges of the log illuminance values for the visual performance functions were from .27 for seeing/glare ratio [with only three standards providing relevant values] to 1.74 for intermediate-distance targets.)

Rankings on the individual visual performance functions

Table 32 lists the ordinal rankings of the standards for the individual visual performance functions from Tables 17 through 28. The functions were ordered in such a way that visibility functions are listed first, followed by glare functions, seeing-to-glare ratio, visual aim, and effects of misaim. (The inverse of the ranking of the reliability of visual aiming [Table 30] was used to estimate effects of misaim.) Table 32 contains information for 14 out of the 15 considered visual performance functions (for homogeneity of the beam we were unable to develop a ranking). Table 33 lists the visual performance functions on which the individual standards scored (or tied) among the top or bottom two standards.

Table 32. Rankings of the standards on the individual visual performance functions in Tables 17 through 28.

	Visual performance function													
Author(s)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV
FMVSS	4.5	9	2.5	3	6	1	1	9	5	2.5	7	9	7	4
ECE	8	5.5	6	8	9	9	9	1.5	1	4.5	2	3	3	8
JIS	10	9	7.5	6.5	7	9	9	10	6	6	7	10	9	2
Burgett et al.	2	7	9	1	10	5	4	8	8.5	9	7	5	4	7
Kosmatka	6.5	9	4.5	4	2	9	9	6	3.5	1	7	7	6	5
Padmos and Alferdinck	1	4	1	6.5	4	3	2	3.5	3.5	9	1	1	2	9
SAE	6.5	5.5	2.5	2	3	2	5	7	2	2.5	7	8	8	3
Schmidt-Clausen	3	2.5	10	5	5	6.5	6.5	1.5	8.5	4.5	7	2	1	10
Taniguchi	9	1	7.5	9	8	4	3	5	8.5	9	7	6	10	1
VEDILIS	4.5	2.5	4.5	10	1	6.5	6.5	3.5	8.5	7	3	4	5	6

I	Intermediate-distance targets
II	Near-distance targets
III	Delineation on hills
IV	Delineation on sags
V	Lateral spread
VI	Right traffic signs
VII	Overhead traffic signs
VIII	Direct glare
IX	Rearview-mirror glare
X	Fog, rain, and snow scatter
XI	Wet-road reflection
XII	Seeing-to-glare ratio
XIII	Visual aiming
XIV	Effects of misaim

Table 33. Visual performance functions on which the individual standards scored (or tied) among the top two or bottom two. The entries with asterisks indicate that the standard scored among the bottom two not because of its photometric recommendations, but because there were no nearby controlled test points.

Author(s)	Among the top two rankings	Among the bottom two rankings
FMVSS	Delineation on hills Right traffic signs Overhead traffic signs Fog, rain, and snow scatter	Near-distance targets* Direct glare Seeing-to-glare ratio
ECE	Direct glare Rearview-mirror glare Wet-road reflection	Lateral spread Right traffic signs* Overhead traffic signs*
JIS		Intermediate-distance targets Near-distance targets* Right traffic signs* Overhead traffic signs* Direct glare Seeing-to-glare ratio Visual aiming
Burgett et al.	Intermediate-distance targets Delineation on sags	Delineation on hills Lateral spread Rearview-mirror glare* Fog, rain, and snow scatter*
Kosmatka	Lateral spread Fog, rain, and snow scatter	Near-distance targets* Right traffic signs* Overhead traffic signs*
Padmos and Alferdinck	Intermediate-distance targets Delineation on hills Overhead traffic signs Wet-road reflection Seeing-to-glare ratio Visual aiming	Fog, rain, and snow scatter* Effects of misaim
SAE	Delineation on sags Delineation on hills Right traffic signs Rearview-mirror glare Fog, rain, and snow scatter	
Schmidt-Clausen	Near-distance targets Direct glare Seeing-to-glare ratio Visual aiming	Delineation on hills Rearview-mirror glare* Effects of misaim
Taniguchi	Near-distance targets Effects of misaim	Intermediate-distance targets Delineation on sags Rearview-mirror glare* Fog, rain, and snow scatter* Visual aiming*
VEDILIS	Near-distance targets Lateral spread	Delineation on sags* Rearview-mirror glare*

Table 34 presents the standards in the increasing order of the mean ordinal rankings on the individual visual performance functions (means of the entries in Table 32). The best mean ranking for Padmos and Alferdinck's proposal is consistent with the fact that this standard scored highest on four individual visual performance functions (see Table 32). The second best mean ranking was for the SAE proposal, consistent with the finding that this proposal did not rank among the bottom two on any of the visual performance functions (see Table 33).

Table 34. Mean ranking of the standards on the individual visual performance functions.

