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16. Abstract

This analytical study examined the potential benefits of applying two embodiments of adaptive lighting to the U.S. and European low-beam patterns: curve lighting that involves shifting the beam horizontally into the curve, and motorway lighting that involves shifting the beam vertically upward.

The curve lighting simulations paired 80-m radius left and right curves with a horizontal beam shift of 15°, and 240-m radius curves with a shift of 10°. The motorway lighting simulations involved upward aim shifts of 0.25° and 0.5°. For both curve and motorway lighting, changes in both visibility and glare illuminance were considered. Market-weighted model year 2000 U.S. and European beam patterns were used.

We conclude that curve lighting, as simulated here, would substantially improve seeing performance on curves for both types of beams. On left curves (but not on right curves) there would be an increase in disability glare for oncoming traffic. No major discomfort-glare problems would be expected. Although the shifted U.S. beams were found to perform slightly better overall than the shifted European beams, the main difference in performance is between the shifted and nominally aimed beams.

Motorway lighting, as simulated here, would also substantially improve seeing performance, with the benefits already present at an upward shift of 0.25°. Because the increases in glare illuminance would be minor, and because motorways often incorporate median barriers or wide separations between lanes of opposing traffic, we do not expect substantial problems with increased glare. The European beams benefit more from this embodiment of motorway lighting than do the U.S. beams. (This is the case because under nominal aim the European beams provide less visibility illuminance and their vertical gradient is steeper.) Nevertheless, the nominally aimed U.S. beams tend to outperform the European beams shifted upward 0.25°.

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INTRODUCTION

A majority of research concerning the low (passing) beam of vehicle headlamps has dealt with attempts to develop a single optimal beam pattern. The hope has been that such a beam pattern would provide satisfactory visibility of all important targets (such as pedestrians, road delineation, and traffic signs), under all relevant conditions (including varieties of road geometry, and during rain, fog, and snow), for all drivers (young and old), *and* at the same time not be glaring for oncoming traffic or preceding traffic (via rearview mirrors). That is a tall order that has not yet been met. For example, the current low beams do not provide sufficiently long visibility for low-contrast objects, resulting in visibility distances that are shorter than the stopping distances from normal travel speeds (e.g., Olson and Sivak, 1983).

It may be possible to exceed the performance of any static beam pattern with dynamically controllable illumination. The basic concept is not new. Even the now famous 1948 Tucker automobile with a single, center-mounted headlamp that turned in response to movement of the steering wheel, was not the first embodiment of this concept. The concept dates to at least the late 1920s (e.g., the Pilot-Ray system). Modern, more complex versions of dynamically controllable headlamp illumination are usually referred to as adaptive or intelligent headlamp systems.

In his comprehensive review of adaptive lighting, Rumar (1997) identified the Lucas Autosensa (Jones and Hicks, 1970) as probably the first advanced adaptive headlighting system built in a prototype series, but never implemented. After somewhat of a hiatus, the late 1980s and early 1990s saw a major revival of interest in adaptive lighting, especially in Japan (e.g., Wada et al., 1989; Kobayashi and Hayakawa, 1991; Sivak et al., 1994; Gotoh and Aoki, 1996; and Aoki et al., 1997).

The next phase of increased research into adaptive lighting started in Europe with a Eureka Project called AFS (Advanced Frontlighting Systems). (See AFS, 1994 and 1996 for early AFS documents.) The current AFS plans specify adaptive lighting for the following six specific situations:

- curves (“bending” light)
- motorways (divided, high-speed roads with large-radius curves)
- adverse weather (wet roads, rain, snowfall, and fog)
- overhead signs
- country (rural)
- town (street lighting, unprotected road users, and intersections)

This European-originated phase of interest in adaptive lighting currently continues throughout the world. The two most promising AFS approaches (curve lighting and motorway lighting) involve, in some embodiments, only horizontal or vertical displacements of a given base beam pattern. Specifically, curve lighting (or bending or swiveling light) involves controlling the horizontal aim of the beam pattern (or a part of it), depending on variables such as the radius of the curve and the speed of the vehicle. Analogously, one implementation of motorway lighting involves adjusting the vertical aim of the beam pattern in response to speed. Of interest in the context of curve and motorway lighting are the consequences of applying such aim manipulations to the U.S. or European beam patterns. Because the differences between these two types of beam pattern are not trivial (see Schoettle, Sivak, and Flannagan, 2001 for market-weighted descriptions of both beam patterns), it is likely that these two beam patterns will benefit differently from such implementations of adaptive lighting. The present study was designed to address this issue; it did not deal with evaluating the benefits of adaptive lighting in comparison to other alternatives, such as using a fixed beam with a wider spread (for curves) or a fixed beam with longer reach (for motorways).

Specifically, the present study consisted of three sets of analyses. The first set examined the differences between the current U.S. and European low-beam patterns. The second set of analyses investigated the effects of changing the horizontal aim of the U.S. and European low beams for curve lighting. The third set studied the effects of changing the vertical aim of the U.S. and European low beams for motorway lighting.

Differences Between the Current U.S. and European Low Beams and Their Influence on Headlamp Performance

Differences between the current U.S. and European low beams

A recently completed study (Schoettle, Sivak, and Flannagan, 2001) presented market-weighted information about the photometry of low-beam headlamps in the U.S. and Europe. That study provided detailed candela matrices based on photometry of lamps for the 20 best selling vehicles each in the U.S. and Europe for model year 2000. The luminous intensities (at 12.8 V) from the individual lamps were weighted by the sales figures of the respective vehicles to derive market-weighted distributions of light output. The isocandela diagrams of the median U.S. and European values of these distributions are shown in Figure 1.

Figure 2 presents the differences between the median U.S. and European values for the central region between 7° left and 7° right. In other words, Figure 2 plots for each point in the candela matrix the differences between the median luminous intensity in the U.S. and the median luminous intensity in Europe. The blue colors indicate areas of the beam pattern where the U.S. median values are greater than the European median values. Conversely, the red colors indicate areas where the European median values are greater than the U.S. median values.

To the left of the vertical, the European lamps provide more illumination in the area that extends downward from about 3/4° below the horizontal (i.e., downward from approximately the location of the cutoff of the European low beams [0.6° below the horizontal]); conversely, above about 3/4° below the horizontal, the U.S. low beams provide more illumination. To the right of the vertical, the European lamps provide more illumination roughly below a line that extends from about the vertical, 1° down to about 7° right, 3.5° down (and in a small area near the horizontal to the right of about 4° right). In the other areas to the right of the vertical, the U.S. lamps provide more illumination.

Restating these observations, we confirm the following, generally acknowledged, differences: Compared to the U.S. lamps, the European lamps provide more illumination in the foreground, more seeing light to the left (except near the horizontal), less seeing light to the right, less illumination for overhead traffic signs, and less glare for oncoming traffic.

The largest single difference (in this central region) in favor of the European low beams is 4,858 cd at 2° left, 2° down. Conversely, the largest single difference in favor of the U.S. low beams is 10,464 cd at 3° right, 1.5° down.

