PARTIAL HARMONIZATION OF INTERNATIONAL STANDARDS FOR LOW-BEAM HEADLIGHTING PATTERNS

Michael Sivak
Michael J. Flannagan

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

Report No. UMTRI-93-11
March 1993

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
UMTRI-93-11		

4. Title and Subtitle
Partial Harmonization of International Standards for Low-Beam Headlighting Patterns

5. Report Date
March 1993

6. Performing Organization Code
390903

7. Author(s)
Michael Sivak and Michael J. Flannagan

8. Performing Organization Report No.
UMTRI-93-11

9. Performing Organization Name and Address
The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150 U.S.A.

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Japan Automobile Standards Internationalization Center
2-6-13 Akasaka, Minato-ku
Tokyo 107, Japan

13. Type of Report and Period Covered
Final Report
April 1, 1992 - March 31, 1993

14. Sponsoring Agency Code

15. Supplementary Notes
Additional gift support for this research was received from Carello Lighting, American Automobile Manufacturers Association (AAMA), International Organization of Motor Vehicle Manufacturers (OICA), and the Swedish Road and Traffic Research Institute (VTI).

16. Abstract
This research was designed to determine a small set of low-beam test points for recommendation as common test points throughout the world. Our recommendation is a compromise among the following three set of inputs: (1) expert opinion, based on a worldwide survey of 119 experts in lighting and vision, (2) current practice, based on an analysis of candela matrices of 150 production low beams, and (3) scientific evidence concerning visibility and glare under nighttime driving conditions.

Expert opinion and scientific evidence did not fully converge on the same test points, with the main difference being in the amount of light recommended for points at which objects need to be seen. While experts suggested light levels comparable to current production outputs, the recommendations based exclusively on scientific evidence would call for light levels of more than ten times the current levels. Therefore, the test points based exclusively on scientific evidence should be viewed only as ideal test points, but we should aim in the future to explore technologies that would make approximations to these test points feasible.

Our compromise recommendation calls for four test points, and it takes into account different test voltages throughout the world. If the proposed set of test points for partial harmonization meet with acceptance, extending this approach to determining additional test points for full harmonization should be considered.

17. Key Words	18. Distribution Statement
Headlamps, headlighting, low beams, dipped beams, international harmonization, standards, visibility, glare, nighttime	Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	49	

ACKNOWLEDGMENTS

This research was performed under contract between the University of Michigan and the Japan Automobile Standards Internationalization Center (JASIC), with the Groupe de Travail "Bruxelles 1952" (GTB) Coordinating Committee acting as an advisory body. Additional gift support for this research was received from Carello Lighting, American Automobile Manufacturers Association (AAMA), International Organization of Motor Vehicle Manufacturers (OICA), and the Swedish Road and Traffic Research Institute (VTI). The support of all these organizations is sincerely appreciated.

Special thanks go to

- our colleagues Takashi Sato, Dennis Battle, and Eric Traube for assistance with various phases of this research;
- Mr. Takeshi Kimura, General Manager and Director of Research Division at JASIC, for advocating the need for this type of research and for arranging this research project;
- Dr. David Moore, chairman of the GTB Coordinating Committee, for his general assistance;
- Mr. Kiyokazu Yokoi, from the Japan Automobile Research Institute, for providing photometric information on 107 European and Japanese low beams;
- the 119 experts who completed the survey;
- GE Lighting, II Stanley, and Inland Fisher Guide Division of General Motors for obtaining photometric information for five low beams each; and
- National Highway Traffic Safety Administration (NHTSA) for allowing us to use photometric information on 28 low beams that was originally obtained by II Stanley under contract between the University of Michigan and NHTSA.

On October 27, 1992, an ad hoc working group met in San Diego (in conjunction with a GTB meeting) to discuss this research project. In addition to the authors, this group included the following persons: Mr. Johan Alferdinck (TNO Institute for Perception), Mr. Kenichi Ando (Japan External Trade Organization), Dr. Louis de Brabander (Belgian Road Safety Institute), Mr. Takeshi Kimura (JASIC), Mr. Gerald Meekel (The Netherlands Department of Road Transport), Dr. David Moore (GTB Coordinating Committee), Mr. Masahiko Naito (JASIC), Mr. Robert Rendu (UTAC), Dr. Kare Rumar (Swedish Road and Traffic Research Institute), Prof. Hans-Joachim Schmidt-Clausen (Technical University of Darmstadt), and Mr. Kiyokazu Yokoi (Japan Automobile Research Institute). Constructive comments provided by these persons are sincerely appreciated.

The research and the recommendation presented in this report do not necessarily represent the views of any of the individuals or organizations listed above. The authors are solely responsible for the content of this report.

CONTENTS

GOAL

The goal of this research was to identify a small number (preferably three) of the most important low-beam test point locations for safety and their accompanying photometric values. Whenever possible, the existing test points in the U.S. and European standards were to be considered first. These test points were then to be recommended for incorporation into the U.S., European, and Japanese specifications. If these common test points were not sufficient to cover the requirements in a particular jurisdiction, additional points might be added.

BACKGROUND

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 inherent in low-beam headlighting. The European approach differs from the U.S. approach primarily in a greater emphasis on protecting oncoming drivers from glare, and in the ease of aiming the headlamp beam visually (relying on the perceptual judgment of the lamp aimer). Consequently, the European low beam has (1) a sharper transition (cutoff) between where the light is needed for seeing and where it might impinge on the eyes of oncoming drivers, and (2) less light above horizontal. 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). (In Japan, low beams have either the U.S.-type pattern [the so-called SAE-J lamps], or the European-type pattern [the so-called ECE-J lamps].)

In the absence of a clear safety advantage of one system over another, there is a strong impetus to "eliminate the necessity for redundant designs and tests which burden manufacturers and customers without commensurate gain in safety value" (Donohue, LeFevre, and Watkins, 1992, p. 1). International harmonization of lighting (and other) standards would benefit small as well as large exporters. Indeed, because the costs involved in redesign, retooling, and testing are relatively constant regardless of the volume of export, the per vehicle expenses *increase* with a decrease in the number of vehicles involved.

This research was envisioned as a realistic first step towards full harmonization of low-beam standards. It was considered important that the recommendations contain only a limited number of test points to minimize the impact in this first phase of harmonization. Thus, we were asked to recommend, preferably, three test points. For reasons discussed in this report, we ended up recommending four test points.

APPROACH

The research considered three types of input (see Table 1). The first type of input was expert opinion, based on a worldwide survey of experts concerning the location and photometric limits for the most important test points. The second type of input was current practice, based on an analysis of photometric beam patterns of 150 low beams that were manufactured for sale in the U.S.A., Europe, and Japan. The third type of input was scientific evidence concerning visibility and glare in nighttime driving.

Table 1

Input to the final recommendation.

Input	Type of input
1	Expert opinion
2	Current practice
3	Scientific evidence

The U.S. and the Japanese standards call for photometry to be performed at 12.8 V. In contrast, the European standard requires the use of a voltage at which the tested lamp produces 750 lm. This is usually achieved at approximately 12 V. Furthermore, the operating voltage of modern cars is frequently between 13 and 14 V. Because light output is dependent on voltage, in the discussion to follow we will assume the voltages and the corresponding light-output correction factors that are listed in Table 2.

Table 2

Assumed voltages and light-output correction factors (adapted from Bergin, 1992).

Condition	Voltage	Light-output correction factor
In-traffic in the U.S., Europe, and Japan	13.5	1.3
Photometry in the U.S. and Japan	12.8	1.0
Photometry in Europe	12.0	0.81

EXPERT OPINION

Questionnaire

The questionnaire consisted of three background questions (affiliation, years of experience, and country), two primary questions, and a question soliciting unstructured comments. The first primary question (see Figure 1) asked for rating of the importance of 16 visual-performance functions that we felt covered the main functions of the low beam. This approach is an extension of the one that we used in a recent study evaluating proposed low-beam standards (Sivak, Helmers, Owens, and Flannagan, 1992). The second primary question (see Figure 2) asked respondents to select representative angular coordinates for the three most important visual-performance functions and the associated photometric limits.

Respondents

A written questionnaire was mailed to 170 experts in headlighting and vision. All members of the following groups were contacted:

- Commission Internationale de l'Eclairage (CIE) TC 4-10
- Commission Internationale de l'Eclairage (CIE) TC 4-22
- Groupe de Travail "Bruxelles 1952" (GTB) Coordinating Committee
- Groupe de Travail "Bruxelles 1952" (GTB) Harmonization Working Group
- American Automobile Manufacturers Association (AAMA) Vehicle Lighting Task Group
- volunteers from the May 1992 Society of Automobile Engineers (SAE) Lighting Committee Meeting in Nashville

Additionally, the questionnaire was sent to our contacts in the areas of lighting and visibility. Table 3 presents a tabulation by country of persons who were contacted and those who responded. Table 4 presents an analogous tabulation by continents. Tables 5 and 6 list the primary affiliations of the respondents and years of experience in lighting/visibility, respectively.

Listed below are 16 main visual-performance functions of low-beam headlamps. Please rate the importance of each of these functions by allocating a total of 160 points among them. Each function should be allocated between 0 and 160 points.

Here are four examples of how you can allocate the points:

- If you feel that all 16 functions are equally important, allocate each function 10 points.
- If you feel that four particular functions are the only important ones, and they are all equally important, allocate each of the four functions 40 points.
- If you feel that two particular functions are the only important ones, and one is three times as important as the other one, assign the more important 120 points and the less important 40 points.
- Finally, if you feel that only one function is important, allocate this function all 160 points.

Please note that these are only **examples**, and that you are free to allocate the points any way you choose, as long as you allocate all 160 points. (We understand that headlighting is an extremely complex field, but to make some progress certain simplifications have to be made. Consequently, while you might not fully agree with the format of this and the next question, we would appreciate your cooperation. The last question in this survey will give you an opportunity for unstructured comments.)

______illumination towards retroreflective traffic signs on the right shoulder

______illumination towards retroreflective overhead traffic signs

______glare illumination towards oncoming traffic

______glare illumination towards traffic via rearview mirrors

______illumination prone to scatter in adverse atmospheric conditions (fog, rain, and snow)

______illumination towards targets on the right side of the road

______illumination towards targets on the left side of the road

______foreground illumination

______illumination for performance on hills

______illumination for performance on sags

______homogeneity (uniformity) of the beam

______illumination prone to glare reflection from wet pavement

______lateral spread

______ratio of seeing illumination and glare illumination, independent of the absolute values

______reliability of visual aiming

______general sensitivity to misaim

Figure 1. The first primary question in the survey of experts.