Author(s)	Mean ranking
Padmos and Alferdinck	3.61
SAE	4.57
FMVSS	5.03
VEDILIS	5.18
Schmidt-Clausen	5.21
ECE	5.54
Kosmatka	5.68
Burgett et al.	6.18
Taniguchi et al.	6.29
JIS	7.71

Using mean ordinal rankings is somewhat arbitrary because, as discussed above, the 15 visual performance functions are not equally important. For example, target visibility is more important than visual-aiming capability. However, there is no consensus on the appropriate weights. Furthermore, deficiencies on certain functions can be remedied by redesign of the vehicle or the roadway. For example, negative consequences of misaim can be reduced by automatic leveling systems, problems with rearview-mirror glare can be dealt with by using electrochromic rearview mirrors, and reflection from wet pavement can be minimized by road surfaces with good draining properties.

Seeing performance vs. glare protection

Seeing and glare are widely viewed as the functions most critical for safety. Consequently, it is not surprising that all of the standards explicitly set photometric minima for seeing performance, and photometric maxima for glare protection. However, only the current Belgian standard (described by de Brabander) directly controls the relation between seeing illumination and glare illumination. We feel that this is an innovative approach, worthy of serious consideration. Therefore, as described above, we computed the ratio of seeing illumination (at 0.5D, 1.25R) and glare illumination (at 0.5U, 3.5L) for the of the standards (see Table 29). The higher this ratio, the better the beam pattern. This ratio varies from 100:1 for Padmos and Alferdinck to 1.8:1 for JIS.

CONCLUSIONS

The aim of this study was to examine several recent proposals for the low-beam headlighting pattern. The analyses did not take into account the technical feasibility of the proposals, but rather focused on the characteristics of all existing standards and proposals for visual performance. Thus, the work here emphasizes human factors rather than technological implementation. The research consisted of (1) documenting the current U.S., European, and Japanese standards as well as the proposals in a common tabular format, (2) performing a comparative analysis of the standards and proposed beam patterns, (3) developing a set of 15 visual performance functions for low-beam patterns, (4) defining the relevant geometry for the visual performance functions, (5) setting criterion illuminance values based on available empirical data, and (6) evaluating the standards and proposals in relation to the criterion values by considering the worst allowed case (i.e., using the specified minima for seeing functions, and the specified maxima for glare visual performance functions). Table 35 lists the considered visual performance functions, the relevant geometries, and the criterion illuminance values.

Table 35. The considered visual performance functions, the relevant geometries, and the criterion illuminances.

Visual performance function	Relevant geometry	Criterion illuminance (lux) Minimum	 Maximum
Intermediate-distance targets	0.5D, 1.25R	33.0	
Near-distance targets	1.25D, 3.75R	33.0	
Delineation on hills	1.25D, 2R	6.4	
Delineation on sags	0.25D, 2R	6.4	
Lateral spread	?	?	
Right traffic signs	0.5U, 2.25R	0.02	
Overhead traffic signs	2U, V	0.02	
Direct glare	0.5U, 3.5L		0.7
Rearview-mirror glare	1.25U, 8.25R		11.0
Fog, rain, and snow scatter	10U, V		?
Wet-road reflection	2D, 3.5L		?
Seeing-to-glare ratio	0.5D, 1.25R vs. 0.5U, 3.5L	?	
Visual aiming	N.A.		
Effects of misaim	N.A.		
Homogeneity of the beam	1.25D, 3.75R vs. 1.25D, V	N.A.	N.A.

The main findings of this study are as follows:

- There is a lack of empirical evidence for data-based criteria to evaluate the proposals on some of the visual performance functions. These functions include light scatter in adverse weather (fog, rain, and snow), light reflected from wet pavement, relation between seeing and glare illuminance, lateral spread, visual aim, effects of misaim, and homogeneity of the beam.
- Since the functional requirements of low beams are multifaceted and complex, it is not surprising that each proposal or standard has its advantages and disadvantages.
- In terms of visibility, none of the proposals or existing standards met our criterion of 33 lux that is necessary for seeing low-contrast targets (like pedestrians) on the right side of the road. This was the case not only for the selected intermediate distance (75 m) but also for the selected near distance (25 m). This is consistent with the long-standing conclusion that we often overdrive our low beam headlamps.
- The choice of an optimal standard is likely to be especially important for a visual performance function that exhibits a wide range of values across different standards. In our analysis the two functions with the widest range of values across different standards were seeing-to-glare ratio and visibility of intermediate-distance targets on the right side of the roadway. The proposal by Padmos and Alferdinck scored highest on both of these functions.
- The relation between seeing illuminance and glare illuminance is likely to capture a substantial part of the functional requirements of low beams. This relation can be quantified, for example, by ratio of log illuminances of these two values. Currently, only the innovative Belgian standard (described by de Brabander) directly controls such ratios. The largest ratio is called for by Padmos and Alferdinck (100:1), followed by Schmidt-Clausen (50:1).
- The proposal by Padmos and Alferdinck (explicitly designed to optimize European-type low beam) had the best mean ranking across the individual functions. The SAE proposal (based on the current U.S.-type beam, but implicitly designed to bridge the gap between the U.S. and European beams) had the second best mean ranking.

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