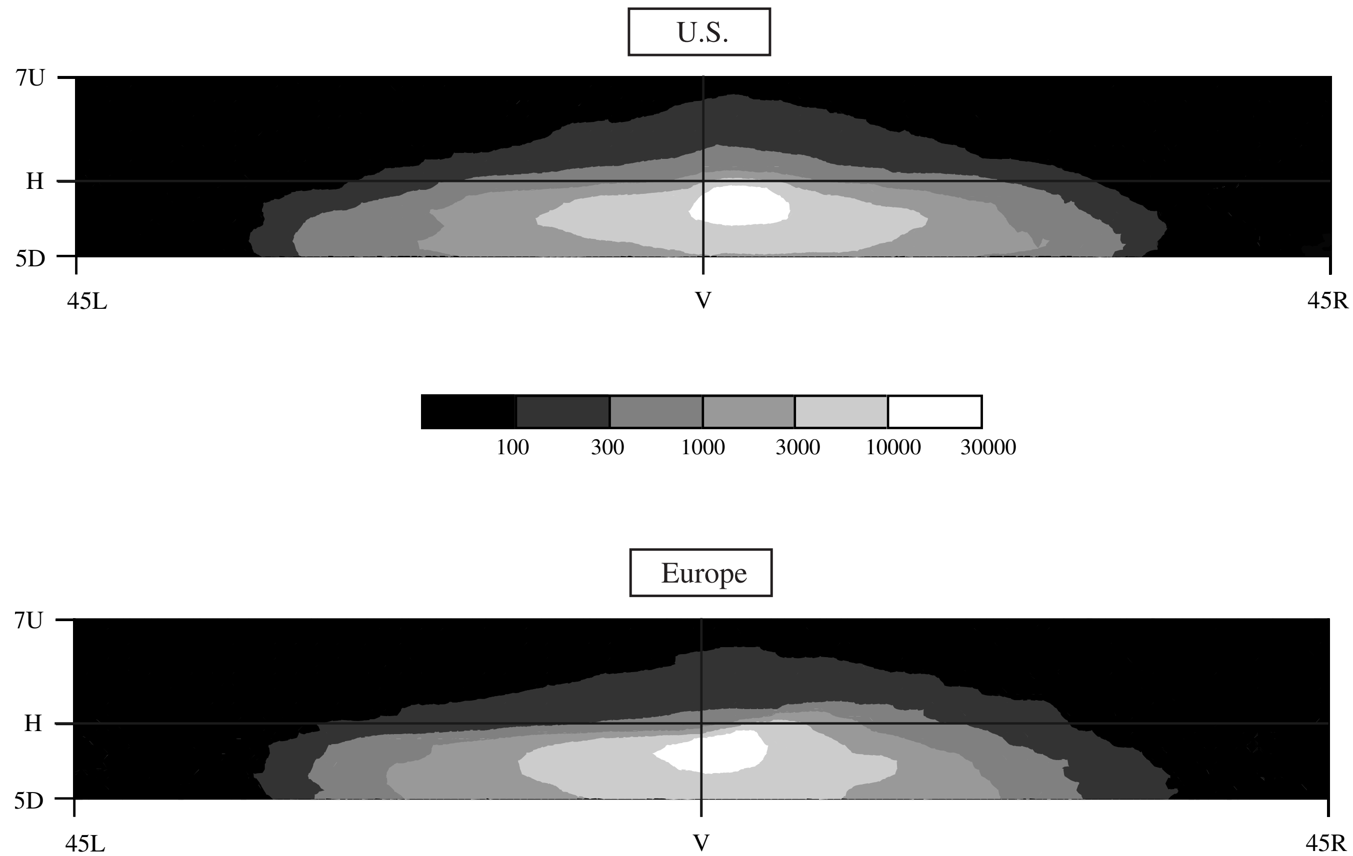

Figure 1. Isocandela diagrams of the median market-weighted U.S. low-beam pattern (top panel) and the median market-weighted European low-beam pattern (bottom panel). (Adapted from Schoettle, Sivak, and Flannagan, 2001).

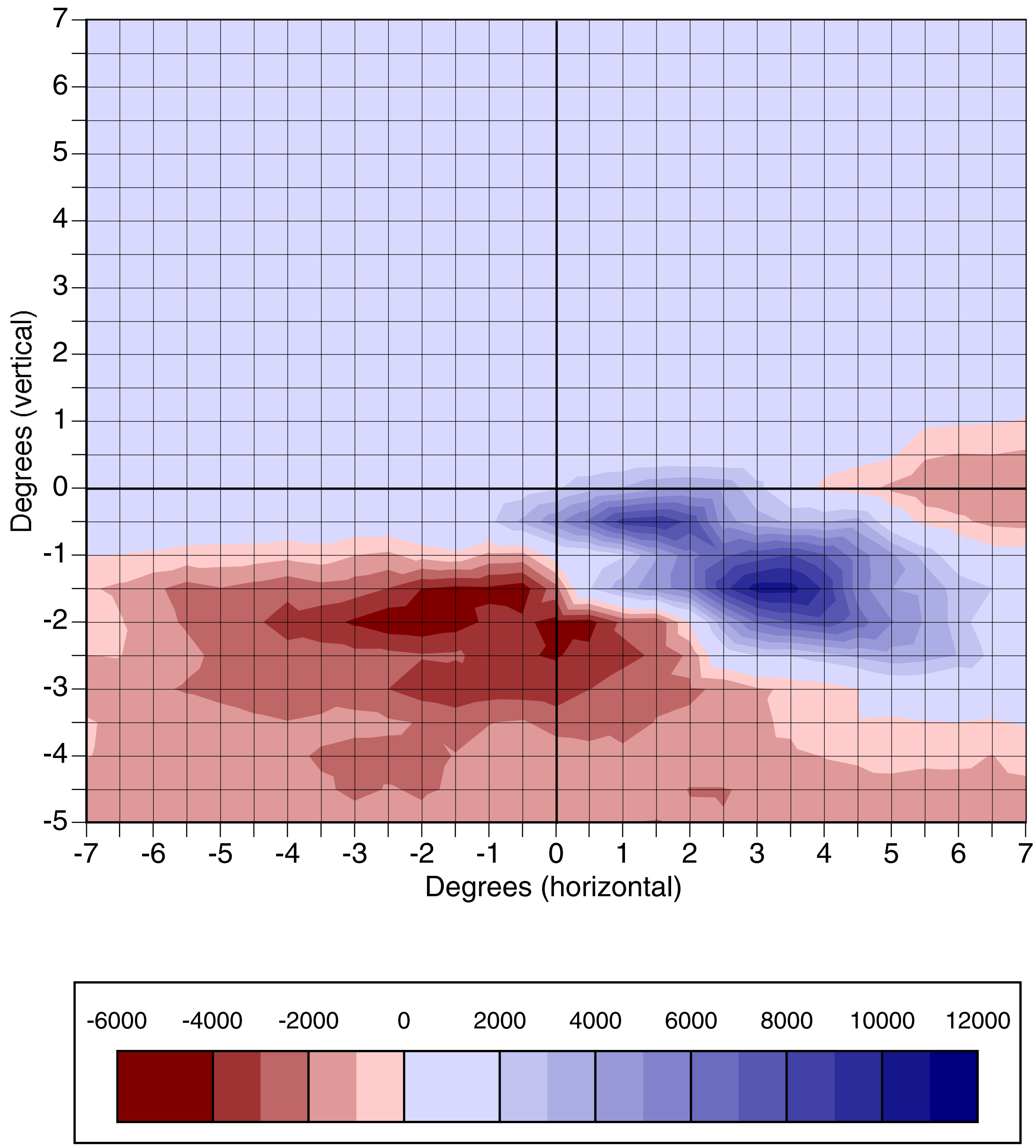

Figure 2. Differences between the median U.S. and the median European luminous intensities in the central part of the two beam patterns. The blue colors indicate areas where the U.S. median values are greater than the European median values. Conversely, the red colors indicate area where the European median values are greater than the U.S. median values.

Because the human visual system is more sensitive to differences between logarithmic (as opposed to linear) units, Figure 2 (which plots differences in linear units) does not accurately represent the differential effects of the two types of beam patterns on driver vision. Consequently, Figure 3 presents the differences between the logarithms of the median values. As in Figure 2, the blue colors in Figure 3 indicate regions of the beam pattern where the log intensities are greater for the U.S. beam pattern. Conversely, the red colors indicate regions where the log intensities are greater for the European beam pattern.

Although the total coverage of all blue colors (and all red colors) is, obviously, the same in both Figure 2 and Figure 3, the magnitudes of the differences in these two figures are not the same. (There are some slight differences in the borders between the blue and red areas that are caused by the differences in interpolation in the linear and logarithmic domains, respectively.) In Figure 3, we see that all of the differences in favor of the European beam in the foreground and on the left side of the beam pattern are less than a third of a log unit. In the area near the horizontal and to the right of about 6° right, the differences exceed a third of a log unit, with the largest single difference being 0.45 log cd (log 1853 cd minus log 662 cd) at 7° right, 0.5° up. The largest differences in log terms (more than 2/3 of a log unit) in favor of the U.S. beam pattern are near the horizontal and between about the vertical and 2° right, with the largest single difference being 0.81 log cd (log 4467 cd minus log 698 cd) at 1.5° right, 0° vertical.