For each of the three visual-performance functions for which you assigned the most points on the previous page, please define (1) the appropriate angular coordinates for a representative situation (in relation to the headlamp axes, and assuming right-hand traffic), and (2) the recommended photometric limits (maximum and/or minimum cd from each headlamp, assuming a two-lamp system).

For certain functions it might not be easy or even possible to come up with appropriate angular coordinates. Therefore, it might be possible that among the three functions with most points there are functions for which you are unable to assign appropriate angular coordinates. If that is the case, please use the three functions with the most points for which you *can* assign appropriate angular coordinates.

Visual-Performance Function	x coordinate (in degrees right or left)	y coordinate (in degrees up or down)	Minimum (cd)	Maximum (cd)

Figure 2. The second primary question in the survey of experts.

Table 3

Distributions of experts who were contacted and those who responded by country.

Country	Contacted (n)	Responded (n)	Responded (%)
U.S.A.	72	45	62
Japan	38	32	84
Germany	15	11	73
United Kingdom	9	5	56
France	7	5	71
Italy	6	4	67
Sweden	5	5	100
Netherlands	4	3	75
Belgium	2	2	100
Spain	2	2	100
Canada	2	1	50
People's Republic of China	1	1	100
Czechoslovakia	1	1	100
Finland	1	1	100
Switzerland	1	1	100
Australia	1	0	0
Hungary	1	0	0
Russia	1	0	0
South Africa	1	0	0
Overall	170	119	70

Table 4

Distributions of experts who were contacted and those who responded by continent.

Continent	Contacted (n)	Responded (n)	Responded (%)
North America	74	46	62
Europe	55	40	73
Asia	39	33	85
Australia	1	0	0
Africa	1	0	0
Overall	170	119	70

Table 5

Primary affiliations of the respondents.

Primary affiliation	Percentage
Industry	70.6
Government	13.4
Academia	5.9
Other	7.6
No affiliation given	2.5

Table 6

Years of experience in lighting/visibility (mean = 17.8).

Years of experience	Percentage
Less than 6	14.3
6-10	20.1
More than 10	63.9
No experience given	1.7

Results: Importance of the 16 visual-performance functions

The results will be presented by the continent of the respondents: North America (all but one from the U.S.A.), Europe (from 11 countries), and Asia (all but one from Japan). (There were not enough respondents from the individual European countries to analyze the European data by country.) The data for all respondents combined will also be shown, presented as means of the three continent means. (This approach was selected because of the unequal number of respondents from the different continents, and a desire to weight each continent equally.)

The first primary question (Figure 1) dealt with the importance of 16 visual-performance functions. The results are summarized in Table 7. The functions rated among the top three in each continent are summarized in Table 8, and their actual ratings are shown in Figure 3.

There is agreement concerning the importance of illumination towards right-side targets and oncoming glare. These two functions were included among the top three functions for respondents from each continent. However, there was less agreement concerning the third most important function. While illumination towards left-side targets was the third most important function for the North American and European experts, the Asian experts ranked this function as number nine. For the Asian experts, foreground illumination was among the three most important functions. Furthermore, they rated it as the most important function. In comparison, foreground was rated as number four in North America and number seven in Europe.

Table 7

Mean expert opinion concerning the importance of 16 visual-performance functions. Respondents were asked to indicate the relative importance of the 16 functions by allocating 160 points among them. The last column lists the means of the three continent means. The entries in bold are the top three functions for each region.

Visual-performance function	North America	Europe	Asia	Overall
Signs on the right shoulder	13.12	7.90	9.91	10.31
Overhead signs	10.60	5.98	6.64	7.74
Oncoming glare	**21.16**	**24.00**	**30.44**	**25.20**
Glare from rearview mirrors	7.36	4.49	2.19	4.68
Atmospheric scatter	7.41	6.23	4.10	5.91
Right-side targets	**21.06**	**26.66**	**28.81**	**25.51**
Left-side targets	**13.29**	**16.15**	5.98	11.80
Foreground	13.14	9.97	**32.32**	**18.48**
Hills	5.21	2.51	0.88	2.87
Sags	5.29	2.40	1.58	3.09
Homogeneity	8.05	12.77	8.56	9.80
Wet pavement reflections	3.18	4.37	1.61	3.06
Lateral spread	9.45	11.32	9.55	10.11
Ratio of seeing and glare illumination	9.56	7.56	4.01	7.04
Visual aiming	5.32	10.26	8.20	7.93
Sensitivity to misaim	6.79	7.42	5.21	6.47

Table 8

Mean rankings of the most important functions, based on the data in Table 7. To include the top three functions for each continent, a total of four functions had to be listed.

Visual-performance function	North America	Europe	Asia	Overall
Right-side targets	2	1	3	1
Oncoming glare	1	2	2	2
Foreground	4	7	1	3
Left-side targets	3	3	9	4

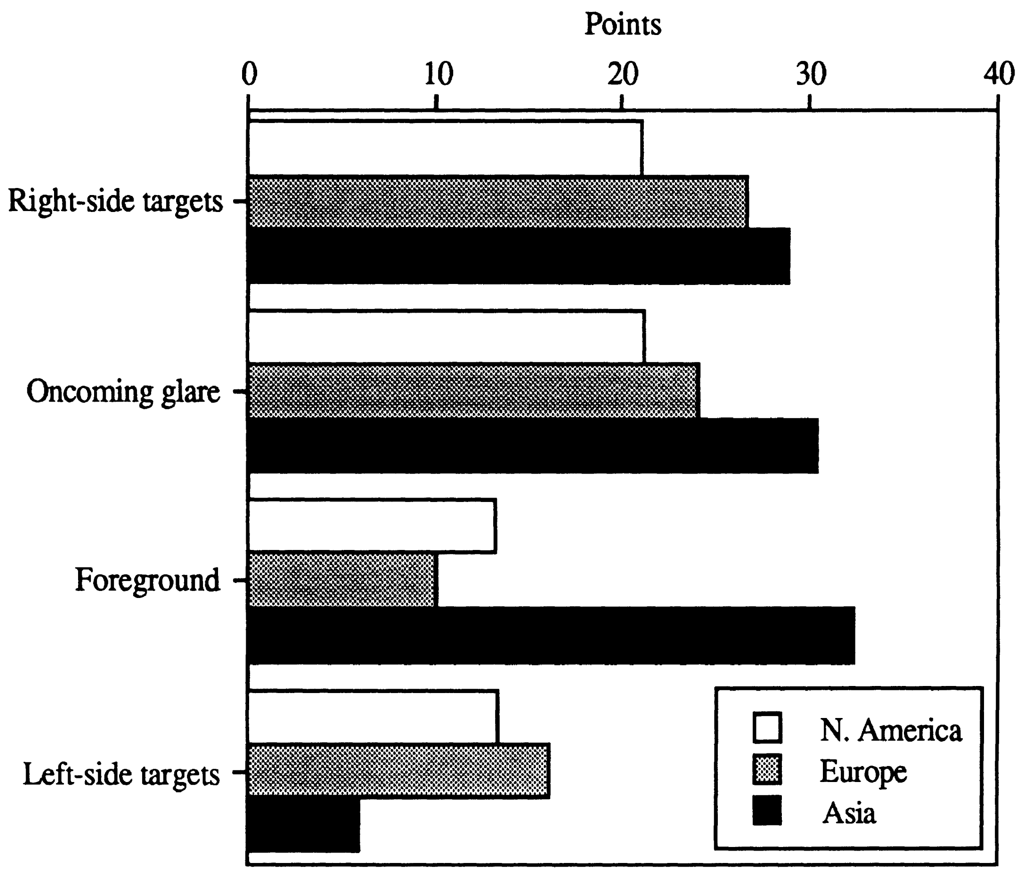


Figure 3. Ratings for the most important visual-performance functions. To include the three most important functions by each continent, a total of four functions had to be listed.

Table 9 lists the number of points assigned to the top three functions. It also lists the corresponding percentages out of the total of 160 points available. Graphical representations of the extent of the coverage by the three most important visual-performance functions are shown in Figure 4.

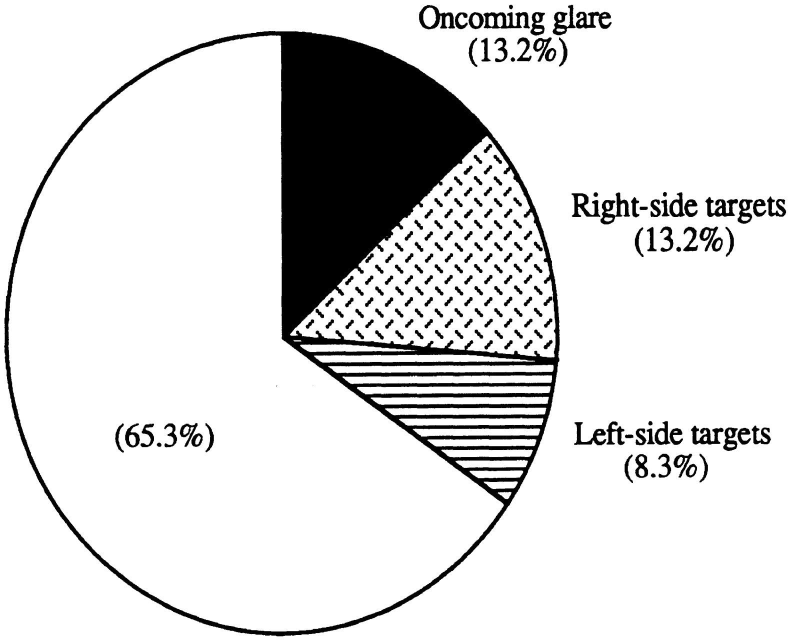
The percentages in Table 9 (and Figure 4) can be used as indicators of how much the experts from different continents believe that the three most important functions can cover all functions that need to be provided by low beams: the higher this percentage, the more the three functions are believed to cover all needed functions. According to this reasoning, the Asian experts had the highest faith in the three most important functions (57.2% coverage of all visual-performance functions), followed by the European experts (41.8% coverage), and the North American experts (34.7% coverage).

Table 9

Extent to which the top three visual functions cover all functions that need to be provided by low beams. The last column is based on the means of the three continent means.