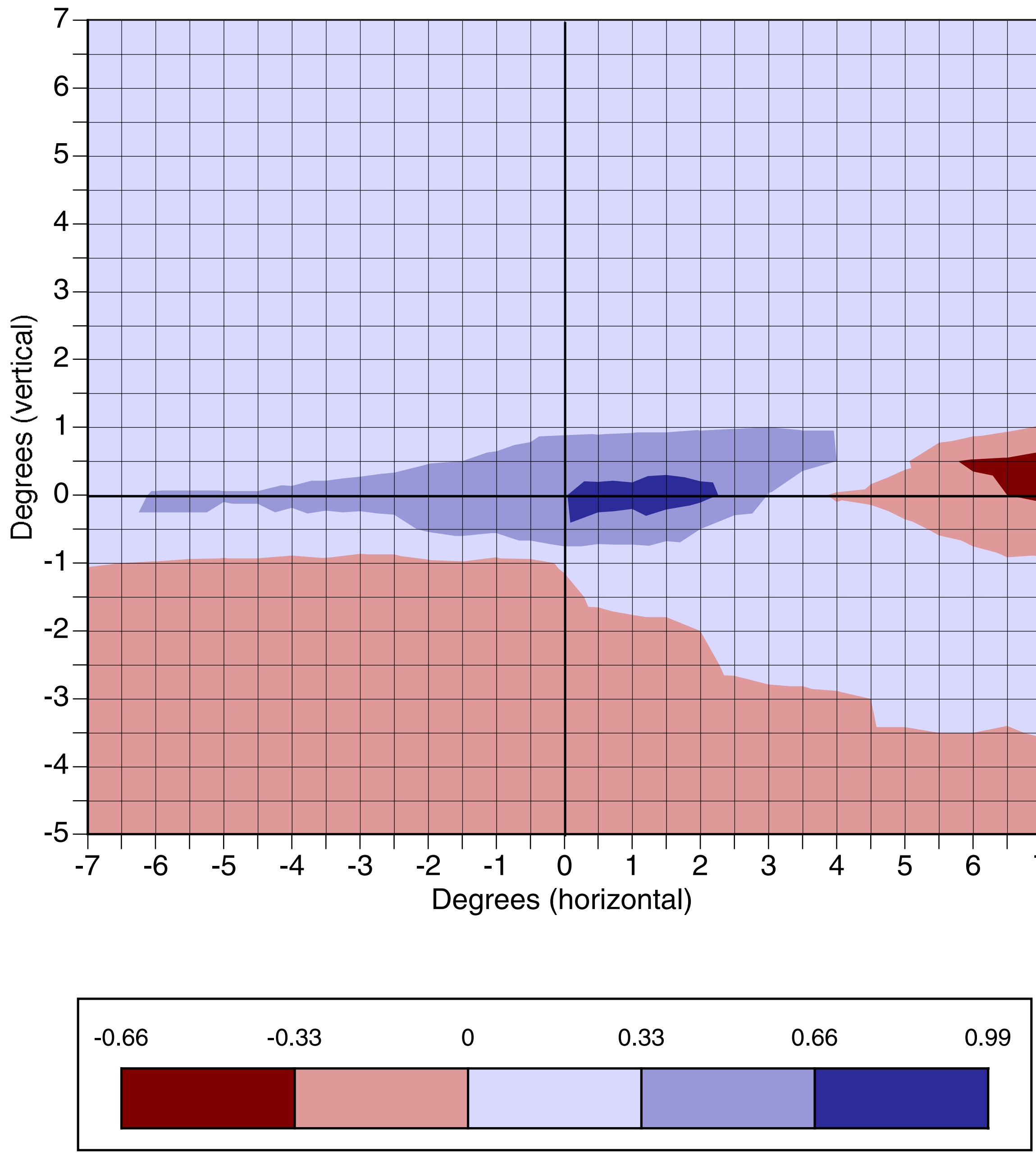

Figure 3. Differences between the log median U.S. and the log median European luminous intensities in the central part of the two beam patterns. The blue colors indicate areas where the U.S. median values are greater than the European median values. Conversely, the red colors indicate area where the European median values are greater than the U.S. median values.

Effects of the differences between the beam patterns on performance

We evaluated the effects of the differences between the median market-weighted beam patterns on 16 headlamp performance aspects (Sivak et al., 2000). These aspects are listed in Table 1. For each of the performance aspects, a typical geometric situation was specified in terms of longitudinal, lateral, and vertical positions (also in Table 1), and the corresponding visual angles from each of the two headlamps were calculated (see Table 2).

Table 1
Positions of representative locations of the performance aspects, where *x* is the longitudinal distance from the headlamps, *y* is the lateral distance from the vehicle centerline, and *z* is the vertical distance from the ground. (All distances are in meters. From Sivak et al., 2000.)

Performance aspect	*x*	*y*	*z*
Visibility of a right pedestrian and road delineation at 100 m	100	1.85	0
Visibility of a right pedestrian and road delineation at 50 m	50	1.85	0
Visibility of a left pedestrian and road delineation at 100 m	100	-5.55	0
Visibility of a left pedestrian and road delineation at 50 m	50	-5.55	0
Visibility of a retroreflective sign; right shoulder at 150 m	150	6.15	2.10
Visibility of a retroreflective sign; center overhead at 150 m	150	0	6.10
Visibility of a retroreflective sign; left shoulder at 150 m	150	-9.85	2.10
Visibility of a vehicle rear reflex reflector; right side at 20 m	20	0.60	0.75
Visibility of a vehicle rear reflex reflector; left side at 20 m	20	-0.60	0.75
Visibility of a target near the road expansion point	∞	0	0.62
Glare towards an oncoming driver at 50 m	50	-3.35	1.11
Glare towards a left mirror in the right adjacent lane at 20 m	20	2.83	0.98
Glare towards a center mirror in the same lane at 20 m	20	0	1.24
Glare towards a right mirror in the left adjacent lane at 20 m	20	-2.83	0.98
Glare from wet pavement towards an oncoming driver at 50 m	17.9	-1.20	0
Foreground illumination at 15 m	15	0	0

Table 2
Angles (in degrees) of the representative locations for the performance aspects, with respect to each of the two headlamps. (From Sivak et al., 2000.)

Performance aspect	Left lamp	Right lamp
Visibility of a right pedestrian and road delineation at 100 m	1.4R, 0.4D	0.7R, 0.4D
Visibility of a right pedestrian and road delineation at 50 m	2.8R, 0.7D	1.5R, 0.7D
Visibility of a left pedestrian and road delineation at 100 m	2.9L, 0.4D	3.5L, 0.4D
Visibility of a left pedestrian and road delineation at 50 m	5.7L, 0.7D	7.0L, 0.7D
Visibility of a retroreflective sign; right shoulder at 150 m	2.6R, 0.6U	2.1R, 0.6U
Visibility of a retroreflective sign; center overhead at 150 m	0.2R, 2.1U	0.2L, 2.1U
Visibility of a retroreflective sign; left shoulder at 150 m	3.5L, 0.6U	4.0L, 0.6U
Visibility of a vehicle rear reflex reflector; right side at 20 m	3.3R, 0.4U	0.1R, 0.4U
Visibility of a vehicle rear reflex reflector; left side at 20 m	0.1L, 0.4U	3.3L, 0.4U
Visibility of a target near the road expansion point	0, 0	0, 0
Glare towards an oncoming driver at 50 m	3.2L, 0.6U	4.5L, 0.6U
Glare towards a left mirror in the right adjacent lane at 20 m	9.6R, 1.0U	6.5R, 1.0U
Glare towards a center mirror in the same lane at 20 m	1.6R, 1.8U	1.6L, 1.8U
Glare towards a right mirror in the left adjacent lane at 20 m	6.5L, 1.0U	9.6L, 1.0U
Glare from wet pavement towards an oncoming driver at 50 m	2.0L, 2.0D	5.6L, 2.0D
Foreground illumination at 15 m	2.1R, 2.4D	2.1L, 2.4D

Table 3 presents the combined luminous intensities from the two lamps for the median U.S. beam pattern and for the median European beam pattern. These calculations assumed a headlamp mounting height of 0.62 m, lamp-to-lamp separation of 1.12 m, and driver eye height of 1.11 m (Sivak et al., 1996).