Measure	North America	Europe	Asia	Overall
Points assigned to the top three functions	55.5	66.8	91.6	69.2
Percentage of the total points available that were assigned to the top three functions	34.7	41.8	57.2	43.3

NORTH AMERICA



EUROPE

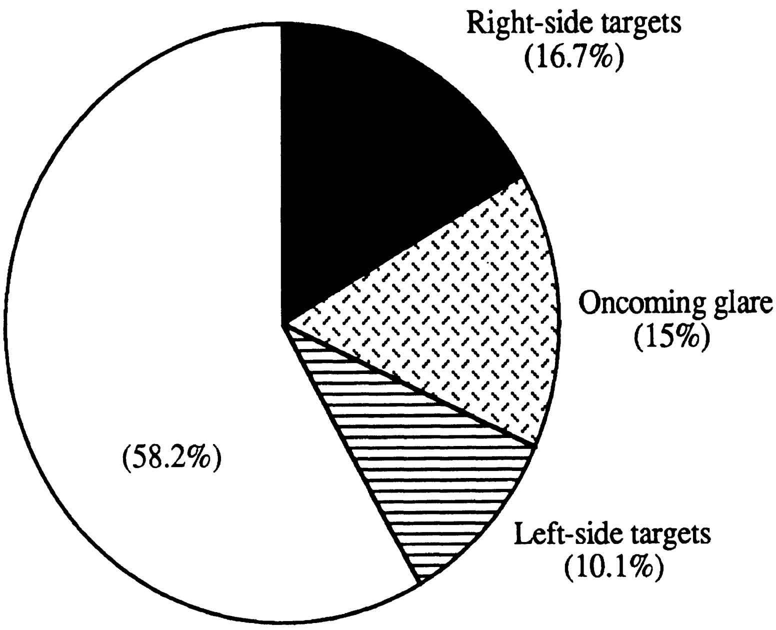
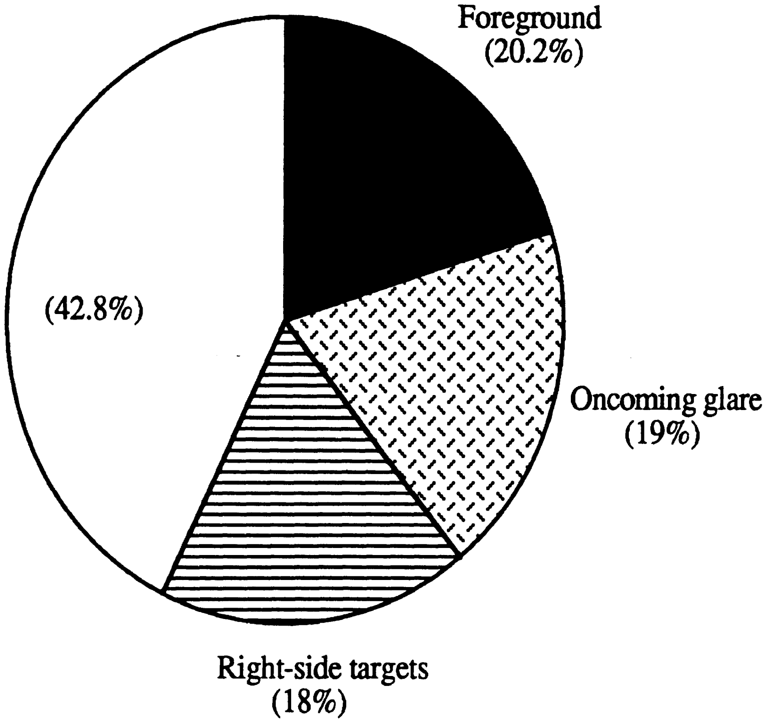
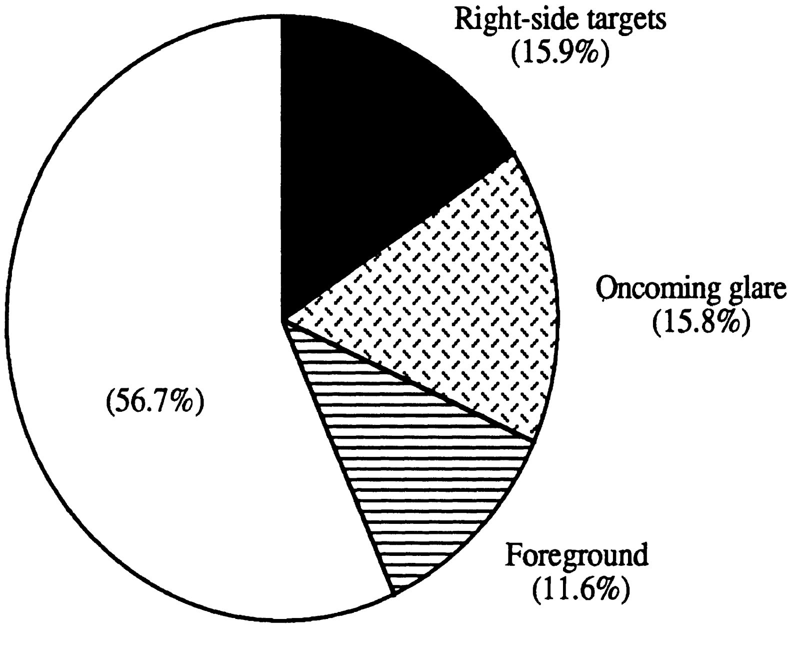


Figure 4. The extent of the coverage of all visual-performance functions provided by the three most important functions, according to the surveyed experts in North America (top panel, this page), Europe (bottom panel, this page), Asia (top panel, facing page), and overall (bottom panel, facing page). The overall entries are the means of the three continent means.

ASIA



OVERALL



Results: Test point locations and the corresponding photometric limits

The second primary question (Figure 2) asked the experts to define, for each of the top three functions, the appropriate angular coordinates for a representative situation (assuming right-hand traffic) and the recommended photometric limits. Again, to cover the top three functions in each continent, four functions needed to be included. The results are shown in Tables 10 through 13. To minimize the effects of outlier responses, the entries in these tables are medians. The results for the top four functions will be discussed in turn.

Illumination towards right-side targets. There was considerable agreement concerning both the vertical angle (0° to 0.5°D) and the horizontal angle (1.4°R to 2°R). The median luminous intensity recommendations had a more substantial range. The minimum luminous intensities ranged from 1,700 cd (in Asia) to 10,000 cd (in both North America and Europe), while the maximum intensities ranged from 17,000 cd (in Asia) to 30,000 cd (in Europe).

Oncoming-glare illumination. The medians for the vertical angle were the same (0.5°U). On the other hand, the recommended horizontal angle in North America (1.5°L) differed substantially from those in Europe and Asia (3.4°L and 3°L, respectively). Similarly, the maximum intensity in North America (1,000 cd) differed from those in Europe and Asia (500 cd and 575 cd, respectively).

Foreground illumination. The median recommended angles had a rather wide range (0.75°D to 2.4°D, and 0.5°R to 2°R), as did the recommended minimum intensities (5,625 cd to 12,000 cd). The maximum intensities were somewhat more consistent (20,000 cd to 27,500 cd).

Illumination towards left-side targets. No angle and intensity information was obtained from the Asian experts, because respondents were asked to provide this information only for the top three functions, and illumination towards left-side targets was not rated among the top three functions by any of the Asian respondents. The North American and European medians were quite similar for the vertical angle (1°D and 0.9°D), the horizontal angle (3.25°L and 4.5°L), and the minimum intensity (1,500 cd and 2,500 cd). However, the maximum intensities differed substantially (3,500 cd and 10,000 cd).

Effects of voltage on photometric recommendations. It is possible that respondents assumed that they should make their photometric recommendations in relation to the existing test voltage in their jurisdictions. If that was the case, then the North American and Asian respondents based their responses, presumably, on 12.8 V, and the European respondents on approximately 12 V. From this point of view, the European responses should be divided by 0.81 (see Table 2) to obtain the approximate photometric values at 12.8 V. This correction would increase all European responses, whether for visibility or glare points. Using such a correction, the median European minima and maxima become 12,346 cd and 37,037 cd for the illumination towards right-side targets, 136 cd and 617 cd for the oncoming-glare illumination, 6,944 cd and 32,407 cd for the foreground illumination, and 3,086 cd and 12,346 cd for the illumination towards left-side targets.

Table 10

Recommended location and photometric limits for a test point that is representative of illumination towards right-side targets. The entries for angles and intensities are medians.

Measure	North America	Europe	Asia
Mean ranking	2	1	3
Vertical angle (°)	0.5D	0.5D	0
Horizontal angle (°)	1.5R	1.4R	2R
Minimum intensity (cd)	10,000	10,000	1,700
Maximum intensity (cd)	20,000	30,000	17,000

Table 11

Recommended location and photometric limits for a test point that is representative of oncoming-glare illumination. The entries for angles and intensities are medians.

Measure	North America	Europe	Asia
Mean ranking	1	2	2
Vertical angle (°)	0.5U	0.5U	0.5U
Horizontal angle (°)	1.5L	3.4L	3L
Minimum intensity (cd)	300	110	*
Maximum intensity (cd)	1,000	500	575

*No minima were listed.

Table 12

Recommended location and photometric limits for a test point that is representative of foreground illumination. The entries for angles and intensities are medians.

Measure	North America	Europe	Asia
Mean ranking	4	7	1
Vertical angle (°)	1.5D	2.4D	0.75D
Horizontal angle (°)	2R	0.5R	0.5R
Minimum intensity (cd)	12,000	5,625	7,000
Maximum intensity (cd)	27,500	26,250	20,000

Table 13

Recommended location and photometric limits for a test point that is representative of illumination towards left-side targets. The entries for angles and intensities are medians. (No angle and intensity information was obtained from the Asian experts, because respondents were asked to provide this information only for the top three functions, and illumination towards left-side targets was not rated among the top three functions by any of the Asian respondents.)

Measure	North America	Europe	Asia
Mean ranking	3	3	9
Vertical angle (°)	1D	0.9D	
Horizontal angle (°)	3.25L	4.5L	
Minimum intensity (cd)	1,500	2,500	
Maximum intensity (cd)	3,500	10,000	

CURRENT PRACTICE

Because the overall goal of this research was to recommend viable test points and photometric limits, information about current practice was important. The underlying logic was that we did not want to recommend test points that would exclude a substantial proportion of current production lamps. Additionally, production lamps are constrained, to some degree, by the available technology. Consequently, photometric data were analyzed for a relatively large sample of production low-beam headlamps.

Sample

This was not a random sample of production lamps. The sample was based primarily on two existing sets of data, one obtained by the Japan Automobile Research Institute, courtesy of Mr. Kiyokazu Yokoi (107 lamps), and one obtained as part of a previous study sponsored by the National Highway Traffic Safety Administration (28 lamps[1]). These two existing sets were supplemented by 15 lamps photometered for this research project. Thus, the total sample included 150 production low beams that were produced by 17 different manufacturers for the U.S., European, and Japanese markets. Table 14 lists the number of lamps by the market for which they were manufactured, and by the source and the year of the respective photometric information. Table 15 provides a breakdown of the lamps by construction.