Table 3
Differences between the combined luminous intensities from the left and right lamps for the median U.S. beam pattern and the median European beam pattern.

Performance aspect	U.S. (cd)	Europe (cd)	U.S. as % of Europe
Visibility of a right pedestrian and road delineation at 100 m	18698	5436	344
Visibility of a right pedestrian and road delineation at 50 m	33919	21940	155
Visibility of a left pedestrian and road delineation at 100 m	3246	1706	190
Visibility of a left pedestrian and road delineation at 50 m	4638	3724	125
Visibility of a retroreflective sign; right shoulder at 150 m	2419	765	316
Visibility of a retroreflective sign; center overhead at 150 m	605	363	167
Visibility of a retroreflective sign; left shoulder at 150 m	953	544	175
Visibility of a vehicle rear reflex reflector; right side at 20 m	3496	1478	236
Visibility of a vehicle rear reflex reflector; left side at 20 m	2012	695	290
Visibility of a target near the road expansion point	4794	1069	448
Glare towards an oncoming driver at 50 m	970	543	178
Glare towards a left mirror in the right adjacent lane at 20 m	768	971	79
Glare towards a center mirror in the same lane at 20 m	676	393	172
Glare towards a right mirror in the left adjacent lane at 20 m	545	357	153
Glare from wet pavement towards an oncoming driver at 50 m	12470	19309	65
Foreground illumination at 15 m	22811	26607	86

The data in Table 3 quantify the general observations made above when discussing the patterns evident in Figure 2. Of primary interest are the following findings: First, the U.S. lamps provide approximately three times the illumination for right-side targets at 100 m, and two times the illumination for left-side targets at 100 m. Second, the increase in illumination with the U.S. lamps for retroreflective signs ranges up to about three-fold (depending on the location of the sign). Third, the glare illumination for an oncoming driver is about twice as large for the U.S. lamps as for the European lamps, but the European lamps provide more wet-road-reflected glare (because of increased foreground illumination) than do the U.S. lamps. Fourth, although the U.S. lamps provide more glare illumination on the center mirror of a car in the same lane and on the right mirror for a car in the left adjacent lane, they provide less glare illumination on the left mirror of a car in the right adjacent lane.

Curve Lighting

General approach

In our simulations of the benefits of applying curve lighting to the two beam patterns, we used two different fixed-radius curves (representing two different speed scenarios) and we applied a fixed horizontal shift to the beam pattern (of a different magnitude for each curve). Of interest were the amount of the combined visibility illumination from the left and right lamp directed toward targets along the right edge of the curve, and the combined glare illumination from the two lamps directed toward an oncoming driver.

Curve scenarios and beam-pattern shifts

The high-speed scenario used a curve with a constant radius of 240 m. For this curve we applied a horizontal shift in the beam pattern of 10°. For the low-speed scenario we used a curve with a constant radius of 80 m. The horizontal shift selected for this curve was 15°.

In both scenarios, the lane width was 3.6 m. Both vehicles (the one with the lamps in question and an oncoming vehicle in the adjacent lane) were positioned in the center of the respective lanes. Both right curves and left curves were considered. Distances into the curve were measured along the left edge of the lane with the lamps in question (i.e., along the line dividing the lane of travel and the left adjacent lane). The distances that were tested correspond to deflection angles in increments of 10°.

Median market-weighted U.S. and European low beams from Schoettle et al. (2001) were used. The headlamp mounting height was set at 0.62 m, lamp separation at 1.12 m, and driver eye height at 1.11 m (Sivak et al., 1996).

Evaluating the visibility and glare illumination

For quantifying the visibility illumination, the relevant targets (e.g., the feet of a pedestrian and road delineation) were assumed to be positioned on the ground and on the right edge line of the lane of travel. The two dependent variables of interest were the combined illuminance from the left and right lamps incident on this edge line (visibility illuminance), and the combined illuminance from the two lamps reaching the eyes of an oncoming driver (glare illuminance).

240-m radius curve, 10° beam shift

Results

The top panel of Figure 4 presents the combined visibility illuminance from the two lamps incident on the right edge line of a left curve with a radius of 240 m, from both the U.S. and European low beams, under nominal aim and under a 10° beam shift to the left. Analogous information for a right curve with the same radius is shown in the bottom panel of Figure 4.

The data in Figure 4 reveal the following trends: First, for both curves under nominal aim, the U.S. beam pattern provides more illuminance than the European beam pattern. Second, the advantage of the U.S. beam is more pronounced on the left curve. Third, shifting the aim 10° into the curve benefits both beam patterns. Fourth, with the shift, the visibility illuminance on the left curve is greater for the U.S. beams at all tested distances. Fifth, with the shift, the visibility illuminance on the right curve is substantially greater with the U.S. beams at intermediate distances (around 85 m); at longer distances the advantage is reversed, but the differences here are smaller than the differences at intermediate distances.

The combined glare illuminance from the left and right lamps reaching the eyes of an oncoming driver on the two curves is shown in Figure 5. In addition, Figure 5 also shows the calculated values of illuminances that would produce a DeBoer discomfort rating of 4, using the Schmidt-Clausen and Bindels equation (Schmidt-Clausen and Bindels, 1974). In these calculations, we made two assumptions. First, we assumed that the adaptation luminance was 1 cd/m^2. Second, in calculating the glare angle for each position in the curve, we assumed that the oncoming driver was looking at the tangent point of the inside curve. (Land and Lee, 1994 have shown that, in both left and right curves, drivers tend to fixate on the tangent point of the inside curve.)

The data in Figure 5 indicate the following patterns: First, on the left curve under nominal aim the U.S. beams provide more illuminance. Second, on the right curve under nominal aim, the differences are small, except that the European beams provide more glare illuminance at intermediate distances (around 85 m), while the U.S. beams provide more glare at near distances (around 40 m). Third, shifting the aim 10° into the left curve increases the glare illuminance for both lamps. Fourth, for both types of lamps, shifting the aim into the right curve decreases the glare illuminance at near distances (around 40 m) and increases the glare illuminance at far distances (beyond about 125 m).

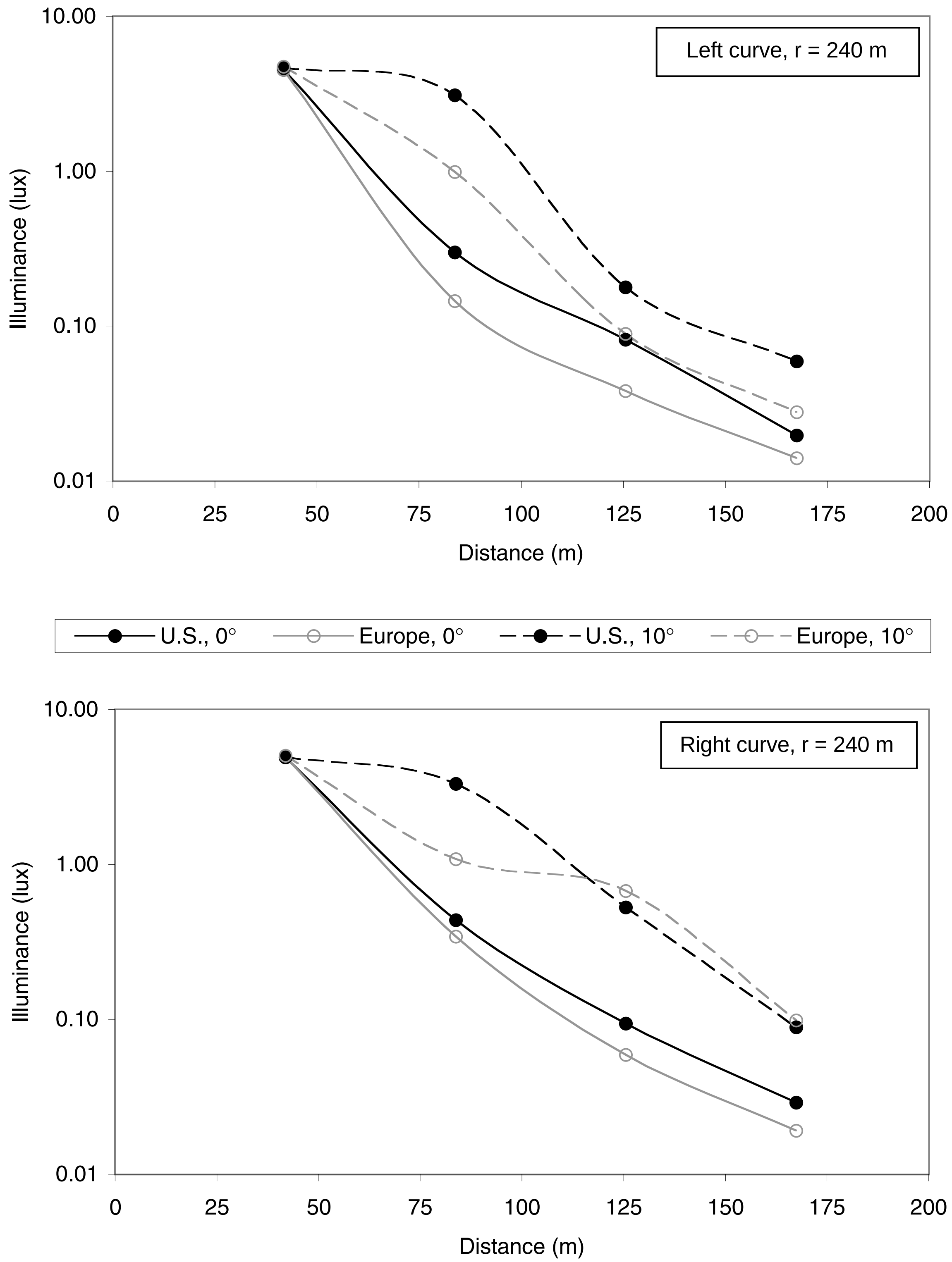

Figure 4. The combined visibility illuminance from the left and right lamps incident on the right edge line of curves with a radius of 240 m, from the U.S. and European low beams, under nominal aim and under a 10° beam shift into the curve.

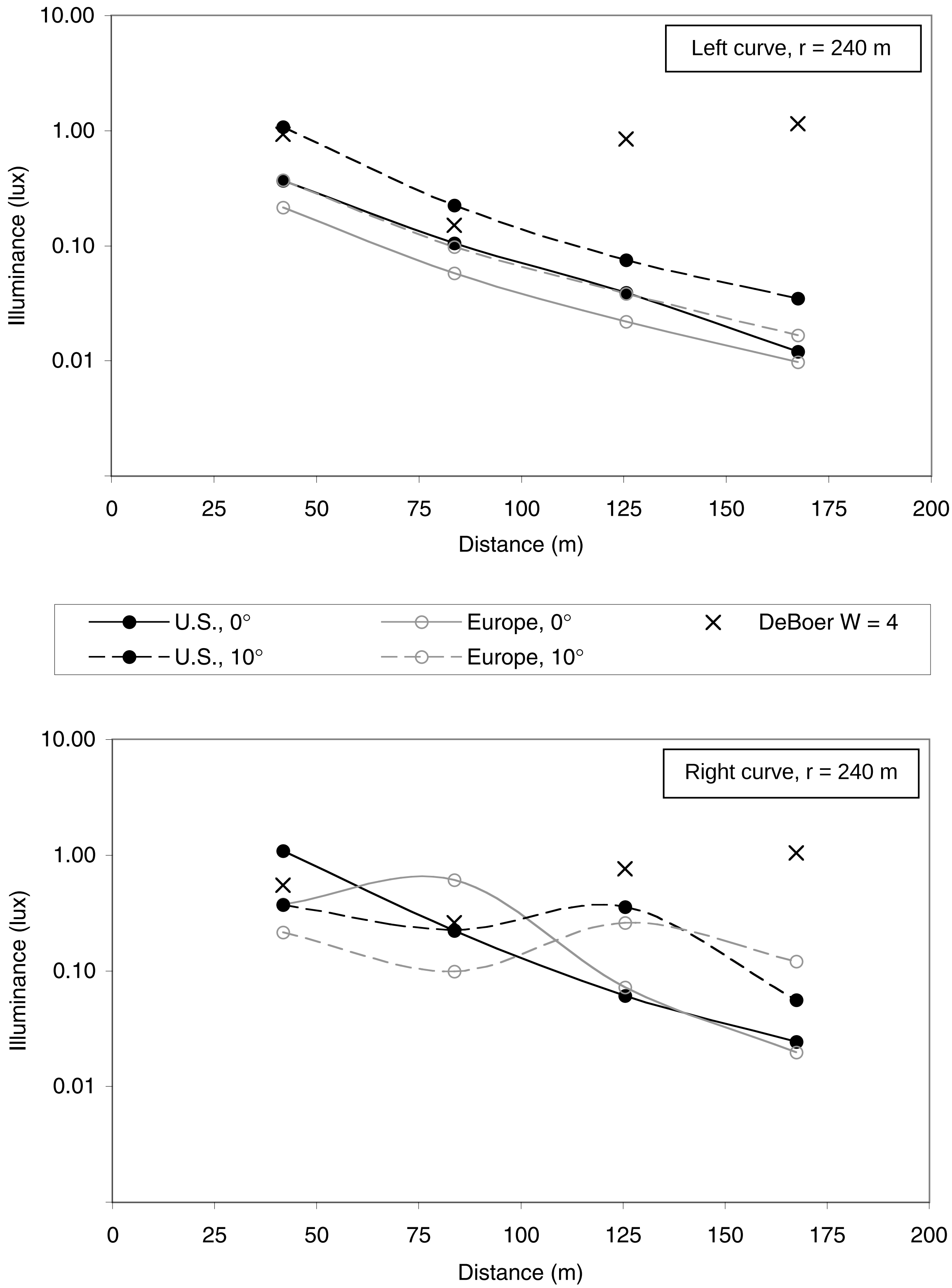

Figure 5. The combined glare illuminance from the left and right lamps reaching the eyes of an oncoming driver on curves with a radius of 240 m, from the U.S. and European low beams, under nominal aim and under a 10° beam shift into the curve. Also included are illuminances needed for a DeBoer discomfort-glare rating of 4.

Table 4 summarizes the main findings for the 240-m radii curves by rank ordering the four beam conditions.

Table 4
Rank ordering of the beam patterns in terms of the overall patterns of visibility illuminance and glare illuminance on curves with the radii of 240 m.

<table>
<tr><th rowspan="2">Rank order</th><th colspan="2">Left curve</th><th colspan="2">Right curve</th></tr>
<tr><th>Visibility</th><th>Glare</th><th>Visibility</th><th>Glare*</th></tr>
<tr><td>1 (best)</td><td>U.S., 10°</td><td>Europe, 0°</td><td>U.S., 10°</td><td>Europe, 10°</td></tr>
<tr><td>2</td><td>Europe, 10°</td><td rowspan="2">Europe, 10°
U.S., 0°
(tie)</td><td>Europe, 10°</td><td>U.S., 10°</td></tr>
<tr><td>3</td><td>U.S., 0°</td><td>U.S., 0°</td><td>Europe, 0°</td></tr>
<tr><td>4</td><td>Europe, 0 °</td><td>U.S., 10°</td><td>Europe, 0°</td><td>U.S., 0°</td></tr>
</table>

* This ranking is in reverse order of the maximum illuminance reached at any distance.

Implications

Unopposed seeing. For both left and right curves, there is a substantial increase (generally between half and a full log unit) in visibility illuminance with a shift of either beam 10° into the curve. Consequently, we conclude that using either the U.S. or the European beam pattern with a shift of 10° would improve seeing in either curve. For both curves, the best performance is obtained with the shifted U.S. beam pattern, and this advantage is especially pronounced on the left curve. However, the major differences are between the nominally aimed and shifted beams, as opposed to the differences between the U.S. and European beams (whether both nominally aimed or both shifted).