The photometric information for each lamp consisted of a candela matrix (in half-degree steps) from 5°U to 5°D (all lamps), and from 30°L to 30°R (117 lamps) or 20°L to 20°R (33 lamps). All lamps were measured at 12.8 V. To facilitate comparisons across jurisdictions, the candela matrices of lamps manufactured for left-hand traffic have been converted to right-hand traffic.

[1]The low-beam data from the National Highway Traffic Safety Administration contained 45 candela matrices. However, only 28 different lamps were measured. The other 17 matrices corresponded to modifications of selected lamps by changing bulbs or varying the amount of dirt on the lenses. Only the 28 basic matrices, not the 17 modifications, were used in the present study.

Table 14

Number of lamps by market, and the source and the year of the photometric information.

Market	Number	Year of the photometry	Source of the photometric data
U.S.A.	43	1990-1993	II Stanley (33*), GE Lighting (5), Inland Fisher Guide Division of GM (5)
Europe	37	1983-1987	Japan Automobile Research Institute (courtesy of Mr. Kiyokazu Yokoi)
Japan	70**	1983-1987	

*Out of the 33 lamps photometered by II Stanley, 28 lamps were photometered in 1990 and 1991 as a part of a research contract between the National Highway Traffic Safety Administration and the University of Michigan, and 5 were photometered in 1993 for this project.
**Out of the 70 Japanese lamps, 48 were ECE-J lamps and 22 were SAE-J lamps.

Table 15

Breakdown of the lamps by construction.

Lamp type	Tungsten or halogen	Filament orientation	U.S. lamps	European lamps	Japanese lamps
9004	halogen	transverse	8		
9006	halogen	axial	9		
9007	halogen	axial			2
H1	halogen	axial		4	
H4	halogen	axial		33	40
H6	halogen	transverse			4
D4	tungsten	axial			8
sealed beam	tungsten	transverse	1		10
sealed beam	halogen	transverse	20		6
sealed beam	halogen	axial	5		
Total			43	37	70

How well do existing lamps meet current U.S., European, and Japanese standards?

These analyses were performed to investigate how well lamps met the standard of the jurisdiction for which they were manufactured, as well as the standards for the other two jurisdictions under consideration. Where necessary, linear interpolation was used. The results are presented in Tables 16 through 18.

U.S. standard (NHTSA, 1991) (see Table 16). The U.S. standard calls for different photometric limits depending on the type of the lamp. The relevant values are specified in Figures 15 and 17 of NHTSA (1991), and in Figures 1 and 2 of SAE (1984). In our analysis we used the values that were appropriate for each lamp. The following three test points and regions were not evaluated: (1) the maximum of 125 cd at 10°U to 90°U (our data were only from 5°D to 5°U), (2) the maximum of 7,000 cd at 4°D, V (applies only for some 4-lamp systems), and (3) the maximum of 5,000 cd at H, V (again applies only for some 4-lamp systems).

For all lamps, the most difficult U.S. test point was 0.5°D, 1.5°R, which contains both a minimum (10,000 or 8,000 cd) and a maximum (20,000 cd). The respective percentages of the U.S., European, and Japanese lamps that did not meet this specification were 33, 68, and 80%, with the minimum requirement being, usually, the difficult aspect. (Over one half of the U.S. misses failed to reach the required minimum, as did all of the European and Japanese misses.) A total of 58% of the U.S. lamps missed at least one test point, 37% at least two test points, and 28% at least three test points. (In the U.S., a 0.25° reaim is permitted in any direction for any test point. This procedure was *not* followed in this study.)

European standard (ECE, 1986) (see Table 17). The European standard calls for performing the photometry when the light output is at 750 lm. This is usually achieved at approximately 12 V. However, all of our lamps were photometered at 12.8 V. Consequently, the obtained luminous intensities were multiplied by 0.81 (see Table 2) to estimate the approximate values at 12 V. (The ECE test points were converted from their original specifications as locations on a vertical screen at 25 m to angular coordinates at the nearest quarter degree. Similarly, the original specifications of illuminances at 25 m were converted to luminous intensities, rounded to the nearest 5 cd.)

The two most difficult European test points were the maximum in Zone 3 (the respective percentages of misses for the U.S., European, and Japanese lamps were 100, 68, and 86%), and the maximum at 0.5°U, 3.5°L (the respective percentages of misses were 91, 49, and 66%). The next most difficult aspect of this standard was the minimum in Zone 4 (for the U.S. lamps), and the minimum at 0.5°D, 1.25°R (for the European and

Japanese lamps). A total of 97% of the European lamps missed at least one test point, 76% at least two test points, and 46% at least three test points.

Japanese standard (JIS, 1984) (converted to right-hand traffic, see Table 18). Since the Japanese standard is, generally, less restrictive than either the U.S. or the European standards, it is not surprising that there were fewer misses against the Japanese standard than against the U.S. or the European standards. Most misses occurred by exceeding the maximum requirement at 0.5°D, 1°L to L. The respective percentages of the U.S., European, and Japanese lamps that exceeded this requirements were 28, 16, and 20%. A total of 31% of the Japanese lamps missed at least one test point, 11% at least two test points, and 4% at least three test points.

Overall. As expected because of the construction differences, the European lamps were better at meeting the maxima requirements than were the U.S. lamps. This was a general pattern, whether the requirements were part of the U.S. or European standard. For example, the European lamps were better than the U.S. lamps at meeting both the European 0.5°U, 3.5°L maximum and the U.S. 0.5°U, 1.5°L to L maximum. Conversely, the U.S. lamps were better, in general, at meeting the minima requirements, whether the requirements were part of the U.S. or European standard. For example, the U.S. lamps were better than the European lamps at meeting both the U.S. 0.5°D, 1.5°R minimum and the European 0.5°D, 1.25°R minimum.

Table 16

Evaluation of the lamps against the current U.S. (FMVSS) standard. The entries in columns 4, 5, and 6 are percentages of lamps not meeting the particular specifications in columns 1, 2, and 3. The lamps were photometered at 12.8 V. (The U.S. standard allows a 0.25° reaim in any direction for any test point. This procedure was *not* followed in this study.)

Test point(s) (°)	Minimum (cd)	Maximum (cd)	U.S. lamps	European lamps	Japanese lamps
1.5U, 1R to R		1,400	12	14	1
1U, 1.5L to L		700	35	0	17
0.5U, 1.5L to L		1,000	19	0	11
0.5U, 1R to 3R		2,700	28	3	3
0.5D, 1.5L to L		3,000/2,500	28	24	23
0.5D, 1.5R	10,000/8,000	20,000	33*	68**	80**
1D, 6L	1,000/750		0	0	1
1.5D, 9L	1,000/750		0	0	0
1.5D, 9R	1,000/750		0	3	0
1.5D, 2R	15,000		5	76	56
2D, 15L	850/700		5	49	4
2D, 15R	850/700		0	51	14
4D, 4R		12,500	0	0	1
At least one test point			58	100	99
At least two test points			37	92	71
At least three test points			28	59	29

*19% of the lamps did not meet the minimum, and 14% exceeded the maximum.
**All of the misses were in respect to the minimum specifications.

Table 17

Evaluation of the lamps against the current European (ECE) standard. The entries in columns 4, 5, and 6 are percentages of lamps not meeting the particular specifications in columns 1, 2, and 3. The lamps were photometered at 12.8 V, but the obtained luminous intensities were multiplied by 0.81 to get the approximate values for 12 V. (The ECE test points were converted from their original specifications as locations on a vertical screen at 25 m to angular coordinates at the nearest quarter degree. Similarly, the original specifications of illuminances at 25 m were converted to luminous intensities, rounded to the nearest 5 cd.)

Test point(s) (°)	Minimum (cd)	Maximum (cd)	U.S. lamps	European lamps	Japanese lamps
0.5U, 3.5L		250	91	49	66
0.5D, 3.5L		7,500	0	0	0
0.5D, 1.25R	7,500		33	78	90
0.75D, 3.5L		9,375	0	0	0
0.75D, V	3,750		9	5	31
0.75D, 1.75R	7,500		9	11	44
1.75D, 9L	1,250		12	5	3
1.75D, 9R	1,250		0	3	0
Zone 1 (1.75D to D)		*	16	3	26
Zone 3**		440	100	68	86
Zone 4***	1,875		84	38	57
At least one test point			100	97	100
At least two test points			100	76	99
At least three test points			77	46	84

*Two times the actual value at 0.75D, 1.75R.

**Two alternatives are specified:

(a) Above horizontal for all points to the left of vertical, and above a 15° line that originates at H,V for all points to the right of vertical.

(b) Above horizontal for all points to the left of vertical, above a 45° line that originates at H,V for points between H,V and 0.5U, 0.5R, and above a 0° line for all points to the right of 0.5U, 0.5R.

***Zone with the following corners: 0.75D, 5.25L; 0.75D, 5.25R; 1.75D, 5.25R; and 1.75D, 5.25L.

Table 18

Evaluation of the lamps against the current Japanese (JIS) standard converted to right-hand traffic. The entries in columns 4, 5, and 6 are percentages of lamps not meeting the particular specifications in columns 1, 2, and 3. The lamps were photometered at 12.8 V.

Test point(s) (°)	Minimum (cd)	Maximum (cd)	U.S. lamps	European lamps	Japanese lamps
1.5U, 1R to R		1,500	9	11	1
1U, 1L to L		1,300	2	0	3
0.5U, 1L to L		1,700	7	0	3
0.5U, 1R to 3R		2,800	28	3	3
0.5D, 1L to L		3,300	28	16	20
0.5D, 2R	3,000	15,000	26*	3*	7**
1D, 6L	600		0	0	0
1.5D, 9L	800		0	0	0
1.5D, 9R	800		0	3	0
1.5D, 2R	7,000		0	0	7
2D, 15L	400		0	16	0
2D, 15R	400		0	19	4
4D, 4R		12,500	0	0	1
At least one test point			37	49	31
At least two test points			26	22	11
At least three test points			21	0	4

*All of the misses were in respect to the maximum specification.
**3% of the lamps did not meet the minimum specification, and 4% did not meet the maximum specification.

SCIENTIFIC EVIDENCE

This task was designed to examine scientific evidence that pertains to the desirable locations and photometric limits of low-beam test points. For points at which objects need to be seen, visibility requirements for low-contrast objects were assessed. Conversely, for points where drivers are exposed to oncoming headlamps, discomfort glare was assessed. Neither the trade-offs between visibility and glare, nor practical constraints were considered. The results of this task were not used directly to form our recommendations. Instead, scientific evidence was only one of the inputs for our decision making, along with expert opinion and current practice.

A limited number of test points in themselves cannot guarantee sufficient performance of a headlamp. Consider an example of three well chosen test points. If we were to produce a beam pattern formed by three narrow "pencil" beams of light that would meet such a 3-point requirement, it would be, most likely, a terrible beam. However, when coupled with the limitations of current technologies, a limited number of well-chosen test points might impose substantial constraints on the overall beam pattern. With this in mind, we will argue for four primary test points, one in each quadrant. The four test points will represent seeing points on the right and left sides of the road, a glare-control point, and a point for retroreflective traffic signs.

Lower right quadrant: Illumination for the right side of the road

Location. The main reason for the existence of headlamps is to illuminate the road ahead. Based on this simple premise, to provide as much of a preview of the road as possible, the location of the test point for this primary function should be at H, V. However, because of the conflict between visibility needs and glare concerns for oncoming drivers, the primary seeing point for the low beams (as opposed to high beams) has been consistently placed below horizontal and to the right of vertical (for right-hand traffic). Additional reasons for placing this test point to the right of vertical are (1) the presence of pedestrians and bicyclists on the right side of the roadway, and (2) the assumed reliance on right edge lines for lane keeping.

A rational approach to setting the vertical coordinate for the right seeing point would be to place this point at or beyond a reasonable stopping distance, so as not to overdrive one's headlamps. Assuming a perception-response time of 2.5 s and a dry pavement (with a deceleration rate of 0.65 g), the total stopping distance from 100 km/h is about 130 m. (A corresponding value for wet pavement [with a deceleration rate of 0.3 g] is substantially greater—about 200 m.) Assuming a headlamp mounting height of 0.6 m, the resulting vertical angle for pavement 130 m in front of the vehicle is 0.25°D (rounded to the nearest quarter degree).

For determining horizontal angle, let us consider a location on the right edge line (1.85 m to the right of the center of the vehicle) at the stopping distances of 130 m. The resulting angle is 0.75°R (rounded to the nearest quarter degree). Thus, the angular coordinates for the location at the right edge line at a reasonable stopping distance for dry pavement are 0.25°D, 0.75°R.

Minimum luminous intensity. As we have argued recently, illumination of 33 lx is necessary

> "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 lx (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 lx—has been used widely as a benchmark for setting the limit of useful visual recognition. The 3 lx 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 lx is not out of line with other current estimates of necessary illumination for perceiving unexpected low-contrast targets. For example, Kosmatka's (1992) calculations for a 7% reflectance target indicate that the illuminance needs to be 32 lx (341,000 cd at 104 m), while Fisher's (1970) analysis (also for a 7% reflectance target), leads to 91 lx (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 lx" (Sivak, Helmers, Owens, and Flannagan, 1992, p. 54).

Using a target illuminance of 33 lx and a stopping distance of 130 m, we can calculate the required luminous intensity. Such a calculation leads to the minimum intensity for each lamp being about 280,000 cd. Finally, since the light must pass through the windshield, we need to correct this value by the transmittance of the windshield. Using a transmittance value of 85%, we obtain 330,000 cd.

Maximum luminous intensity. From the visibility point of view (disregarding glare concerns), there is no need for a maximum.

Summary. The derived location and photometric limits for the primary test point in the lower right quadrant are summarized in Table 19.

Table 19

The location and photometric limits for the primary test point in the lower right quadrant. The minimum luminous intensity is based exclusively on scientific evidence concerning visibility of low-contrast objects; it does not take into account the feasibility of achieving such a value.

Location of the test point (°)	Minimum luminous intensity (cd)	Maximum luminous intensity (cd)
0.25D, 0.75R	330,000	none

Lower left quadrant: Illumination for the left side of the road

Location. A test point to the left of vertical and below horizontal would control the visibility on the left side of the road. It can be argued that the visibility on the left side does not need to exceed the stopping distance, because objects at this test point are displaced laterally more than are objects at the corresponding test point on the right side. However, it is not clear what would be a reasonable alternative to the stopping distance as a criterion. Thus, we used the same arguments as for the right seeing point above. The desired seeing distance for a target on the left side is then also 130 m, with a corresponding vertical angle of 0.25°D. A target on the left edge line of a two-lane roadway is about 5.5 m from the center of the vehicle. Consequently, the horizontal angle is 2.5°L.

Minimum luminous intensity. Again, based on calculations analogous to those for the right seeing test point, the minimum luminous intensity is 330,000 cd.

Maximum luminous intensity. From the visibility point of view (disregarding glare concerns) there is no need for a maximum.

Summary. The derived location and photometric limits for the primary test point in the lower left quadrant are summarized in Table 20.

Table 20

The location and photometric limits for the primary test point in the lower left quadrant. The location and the minimum luminous intensity are based exclusively on scientific evidence concerning visibility of low-contrast objects; they do not take into account the feasibility of achieving such values.

Location of the test point (°)	Minimum luminous intensity (cd)	Maximum luminous intensity (cd)
0.25D, 2.5L	330,000	none

Upper left quadrant: Glare for oncoming traffic

Location. A glare-control test point should be located at the angle that corresponds to the condition of peak glare experienced by oncoming drivers. For low beams, the peak glare occurs on curves. However, the peak glare exposure on curves is relatively transient (in comparison to the length of the exposure on straight sections of road). Since longer exposures lead to more discomfort glare (Olson and Sivak, 1984b), a reasonable scenario for a glare point would assume a straight two-lane roadway.

Data of Mortimer and Olson (1974) can be used to determine the location for a glare-control test point. Mortimer and Olson's data include information on the effect of the distance between the observer's car and an oncoming (glare) car on visibility distances. Their data, for both a U.S. and a European low beam, indicate that the intervehicle distance at which visibility was minimum depended on the nature and the location of the target. In general, however, the minimum visibility was achieved for vehicle distances of 120 to 60 m (400 to 200 feet) (Mortimer and Olson, 1974, Figure 43). Taking the midpoint of this range, Mortimer and Olson's data suggest that the glare effect (dependent on the combination of the illumination at the eyes and the glare angle) was maximal at a vehicle separation of about 90 m. If we assume a standard lane width of 3.7 m (and thus a lateral separation between the driver and the headlamps of the oncoming vehicle of 3.3 m), then the peak glare at 90 m distance yields a glare angle is 2° (rounded to the nearest quarter degree). Based on headlamp mounting height of 0.6 m and driver eye position of 1.1 m above the roadway, the corresponding vertical angle is about 0.25°U (rounded to the nearest quarter degree).

Maximum luminous intensity. The issue that we will address now is "How much glare can an oncoming driver tolerate at a distance of 90 m?" The traditional view (e.g., Holladay, 1926) is that glare has two separate effects on the observer. *Disability* glare refers to an objective impairment in visual performance. *Discomfort* glare refers to subjective impression of discomfort. In the automobile context it is usually discomfort glare that is considered the limiting aspect.

The most widely accepted model of discomfort glare is that of Schmidt-Clausen and Bindels (1974), which relates discomfort glare rating on the so-called de Boer scale (de Boer, 1967) to the illuminance at the eyes, the glare angle, and the adaptation luminance. The full equation for the model is:

$$W = 5.0 - 2 \log \frac{E_B}{C_{poo}\left[1+\sqrt{\frac{L_U}{C_{pL}}}\right]\theta^{0.46}}$$

where W is a discomfort glare rating on the de Boer scale, E_B is the illumination at the observer's eye point in lx, C_{poo} is a constant equal to 3.0×10^{-3} lx $min^{-0.46}$, L_U is the luminance to which the observer is adapted in cd/m^2, C_{pL} is a constant equal to 4.0×10^{-2} cd/m^2, and θ is the visual angle in minutes between the glare source and the observer's visual fixation point. The de Boer scale is a nine-point scale, with qualifiers only for the odd points: 1 (unbearable), 2, 3 (disturbing), 4, 5 (just acceptable), 6, 7 (satisfactory), 8, 9 (just noticeable). The usual cutoff for tolerable glare in the automobile context has been the value 4 (e.g., Bhise et al., 1977).

An apparently straightforward approach to determining the maximum illumination for de Boer glare rating of 4 would be to solve the Schmidt-Clausen equation for W = 4 and the glare angle of interest. However, another important parameter in the Schmidt-Clausen and Bindels model is the adaptation luminance. The problem here is that there is no general agreement concerning the value of adapting luminance to be used for typical nighttime driving. For example, Flannagan, Sivak, Ensing, and Simmons (1989) used a value of 0.034 cd/m^2, but the data from Olson, Aoki, Battle, and Flannagan (1990) suggest that the proper estimate for the adaptation luminance on a road without fixed lighting, when using typical U.S. low beams, is about 1 cd/m^2. The high sensitivity of the Schmidt-Clausen and Bindels prediction of glare rating to the value of adaptation luminance is shown in Table 21. This table shows the maximum illuminance at the eyes of the observer for de Boer values of 4 when the glare angle is 121 minutes—the angle corresponding to the situation of peak glare on a two-lane roadway. (The value of 121 minutes was derived as the relevant glare angle, based on the relevant vertical angle [0.25°U] and horizontal angle [2°L].) Table 21 also includes the corresponding luminous intensities for each of two lamps.

Table 21

Maximum total illuminance (and the corresponding luminous intensity for each of two headlamps) to keep the de Boer glare rating at 4, as a function of adaptation luminance. These values were derived from the model of Schmidt-Clausen and Bindels (1974), assuming a glare angle of 121 minutes, a longitudinal separation between the two vehicles of 90 m, and a windshield transmittance of 85%.

Adaptation luminance (cd/m^2)	Maximum total illuminance for de Boer rating of 4 (lx)	Maximum luminous intensity for each headlamp (cd)
1.0	0.52	2,478
0.1	0.22	1,048
0.034	0.17	810

An additional complicating issue is that the Schmidt-Clausen and Bindels model is based on laboratory studies, and it tends to predict somewhat higher ratings of discomfort than those obtained in a field setting (Olson and Sivak, 1984a). Furthermore, discomfort-glare ratings are affected by a variety of factors, such as the range of other stimuli presented in the same experimental session (Olson and Sivak, 1984a), prior experience with different glare levels (Sivak, Olson, and Zeltner, 1989), and the difficulty of a concurrent task (Sivak, Flannagan, Ensing, and Simmons, 1991). Consequently, we are not on solid ground in estimating the maximum luminous intensity for tolerable glare. With this caveat in mind, we propose a maximum of 1,000 cd.