Disability glare. In the left curve, there is an increase (about half a log unit) in glare illuminance for oncoming traffic for either beam. This is of some concern from the disability-glare point of view. In a transition period, when only a few vehicles would be equipped with curve lighting, there would be a reduction in seeing for opposing traffic. However, in the right curve, shifting the beam would actually result in a decrease in glare illuminance at near distances, where the glare illuminance with the nominally aimed beams is the greatest. Although there is an increase in glare illuminance with the shifted beams at long distances, the glare illuminance with the nominally aimed beams is relatively low at those distances. Consequently, disability glare should not be a problem in the right curve.

Discomfort glare. In the left curve, for the European beams the increased glare illuminance never reaches the levels needed for a rating of 4 on the DeBoer discomfort-glare scale; for the U.S. beams this happens at the near distances, but even here the increased illuminances only slightly exceed the levels needed for a rating of 4. In the right curve, the drop in glare illuminance at near distances is such that the shifted illuminance (for both beam patterns) is below the values needed for a rating of 4. At far distances there is an increase in glare illuminance with the shift, but the glare illuminance with the nominally aimed beams is relatively low there, and thus the increased illuminance never exceeds the levels needed for a rating of 4. Finally, our calculations assumed that the oncoming driver is *always* fixating the tangent point of the inside curve. At certain distances, this strategy would lead to very small glare angles, and consequently, very low levels of illuminance needed for a rating of 4. Because drivers do not always fixate the tangent point, our calculations are rather conservative. This consideration, along with the fact that even with this conservative approach the glare illuminance rarely exceeds the levels needed for a rating of 4, we conclude that discomfort glare is unlikely to be a problem with the shifted beams.

80-m radius curve, 15° beam shift

Results

Figure 6 presents the combined visibility illuminance from the two lamps incident on the right edge line of a left curve with a radius of 80 m, from the U.S. and European low beams, under nominal aim and under a 15° beam shift into the curve. The combined glare illuminance from the left and right lamps reaching the eyes of an oncoming driver on the two curves is shown in Figure 7.

Examination of Figure 6 reveals the following trends: First, under nominal aim, the U.S. beam pattern provides more visibility illuminance on the right curve, while on the left curve the two beam patterns perform similarly. Second, for the right curve, shifting the aim 15° into the curve benefits both beam patterns throughout the range of tested distances, and these benefits are major (generally between half and a full log unit). Third, for the left curve, at very near distances (around 15 m) there is a *reduction* in visibility illuminance with the shifted beams. Because the visibility illuminance with the nominally aimed U.S. or European beams is very high at these distances, even after this reduction the visibility illuminance remains sufficiently high (i.e., above 10 lux). However, at intermediate and long distances, where the visibility illuminance with the nominally aimed beams is relatively low, there is an increase in the visibility illuminance for the shifted beams. Fourth, with the shift, the illuminance on the right curve is greater for the European beams at near distances, but greater for the U.S. beams at far distances. Fifth, with the shift, the illuminance on the left curve is greater for the U.S. beams throughout the tested range.

Turning to the glare illuminance (Figure 7), we see the following patterns: First, on the left curve under nominal aim, the U.S. beam pattern provides more illuminance, but the differences are small. Second, on the right curve under nominal aim, although there is more illuminance with the U.S. beams at near and far distances, there is more illuminance with the European beams at intermediate distances (around 40 m). Third, shifting the aim 15° into the left curve increases the glare illuminance for both lamps, but more so for the U.S. lamps; the average magnitude of these increases is about half a log unit. Fourth, shifting the aim into the right curve decreases the glare illuminance at near distances and increases the glare illuminance at intermediate and long distances (for both types of lamps); the increases at long distances are greater for the European beams. Fifth, the changes in the glare illuminance over distance are smaller with the beam shift than without the beam shift.

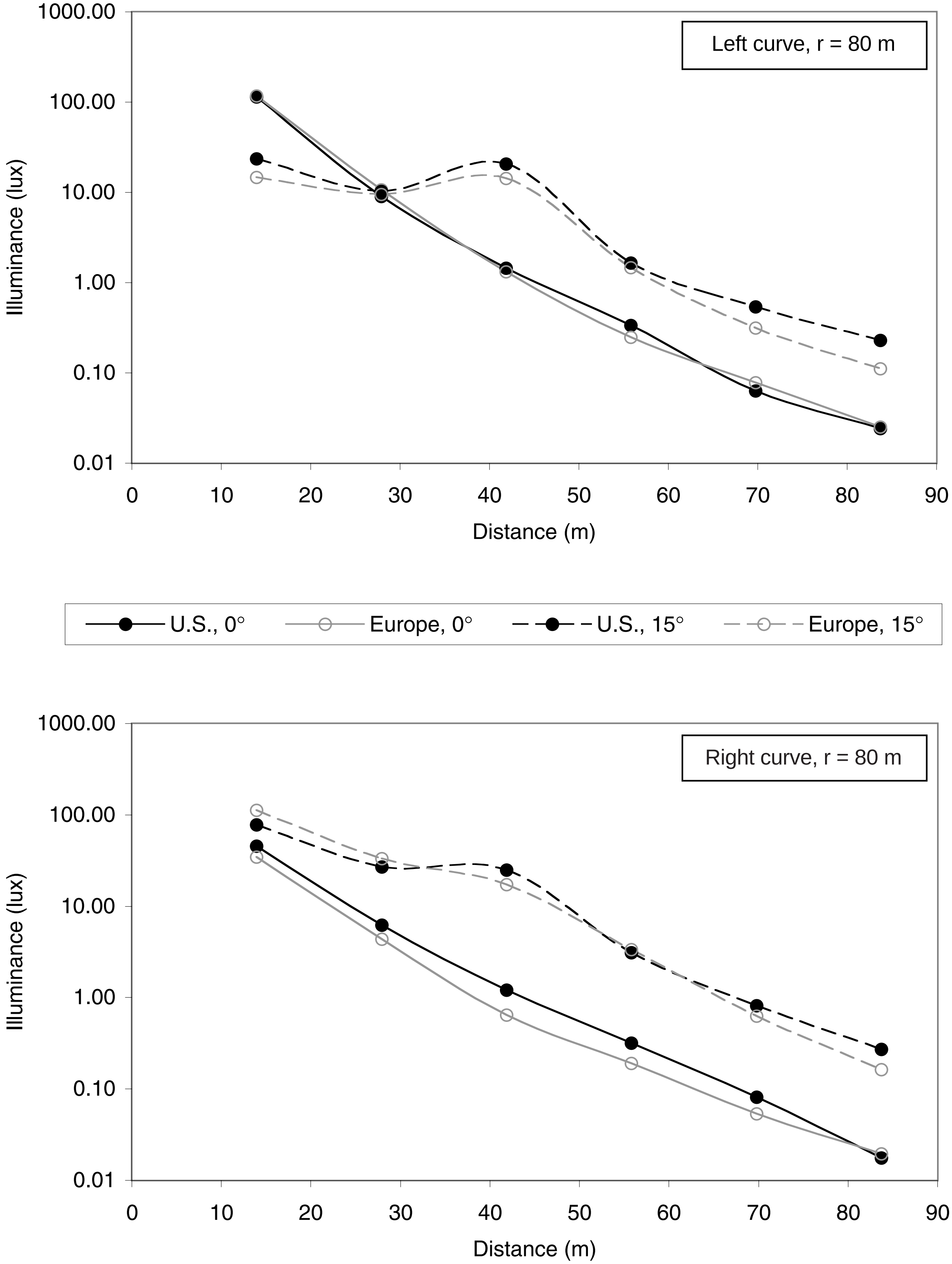

Figure 6. The combined visibility illuminance from the left and right lamps incident on the right edge line of curves with a radius of 80 m, from the U.S. and European low beams, under nominal aim and under a 15° beam shift into the curve.