Minimum luminous intensity. To assure that there will be some light directed in this general direction for retroreflective traffic signs, a minimum of 100 cd is recommended. This minimum requirement will not adversely affect glare. The Schmidt-Clausen and Bindels equation predicts a substantial difference in discomfort glare between the proposed minimum of 100 cd and the proposed maximum of 1,000 cd. For example, assuming adaptation luminance of 0.1 cd/m^2, the predicted de Boer glare rating for 100 cd is about 6.0—half-way between "just acceptable" and "satisfactory," and two units less glaring than the predicted glare rating of about 4.0 for 1,000 cd.

Summary. The derived location and photometric limits for the primary test point in the upper left quadrant are summarized in Table 22.

Table 22

The location and photometric limits for the primary test point in the upper left quadrant. The location and the maximum luminous intensity are based on inconclusive scientific evidence concerning glare, while the minimum luminous intensity is designed to provide a nominal amount of illumination for retroreflective traffic signs.

Location of the test point (°)	Minimum luminous intensity (cd)	Maximum luminous intensity (cd)
0.25U, 2L	100	1,000

Upper right quadrant: Illumination for retroreflective traffic signs

The primary reason for illumination in the upper right quadrant is the presence of retroreflective traffic signs. Retroreflective signs reflect light back towards the source of illumination in a narrow cone. They rely on illumination from headlamps for their nighttime conspicuity and legibility. The calculations to follow are based on legibility considerations alone, and they assume a legibility distance of 150 m.

Location. A typical shoulder-mounted sign is 4.3 m to the right of the right edge line and 2.1 m above the roadway (e.g., Woltman and Szczech, 1989). Assuming a lane width of 3.7 m and a headlamp mounting height of 0.6 m, the resulting angular coordinates for such a sign at a distance of 150 m are 0.5°U, 2.25°R (rounded to the nearest quarter degree).

Minimum luminous intensity. A recent review of the sign-legibility literature concluded that an optimal sign luminance is 75 cd/m^2 (Sivak and Olson, 1985). A typical retroreflectance for a new white encapsulated-lens traffic-sign material is about 300 cd/lx/m^2 at an observation angle of 0.2°. (The observation angle is formed by the locations of the driver's eyes, traffic sign, and headlamp.) It turns out that in the present situation (sign mounting height of 2.1 m, driver eye position above the roadway of 1.1 m, headlamp mounting height of 0.6 m, and distance from eye to sign of 150 m) the observation angle is approximately 0.2°. However, because signs in use might average about 50% of the efficiency of new signs, a reasonable effective *in situ* retroreflectance for present calculations is 150 cd/lx/m^2.

To obtain a sign luminance of 75 cd/m^2 using a material with an effective retroreflectance of 150 cd/lx/m^2, the illuminance on the sign needs to be about 0.5 lx (75/150). To obtain illuminance of 0.5 lx at the face of the sign at a distance of 150 m, the luminous intensity directed towards the sign from each of the two lamps needs to be about 5,625 cd (0.5/2 x 150^2). Finally, assuming a windshield transmittance of 85%, we obtain 6,618 cd, rounded to 6,600 cd.

Maximum luminous intensity. The concerns with backscatter in fog, rain, and snow suggest a need for a maximum in this direction. However, empirical data are not sufficient to set a reasonable maximum.

Summary. The derived location and photometric limits for the primary test point in the upper right quadrant are summarized in Table 23.

Recapitulation

The four test points and their photometric limits that were derived exclusively on the basis of scientific evidence are summarized in Table 24. These values apply to actual in-traffic voltages.

Table 23

The location and photometric limits for the primary test point in the upper right quadrant. The location and the minimum luminous intensity are based on scientific evidence concerning the legibility of retroreflective traffic signs.

Location of the test point (°)	Minimum luminous intensity (cd)	Maximum luminous intensity (cd)
0.5U, 2.25R	6,600	none

Table 24

The locations and photometric limits of four test points that were derived based exclusively on scientific evidence. These values apply to in-traffic voltages and they do not take into account the feasibility of achieving such values.

Rationale	Location of the test point (°)	Minimum luminous intensity (cd)	Maximum luminous intensity (cd)
Illumination for the right side of the road	0.25D, 0.75R	330,000	none
Illumination for the left side of the road	0.25D, 2.5L	330,000	none
Glare for the oncoming traffic	0.25U, 2L	100	1,000
Illumination for retroreflective traffic signs	0.5U, 2.25R	6,600	none

COMPROMISE AMONG EXPERT OPINION, CURRENT PRACTICE, AND SCIENTIFIC EVIDENCE

The goal of this research was to recommend a limited number of low-beam test points for acceptance by agencies regulating vehicle headlighting throughout the world. Furthermore, to increase the likelihood of acceptance, we were asked to consider existing test points whenever possible. We recognized that the eventual recommendations would have to be based on a compromise among expert opinion, current practice, and scientific evidence. This section of the report describes our attempt at reaching such a compromise. Table 25 summarizes how expert opinion, current practice, and scientific evidence were used to reach our recommendations.

Table 25

Influence of expert opinion, current practice, and scientific evidence on our recommendations.

Aspect	Primary information used
Most important visual-performance functions	Expert opinion
Location of the test points	Scientific evidence and current practice
Photometric limits	Current practice and scientific evidence

Most important visual-performance functions of low beams

The goal of this research was to determine a small number of the most important test points (with the "small" being defined as about three) so as to minimize the number of potential changes to the existing standards. Consequently, we limited ourselves to considering only three or four test points.

The three most important visual-performance functions based on the opinion of the surveyed experts in each of the three continents (North America, Europe, and Asia) are listed in Table 26. Based on the information in Table 26, to include the top three functions from each continent, we would need to consider a total of four functions: right-side targets, oncoming glare, left-side targets, and foreground. In comparison, the four functions that we discussed in the preceding section on Scientific Evidence are right-side targets, left-side targets, oncoming glare, and retroreflective traffic signs. This later set of four functions was based on two considerations. First, we wanted a test point in each quadrant of the visual field to impose a certain degree of constraint on the total beam pattern. Second, within each quadrant we selected a visual-performance function that we judged to be the dominant function in that quadrant. There is only one inconsistency between these two sets of four functions: The set based on expert opinion includes foreground, while the set based on scientific evidence includes retroreflective traffic signs.

Table 26

The three most important visual-performance function on each continent, based on the opinion of the surveyed experts. The last column is derived by averaging the mean ratings by each continent.

Rank order	North America	Europe	Asia	Overall
1	Oncoming glare	Right-side targets	Foreground	Right-side targets
2	Right-side targets	Oncoming glare	Oncoming glare	Oncoming glare
3	Left-side targets	Left-side targets	Right-side targets	Foreground

Locations of the recommended test points

Right-side targets. The proposed location—0.5°D, 1.25°R—is identical to the ECE 75R test point. It corresponds to the location of a target at a distance of 75 m on the right edge line, assuming a road width of 3 m (as used in ECE, 1986), or slightly to the left of the right edge line, assuming a road width of 3.7 m. While, ideally, we would have liked to see this test point further down the road (i.e., closer to horizontal), it is probably as close to horizontal as is currently practical.

Left-side targets. The proposed location—0.5°D, 3.5°L—is identical to the ECE 75L test point. It corresponds to a location of a target at a distance of 75 m on the left edge line of a lane adjacent to the left, assuming a road width of 3 m (as used in ECE, 1986), or slightly to the right of this line, assuming road width of 3.7 m. Again, while ideally, we would have liked to see this test point further down the road (i.e., closer to horizontal), it is probably as close to horizontal as is currently practical.

Oncoming glare. The literature that we have reviewed above suggests that, in a two-lane meeting situation, peak glare occurs at a distance of about 90 m, yielding an angle of 0.25°U, 2°L. The existing relevant standards all have glare-control test points. In the U.S. it is 0.5°U, 1.5°L to L (the limiting point being at 1.5°L), in Europe 0.5°U, 3.5°L, and in Japan 0.5°U, 1°L to L (the limiting point being at 1°L). Furthermore, a recent SAE recommendation calls for controlling 0.5°U, 1.5°L (SAE, 1991). We recommend the U.S.-based 0.5°U, 1.5°L, because it is nearer to our calculated maximum glare at 0.25°U, 2°L than either the European or Japanese glare-control test point.

Foreground. Foreground illumination was rated by experts from Asia as the most important function. Consequently, we are including a test point to evaluate the foreground (or more accurately, mid-range) illumination. According to the surveyed experts from Asia, the median desired location of such a test point is 0.75°D, 0.5°R, consistent with a recent recommendation by Taniguchi et al. (1989). However, at 0.75°D, there is no real concern with glare (even with some misaim). Consequently, this point need not be offset to the right. We recommend placing this point on vertical, so that it will specify illumination straight ahead, and be coincident with the current ECE 50V test point.

Summary. The locations of the four recommended test points are listed in Table 27.

Table 27

Recommended locations for the test points.

Visual-performance function	Location of the test point (°)
Right-side targets	0.5D, 1.25R
Left-side targets	0.5D, 3.5L
Oncoming glare	0.5U, 1.5L
Foreground	0.75D, V

Photometric limits of the recommended test points

General approach. Our calculations (Table 24) indicate that to detect low-contrast objects, the luminous intensity for the test points dealing with visibility would need to be at least one order of magnitude greater than the luminous intensities of current low beams. Therefore, it would be unrealistic to recommend, for these test points, luminous intensities based on scientific evidence alone. On the other hand, the results of our calculations concerning the maximum tolerable glare are more consistent with the current glare values. Consequently, the general approach in reaching the recommended luminous intensities has been as indicated in Table 28.

Step 1: Oncoming glare. Using the equation of Schmidt-Clausen and Bindels (1974), we can solve for the maximum illumination at the eyes of the oncoming traffic for the de Boer discomfort-glare value of 4, given the angle of interest. Since the test point in question is at 0.5°U, 1.5°L, the glare angle is about 95 minutes. The Schmidt-Clausen and Bindels equation predicts that for this angle and for adaptation luminance of 0.1 cd/m^2, the de Boer value 4 is reached when illuminance is 0.2 lx. Taking into account the transmittance of the windshield (85%) and the presence of two headlamps, we arrive at illuminance of 0.12 lx. In turn, to have illuminance of 0.12 lx, the luminous intensity in that direction from a distance of 122 m (the distance corresponding to the oncoming vehicle at a lateral angle of 1.5°L in the adjacent lane) would need to be 1,786 cd at 13.5 V. Using the correction factors in Table 2, we obtain a maximum of 1,374 cd at 12.8 V.

Table 28

General approach in reaching the recommended luminous intensities.