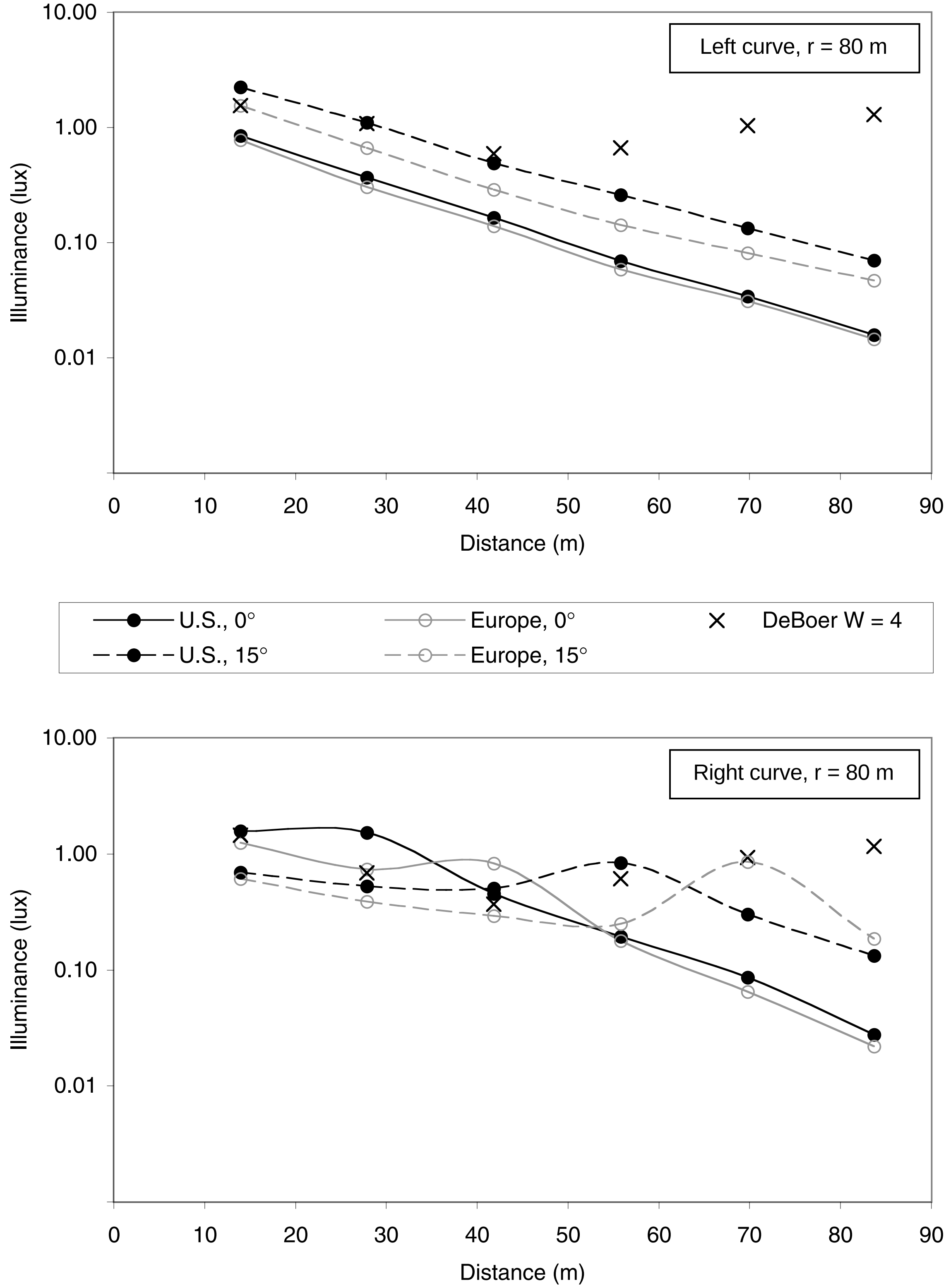

Figure 7. The combined glare illuminance from the left and right lamps reaching the eyes of an oncoming driver on curves with a radius of 80 m, from the U.S. and European low beams, under nominal aim and under a 15° beam shift into the curve. Also included are illuminances needed for a DeBoer discomfort-glare rating of 4.

Table 5 summarizes the main findings for the 80-m radii curves by rank ordering the four beam conditions.

Table 5
Rank ordering of the beam patterns in terms of the overall visibility illuminance and glare illuminance on curves with the radii of 80 m.

Rank order	Left curve		Right curve	
	Visibility	Glare	Visibility*	Glare**
1 (best)	U.S., 15°	Europe, 0°	U.S., 15°	Europe, 15° U.S., 15° (tie)
2	Europe, 15°	U.S., 0°	Europe, 15°	
3	Europe, 0° U.S., 0° (tie)	Europe, 15°	U.S., 0°	Europe, 0°
4		U.S., 15°	Europe, 0°	U.S., 0°

* The shifted U.S. beam is ranked over the shifted European beam because the shifted U.S. beam provides more illuminance at longer distances—the distances where the illuminance from the nominally aimed beams is especially low.

** This ranking is in reverse order of the maximum illuminance reached at any distance.

Implications

Unopposed seeing. For both left and right curves, there is a substantial increase (generally between half and a full log unit) in visibility illuminance with a shift of either beam 15° into the curve. Consequently, we conclude that using either the U.S. or the European beam pattern with a shift of 15° would improve seeing in either curve. For both curves, the best performance is obtained with the shifted U.S. beam pattern. However, the differences between the performance of the shifted U.S. beam pattern and the shifted European beam pattern are not large. In other words, the major differences are between the nominal beams and the shifted beams, as opposed to the differences between the U.S. and European beams (whether both nominally aimed or both shifted).

Disability glare. In the left curve, there is an increase (averaging about half a log unit) in glare illuminance for the oncoming traffic for either beam. This is of some concern from the disability-glare point of view. In a transition period, when only a few vehicles would be equipped with curve lighting, there would be a reduction in seeing for opposing traffic. However, in the right curve, shifting the beam would actually result in a decrease in glare illuminance at near distances, where the glare illuminance with the nominally aimed beams is greatest. Although there is an increase in glare illuminance with the shifted beams at long distances, the glare illuminance with the nominally aimed beams is relatively low at those distances. Therefore, disability glare should not be a problem on the right curve.

Discomfort glare. In the left curve, the increased glare illuminance does not reach the levels needed for a rating of 4 on the DeBoer discomfort-glare scale, except at the nearest distance tested. In the right curve, at near distances the glare illuminance for the nominally aimed is predicted to produce a rating of less than 4 (i.e., worse than 4) for the U.S. lamps and near 4 for the European lamps. As indicated above, at near distances the shifted beams actually produce less glare illuminance than the nominally aimed beams, with the illuminance from the shifted beams falling below the values needed for a rating of 4 (for both types of lamps). At far distances there are increases in glare illuminance with the shift, but the glare illuminance with the nominally aimed beams is relatively low there (for either the U.S. or European beams), and the increased illuminance (with one exception) does not exceed the levels needed for a rating of 4. Because of these results, and because drivers do not always fixate the tangent point as assumed in our calculations (which, in some situations, leads to very low illuminances needed for a rating of 4), discomfort glare is unlikely to be a problem with the shifted beams.

Conclusions

For curves of both radii and both directions, there is a substantial increase in visibility illuminance with a shift of either the U.S. or the European beam into the curve. This applies to all conditions where the visibility illuminance with the nominally aimed beams is relatively low. Thus, shifting the beam would result in better seeing for the user. For all situations, the best seeing performance is obtained with the shifted U.S. beam pattern. However, the differences (except for the left, 240-m radius curve) are not large.

For left curves (but not for right curves) of both radii, there would be some reduction in seeing by opposing traffic due to increased disability glare. (Because there will not always be an opposing vehicle, disability effects will occur somewhat less frequently than the visibility benefits, which will apply to every curve.) The changes in the glare illuminance with the shifted beams are unlikely to lead to unacceptable discomfort glare.

In general, the major differences between the nominally aimed and shifted beams are greater than those between the U.S. and European beams.