Step	Procedure
1	Based on limited available scientific evidence and on current practice, determine the maximum and minimum values for the oncoming-glare test point
2	Based on current practice, determine a reasonable minimum ratio between the luminous values at the right seeing test point and the oncoming-glare test point
3	Multiply the maximum glare value from Step 1 by the ratio in Step 2 to obtain the minimum luminous intensity for the right seeing test point
4	Based on current practice, determine a reasonable minimum ratio between the luminous values at the left seeing test point and the oncoming-glare test point
5	Multiply the maximum glare value from Step 1 by the ratio in Step 4 to obtain the minimum luminous intensity for the left seeing test point
6	Based on current practice, determine minimum and maximum for the foreground test point

The above derived maximum of 1,374 cd was based on adaptation luminance of 0.1 cd/m². However, according to the Schmidt-Clausen and Bindels equation, this value would increase with an increase in adaptation luminance. For example, if we use an adaptation luminance of 1 cd/m² (based on the data of Olson et al., 1990), the analogous calculations would lead to a maximum of 3,114 cd. However, the current maxima at this point (1,000 cd at 12.8 V in the U.S.A., and 440 cd at 12 V or 550 cd at 12.8 V in Europe) are already *below* the derived value even for adaptation luminance of 0.1 cd/m². Therefore, based on the current standards, the calculations above, and the distributions of the actual values at this point for our sample of 150 lamps (see Table 29), we recommend, as a reasonable compromise, a maximum of 750 cd at 12.8 V (or 600 cd at 12 V). (To the extend that future European lamps will be utilizing free-shape reflectors but no shields, their future glare values are likely to be somewhat greater than those in Table 29.)

The illumination above horizontal, in addition to being a potential source of glare, is vital for effective functioning of retroreflective traffic signs. The angle of interest (0.5°U, 1.5°L) can correspond to traffic signs mounted on the left side of a straight roadway, or signs mounted on the right side of a left curve (Sivak, Gellatly, and Flannagan, 1991). Consequently, there is concern that there be some light above horizontal. This concern is evident in recent changes to the U.S. low-beam pattern that for the first time introduce minima above horizontal (NHTSA, 1992). These changes call for minima of 64 cd at 4°U, 8°L and 8°R; 135 cd at 2°U, 4°L; 200 cd at 1.5°U, 1°R to 3°R; and 500 cd at 0.5°U, 1°R to 3°R. Similarly, the European VEDILIS proposal (VEDILIS, 1990) contains several minima above horizontal, including 125 cd at 0.75°U, 5.25°L to 5.25°R. Finally, a recent SAE proposal (SAE, 1991) includes a minimum of 300 cd at the point under discussion—0.5°U, 1.5°L. We recommend a minimum of 280 cd. This recommendation is not based on considerations of sign detectability or legibility. This value was selected because, in the opinion of the experts that generated the SAE proposal, a ratio of 3:8 between the minimum and the maximum at this test point is realistically achievable (SAE, 1991).

Table 29

Luminous intensities at the oncoming-glare test point (0.5°U, 1.5°L) for our sample of 150 low beams. (Test voltage: 12.8 V.)

Market	Minimum	25th percentile	Median	75th percentile	Maximum
U.S.A.	246	576	779	969	2,210
Europe	147	266	313	399	686
Japan	150	320	458	623	1,868

Step 2: Reasonable minimum ratio between the luminous intensity values at the right seeing test point and the oncoming-glare test point. To arrive at a reasonable minimum value, we examined the 150 lamps in our sample for the ratio between the luminous intensities at the right seeing point (0.5°D, 1.25°R) and at the oncoming-glare point (0.5°U, 1.5°L). The results are shown in Table 30. Based on the information in Table 30, we selected 13 as a reasonable minimum value for this ratio.

Step 3: Minimum luminous intensity for the right seeing test point. To obtain the minimum luminous intensity for the right seeing test point, we multiplied the maximum for the glare-control point (750 cd) with the minimum ratio between the right seeing point and glare-control point derived immediately above (13), for a resulting luminous intensity of 10,000 cd (after rounding) at 12.8 V. In comparison, Table 31 describes the luminous intensities at this test point for our sample of 150 low beams. This proposal is only a minor modification of the current U.S. and European standards. The current U.S. standard specifies 10,000 cd (8,000 cd for some lamps) at 0.5°D, 1.5°R (FMVSS, 1991), while the European standard specifies 7,500 cd (at 12 V, or *de facto* 9,250 cd at 12.8 V) at 0.5°D, 1.25°R (ECE, 1986).

Table 30

Ratios between the luminous intensity values at the right seeing test point (0.5°D, 1.25°R) and the oncoming-glare test point (0.5°U, 1.5°L) for our sample of 150 low beams.

Market	Minimum	25th percentile	Median	75th percentile	Maximum
U.S.A.	5.0	10.7	14.7	18.3	44.2
Europe	4.6	20.2	24.8	30.3	72.7
Japan	3.5	6.8	10.2	15.2	33.8

Table 31

Luminous intensities at the right seeing test point (0.5°D, 1.25°R) for our sample of 150 low beams. (Test voltage: 12.8 V.)

Market	Minimum	25th percentile	Median	75th percentile	Maximum
U.S.A.	3,915	8,215	11,175	13,435	27,000
Europe	3,150	7,027	7,956	9,006	12,231
Japan	1,378	3,693	5,246	7,100	13,769

Step 4: Reasonable minimum ratio between the luminous intensity values at the left seeing test point and the oncoming-glare test point. The ratios of the luminous intensities at the left seeing test point (0.5°D, 3.5°L) and the oncoming-glare test point (0.5°U, 1.5°L) are summarized in Table 32. Based on the information in Table 32, we selected 1.8 as a reasonable minimum value for this ratio.

Step 5: Minimum luminous intensity for the left seeing test point. To obtain the minimum luminous intensity for the left seeing point, we multiplied the maximum for the glare-control point (750 cd) with the minimum ratio between the left seeing point and glare-control point derived immediately above (1.8), for a resulting luminous intensity of 1,350 cd (after rounding) at 12.8 V. In comparison, Table 33 describes the luminous intensities at this test point for our sample of 150 low beams. Although the 1,350 cd value is lower than the levels recommended by the experts (see Table 13), those recommendations apply to locations further below horizontal than our proposed test point. (The North American experts recommended 1,500 cd at 1°D, 3.25°R, while the European experts recommended 2,500 cd at presumably 12 V, or 3,000 cd at 12.8 V, at 0.9°D, 4.5°L.)

Table 32

Ratios between the luminous intensity values at the left seeing test point (0.5°D, 3.5°L) and the oncoming-glare test point (0.5°U, 1.5°L) for our sample of 150 low beams.

Market	Minimum	25th percentile	Median	75th percentile	Maximum
U.S.A.	0.9	1.3	1.7	2.3	4.2
Europe	1.2	3.0	3.9	6.7	14.8
Japan	1.1	2.0	3.0	3.9	7.9

Table 33

Luminous intensities at the left seeing test point (0.5°D, 3.5°L) for our sample of 150 low beams. (Test voltage: 12.8 V.)

Market	Minimum	25th percentile	Median	75th percentile	Maximum
U.S.A.	574	1,028	1,222	1,800	3,700
Europe	302	1,011	1,406	1,776	4,293
Japan	361	933	1,259	2,006	3,837

Step 6. Minimum and maximum illumination for the foreground (mid-range) test point. The issue of foreground illumination is rather controversial. It is obvious that foreground illumination is needed for traveling at low speeds, because at low speeds foreground illumination can reach beyond the stopping distance. However, drivers tend to like foreground illumination at any speed, even at speeds that are too fast for them to benefit from having foreground objects illuminated.

The effects of foreground illumination on the visibility of *distant* targets are complex and not fully understood. On one hand, higher foreground illumination raises the light adaptation level, and thus results in raised threshold for targets down the road. This applies if the eye-fixation pattern is held the same across conditions. On the other hand, there is some evidence that when foreground illumination is increased, drivers tend to spend more time fixating further down the road, towards the focus of expansion (Olson and Sivak, 1983). Thus, foreground illumination might prove to be beneficial because the fovea (the most sensitive portion of the retina) is directed closer to the focus of expansion—generally considered to be a desirable strategy.

Because of the lack of scientific evidence concerning the desirable level of foreground illumination, we relied on current practice in selecting the recommended photometric limits. Table 34 describes the luminous intensities at the recommended foreground test point for our sample of 150 low beams. The European standard calls for a minimum of 3,750 cd (at approximately 12 V, and thus 4,600 cd at 12.8 V) at 0.75°D, V, and Taniguchi et al. (1989) recommend a minimum of 6,550 cd (at 12.8 V) at 0.75°D, 0.5°R. Based on these two recommendations, and the data in Table 34, we recommend adaptation of the European minimum of 3,750 cd at 12 V, or 4,600 cd at 12.8 V. To assure that the maximum illumination is not at this point but further down the road and to the right of vertical, we recommend the maximum at this point to be no greater than the actual value at 0.5°D, 1.25°R.

Table 34

Luminous intensities at the foreground (mid-range) seeing test point (0.75°D, V) for our sample of 150 low beams. (Test voltage: 12.8 V.)

Market	Minimum	25th percentile	Median	75th percentile	Maximum
U.S.A.	1,488	5,711	7,485	10,376	15,545
Europe	3,828	6,012	7,409	8,216	11,406
Japan	1,732	4,103	5,728	7,722	11,337

RECOMMENDATIONS

The recommended test points and the photometric limits are summarized in Table 35 for three test voltages (13.5, 12.8, and 12 V). The interrelations between the different voltage sets are based on the light-output correction factors in Table 2. The recommended test points and the photometric limits for 12.8 V are shown in Figure 5, overlaid on a perspective drawing of a roadway.

Table 35

Recommended test points and the corresponding photometric limits by test voltage.

Rationale	Location (°)	Minimum (cd)			Maximum (cd)		
		13.5 V (in use)	12.8 V	12 V	13.5 V (in use)	12.8 V	12 V
Visibility of targets such as pedestrians on the right side of the lane	0.5D, 1.25R	13,000	10,000	8,100	none	none	none
Visibility of targets such as pedestrians on the left side of the adjacent lane	0.5D, 3.5L	1,750	1,350	1,100	none	none	none
Glare control for oncoming drivers	0.5U, 1.5L	360	280	230	1,000	750	600
Visibility of obstacles in the center of the lane	0.75D, V	6,000	4,600	3,750	no greater than the actual value at 0.5D, 1.25R		

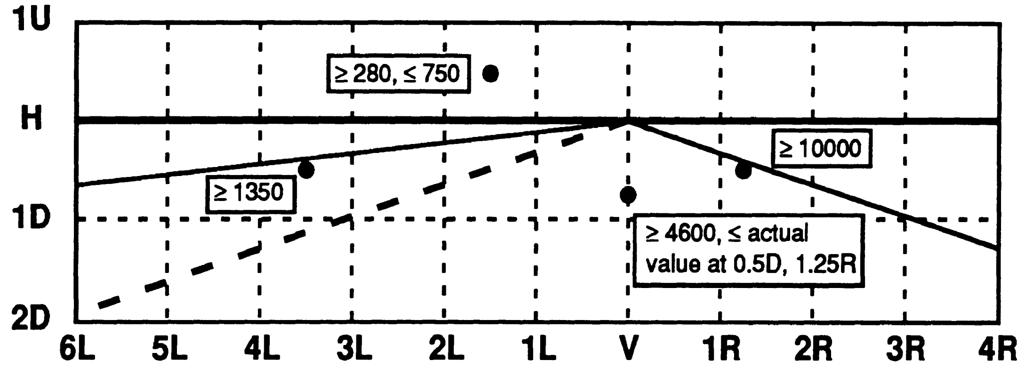


Figure 5. The recommended test points and the photometric limits for a test voltage of 12.8 V, overlaid on a drawing of a straight, level roadway viewed from the perspective of a headlamp (lane width: 3.7 m, headlamp lateral position: center of the lane, and headlamp mounting height: 0.6 m). The figure illustrates the fact that for a lane width of 3.7 m the rightmost and leftmost points are just inside the edge lines of the road. For a lane width of 3.0 m (as assumed by the current ECE standard), these two points overlie the edge lines exactly.

CONCLUSIONS

This research was designed to determine a small set of low-beam test points for recommendation as the common test points throughout the world. We considered three sets of inputs in arriving at the recommendations: (1) expert opinion, based on a worldwide survey of 119 experts in lighting and vision, (2) current practice, based on an analysis of candela matrices of 150 production low beams, and (3) scientific evidence concerning visibility and glare under nighttime driving conditions.

Expert opinion and scientific evidence did not fully converge on the same test points. The most likely reason for this is that expert opinion might already take into account current practice and the limits imposed by current technologies. While there were differences between the locations of the test points based on expert opinion and scientific evidence, the main difference was in the amount of light recommended for points at which objects need to be seen. While experts recommended light levels comparable to current production outputs (see Tables 10 through 13), the test points based exclusively on scientific evidence (Table 24) indicate that the desirable illumination for seeing purposes is more than ten times the current levels. Although, the test points and their photometric limits based exclusively on scientific evidence (Table 24) should be viewed only as ideal, we should aim in the future to explore technologies that would make approximations to these test points feasible.

Our recommended four test points, which are a compromise among expert opinion, current practice, and scientific evidence on visibility and glare, are summarized in Table 35. These recommendations take into account the different test voltages used throughout the world, but they disregard the fact that the locations of the two lamps on a vehicle are not identical (cf., Burgett, Matteson, Ulman, and Van Iderstine, 1989).

The proposed recommendations do not necessarily constitute a blueprint for improved low-beam headlighting. That was not the goal of this research. The goal was to provide a viable recommendation for partial harmonization of the existing divergent approaches. However, the actual differences in photometric standards are not great, especially when different test voltages are taken into account. Thus, the proposed test points would require, generally, only modest adjustments to existing standards, especially in the U.S. and Europe.

The proposed four test points do not cover all of the visual-performance functions required from a low-beam headlighting system. (Probably the next function that should be dealt with is the illumination for retroreflective traffic signs, to be controlled by a test point in the upper right quadrant.) Consequently, if the proposed set of test points for partial harmonization meet with acceptance, serious consideration should be given to the examination of the feasibility of extending this approach to determining additional test points for full harmonization.

REFERENCES

Bergin, J. (1992, May). [Light output from a halogen source as a function of voltage]. Unpublished handout. Meeting of the Society of Automotive Engineers (SAE) Lighting Committee, Nashville.

Bhise, V.D., Farber, E.I., Saunby, C.S., Troell, G.M., Walunas, J.B., and Bernstein, A. (1977). *Modeling vision with headlights in a system context* (SAE Technical Paper Series No. 770238). Warrendale, PA: Society of Automotive Engineers.

Burgett, A., Matteson, L., Ulman, M., and Van Iderstine, R. (1989). Relationship between visibility needs and vehicle-based roadway illumination. *Proceedings of the 12th International Conference on Experimental Safety Vehicles*, Volume II, pp. 765-774. Washington, D.C.: National Highway Traffic Safety Administration.

de Boer, J.B. (1967). Visual perception in road traffic and the field of vision of the motorist. In J.B. de Boer (Ed.), *Public lighting*. Eindhoven, The Netherlands: Philips Technical Library.

Donohue, R.J., LeFevre, R.L., and Watkins, L.D. (1992). International harmonization of motor vehicle safety regulations (Technical Paper No. 925200). *Proceedings of the 24th FISITA Congress,* Part 1, pp. 1-7. London, England: The Institution of Mechanical Engineers.

ECE (Economic Commission for Europe). (1986). *Agreement concerning the adoption of uniform conditions of approval and reciprocal recognition of approval for motor vehicle equipment and parts* (ECE Regulation 20). Geneva: United Nations.

Fisher, A.J. (1970). A basis for a vehicle headlighting specification. *IES Lighting Review* (Australia), *32*, No. 1 and 2.

Flannagan, M., Sivak, M., Ensing, M., and Simmons, C.J. (1989). *Effects of wavelength on discomfort glare from monochromatic sources* (Report No. UMTRI-89-30). Ann Arbor, Michigan: The University of Michigan Transportation Research Institute.

FMVSS (Federal Motor Vehicle Safety Standard). (1991). Standard No. 108. Lamps, reflective devices, and associated equipment. In, *Code of federal regulations [Title] 49*. Washington, D.C.: Office of the Federal Register.

Holladay, L.L. (1926). The fundamentals of glare and visibility. *Journal of the Optical Society of America and Review of Scientific Instruments*, *12*, 271-319.

JIS (Japanese Industrial Standard) D 5500B1-1984. (1984). Tokyo: Japanese Standards Association.

Kosmatka, W.J. (1992). *Obstacle detection rationale for upper beam intensity* (unpublished manuscript). Nela Park, Ohio: GE Lighting.

Leibowitz, H.W. (1987). Ambient illuminance during twilight and from the full moon. In *Night vision: Current research and future directions* (pp. 19-22). Washington, D.C. National Academy Press.

Leibowitz, H.W. and Owens, D.A. (1991). Can normal outdoor activities be carried out during civil twilight? *Applied Optics, 30,* 3501-3503.

Mortimer, R.G. and Olson, P.L. (1974). *Development and use of driving tests to evaluate headlamp beams* (Report No. UM-HSRI-74-14). Ann Arbor, Michigan: The University of Michigan, Highway Safety Research Institute.

NHTSA (National Highway Traffic Safety Administration) (1992). Docket No. 85-15; Notice 12. *Federal Register, 58*(7), 3856-3868.

Olson, P.L. (1977). *The relative merits of different low-beam headlighting systems* (Report No. UM-HSRI-77-55). Ann Arbor: The University of Michigan, Highway Safety Research Institute.

Olson, P.L., Aoki, T., Battle, D.S., and Flannagan, M.J. (1990). *Development of a headlight system performance evaluation tool* (Report No. UMTRI-90-41). Ann Arbor, Michigan: The University of Michigan Transportation Research Institute.

Olson, P.L. and Sivak, M. (1983). Automotive headlighting: Effect of foreground illumination. *Perceptual and Motor Skills, 57,* 1036-1038.

Olson, P.L. and Sivak, M. (1984a). Discomfort glare from automotive headlights. *Journal of the Illuminating Engineering Society, 13,* 296-303.

Olson, P.L. and Sivak, M. (1984b). Glare from automobile rear-vision mirrors. *Human Factors, 26,* 269-282.

Owens, D.A., Francis, E.L., and Leibowitz, H.W. (1989). *Visibility distance with headlights: a functional approach* (SAE Technical Series No. 890684). Warrendale, PA: Society of Automotive Engineers.

Padmos, P. and Alferdinck, J.W.A.M. (1988). *Optimal light intensity distribution of the low beam of car headlamps* (Report No. IZF 1988 C-9/E). Soesterberg, The Netherlands: TNO Institute for Perception.

Rumar, K., Helmers, G., and Thorell, M. (1973). *Obstacle visibility with European Halogen H4 and American sealed beam headlights* (Report No. 133). Uppsala, Sweden: Uppsala University, Department of Psychology.

SAE (Society of Automotive Engineers). (1984). *Sealed beam headlamp units for motor vehicles* (SAE Recommended Practice J579). Warrendale, PA: SAE.

SAE (Society of Automotive Engineers). (1991). *Low beam design guide and conformance requirements* (Proposal 7A, Headlamp Beam Pattern Task Force). Warrendale, PA: SAE.

Schmidt-Clausen, H.J. and Bindels, J.T.H. (1974). Assessment of discomfort glare in motor vehicle lighting. *Lighting Research and Technology, 6*, 79-88.

Sivak, M., Flannagan, M., Ensing, M., and Simmons, C.J. (1991). Discomfort glare is task dependent. *International Journal of Vehicle Design, 12*, 152-159.

Sivak, M., Gellatly, A.W., and Flannagan, M. (1991). *Minimum light above horizontal of low-beam headlamps for nighttime legibility of traffic signs* (Report No. UMTRI-91-3). Ann Arbor, Michigan: The University of Michigan Transportation Research Institute.

Sivak, M., Helmers, G., Owens, D.A., and Flannagan, M. (1992). *Evaluation of proposed low-beam headlighting patterns* (Report No. UMTRI-92-14). Ann Arbor, Michigan: The University of Michigan Transportation Research Institute.

Sivak, M. and Olson, P.L. (1985). Optimal and minimal luminance characteristics for retroreflective highway signs. *Transportation Research Record, 1027*, 53-57.

Sivak, M., Olson, P.L., and Zeltner, K.A. (1989). Effect of prior headlighting experience on ratings of discomfort glare. *Human Factors, 31*, 391-395.

Taniguchi, M., Kitagawa, M., and Jin, M. (1989). *Research in Japan on the photometric design guidelines of headlamp passing beams.* Tsukuba, Japan: Japan Automobile Research Institute.

VEDILIS. (1990). *System specifications for field test.* Eureka Project 273.

Woltman, H.L. and Szczech, T.J. (1989). Sign luminance as a methodology for matching driver needs, roadway variables, and signing materials. *Transportation Research Record, 1213*, 21-26.