Motorway Lighting

General approach

In these simulations we examined the consequences of adjusting the vertical aim of the U.S. and European low beams in response to speed. Specifically, we evaluated the effects of shifting the aim upward on the same 16 performance aspects described in Table 1, with the following exceptions: Because we simulated motorway situations, for direct glare and for wet-road reflected glare we assumed that the oncoming vehicle was *two* lanes over, and the lane width in these analyses was 3.7 m. Again, the median, market-weighted U.S. and European beams from Schoettle et al. (2001) were used.

Beam-pattern shifts

We selected two levels of vertical shift, 0.25° up and 0.5° up. The larger shift (0.5° up) was selected as the maximum possible value using the European beam pattern, given that this pattern has the vertical cutoff nominally positioned about 0.6° (1%) below the horizontal. The smaller shift (0.25° up) was used as a more realistic value to be implemented.

Results

Tables 6 and 7 present the effects of shifting the U.S. and European beams either 0.25° up or 0.5° up on the 16 performance aspects as percentages of illuminance with nominal aim. As is evident from Tables 6 and 7, aiming either type of lamp upward increases both the visibility and glare illuminance, with the effects being larger as the shift in aim increases. (Decreases in foreground illuminance and no changes in wet-road-reflected glare with increases in vertical aim are the only exceptions.)

Table 6
The effects of shifting the U.S. and European low beams 0.25° up on the 16 performance aspects. The entries are percentages of illuminance.

Performance aspect	U.S., 0.25° as % of U.S., 0°	Europe, 0.25° as % of Europe, 0°
Visibility of a right pedestrian and road delineation at 100 m	137	221
Visibility of a right pedestrian and road delineation at 50 m	121	136
Visibility of a left pedestrian and road delineation at 100 m	147	220
Visibility of a left pedestrian and road delineation at 50 m	134	168
Visibility of a retroreflective sign; right shoulder at 150 m	160	181
Visibility of a retroreflective sign; center overhead at 150 m	111	110
Visibility of a retroreflective sign; left shoulder at 150 m	133	115
Visibility of a vehicle rear reflex reflector; right side at 20 m	165	194
Visibility of a vehicle rear reflex reflector; left side at 20 m	139	120
Visibility of a target near the road expansion point	178	183
Glare towards an oncoming driver at 50 m*	128	118
Glare towards a left mirror in the right adjacent lane at 20 m	125	180
Glare towards a center mirror in the same lane at 20 m	111	110
Glare towards a right mirror in the left adjacent lane at 20 m	121	111
Glare from wet pavement towards an oncoming driver at 50 m*	101	100
Foreground illumination at 15 m	88	91

*The oncoming driver was assumed to be two lanes over.

Table 7
The effects of shifting the U.S. and European low beams 0.5° up on the 16 performance aspects. The entries are percentages of illuminance.

Performance aspect	U.S., 0.5° as % of U.S., 0°	Europe, 0.5° as % of Europe, 0°
Visibility of a right pedestrian and road delineation at 100 m	170	435
Visibility of a right pedestrian and road delineation at 50 m	130	145
Visibility of a left pedestrian and road delineation at 100 m	219	451
Visibility of a left pedestrian and road delineation at 50 m	158	234
Visibility of a retroreflective sign; right shoulder at 150 m	236	287
Visibility of a retroreflective sign; center overhead at 150 m	124	122
Visibility of a retroreflective sign; left shoulder at 150 m	173	132
Visibility of a vehicle rear reflex reflector; right side at 20 m	297	393
Visibility of a vehicle rear reflex reflector; left side at 20 m	215	185
Visibility of a target near the road expansion point	256	267
Glare towards an oncoming driver at 50 m*	160	138
Glare towards a left mirror in the right adjacent lane at 20 m	151	267
Glare towards a center mirror in the same lane at 20 m	130	125
Glare towards a right mirror in the left adjacent lane at 20 m	144	123
Glare from wet pavement towards an oncoming driver at 50 m*	100	100
Foreground illumination at 15 m	74	82

*The oncoming driver was assumed to be two lanes over.

Table 8 shows the differences between the beams in the illuminance for the 16 performance aspects as a function of the magnitude of the vertical shift. As indicated earlier, the U.S. beams with nominal aim deliver more illuminance for both the right- and left-side targets than do the European beams. As the vertical shift increases, these differences decrease, and in the case of the left-side targets the differences reverse at 0.5° up. On the other hand, the European beams with nominal aim deliver more glare illuminance for the left mirror and more foreground illuminance. These differences increase as the beam shift upward increases. Finally, with the changes in the vertical aim, the relative differences between the beams remain approximately the same for traffic signs, rear vehicle reflectors, targets near the road expansion point, center- and right-mirror glare, and wet-road-reflected glare.

As we noted earlier, with nominal aim, the U.S. beam produces more illuminance than does the European beam for most performance aspects. Because shifting the aim upward produces more illuminance for these aspects, Table 9 compares the performance of the nominally aimed U.S. beams with the performance of the European beams aimed either 0.25° up or 0.5° up.

Concentrating on the beam shift of 0.25° up (the more realistic of the two studied levels), we find that the nominally aimed U.S. beams provide more illuminance for several performance aspects than do the European beams shifted 0.25° up. These aspects include targets on the right side, retroreflective signs, rear vehicle reflectors, and targets near the road expansion point. Additional advantages of the nominally aimed U.S. beam are less left-mirror glare and less wet-road-reflected glare. On the other hand, the nominally aimed U.S. beam, in comparison to the European beam shifted 0.25° up, produces less illuminance for targets on the left side, more direct glare, and more center-mirror and right-mirror glare.

Table 8
The differences between the U.S. and European low beams on the 16 performance aspects as a function of vertical aim. The entries are percentages of illuminance.

Performance aspect	U.S. as % of Europe		
	0°	0.25° up	0.5° up
Visibility of a right pedestrian and road delineation at 100 m	344	214	134
Visibility of a right pedestrian and road delineation at 50 m	155	137	139
Visibility of a left pedestrian and road delineation at 100 m	190	128	92
Visibility of a left pedestrian and road delineation at 50 m	125	99	84
Visibility of a retroreflective sign; right shoulder at 150 m	316	279	260
Visibility of a retroreflective sign; center overhead at 150 m	167	168	170
Visibility of a retroreflective sign; left shoulder at 150 m	175	203	229
Visibility of a vehicle rear reflex reflector; right side at 20 m	236	202	179
Visibility of a vehicle rear reflex reflector; left side at 20 m	290	337	336
Visibility of a target near the road expansion point	448	435	431
Glare towards an oncoming driver at 50 m*	182	198	211
Glare towards a left mirror in the right adjacent lane at 20 m	79	55	45
Glare towards a center mirror in the same lane at 20 m	172	174	178
Glare towards a right mirror in the left adjacent lane at 20 m	153	166	178
Glare from wet pavement towards an oncoming driver at 50 m*	82	82	83
Foreground illumination at 15 m	86	83	77

*The oncoming driver was assumed to be two lanes over.

Table 9
Comparisons of the performance of the U.S. beams with nominal aim to the European beams with the aim of 0.25° up or 0.5° up.

Performance aspect	U.S., 0° as % of	
	Europe, 0.25°	Europe, 0.5°
Visibility of a right pedestrian and road delineation at 100 m	156	79
Visibility of a right pedestrian and road delineation at 50 m	114	107
Visibility of a left pedestrian and road delineation at 100 m	86	42
Visibility of a left pedestrian and road delineation at 50 m	74	53
Visibility of a retroreflective sign; right shoulder at 150 m	174	110
Visibility of a retroreflective sign; center overhead at 150 m	151	137
Visibility of a retroreflective sign; left shoulder at 150 m	152	132
Visibility of a vehicle rear reflex reflector; right side at 20 m	122	60
Visibility of a vehicle rear reflex reflector; left side at 20 m	242	156
Visibility of a target near the road expansion point	245	168
Glare towards an oncoming driver at 50 m*	154	132
Glare towards a left mirror in the right adjacent lane at 20 m	44	30
Glare towards a center mirror in the same lane at 20 m	157	138
Glare towards a right mirror in the left adjacent lane at 20 m	137	124
Glare from wet pavement towards an oncoming driver at 50 m*	82	82
Foreground illumination at 15 m	94	105

*The oncoming driver was assumed to be two lanes over.

Conclusions

Our simulations indicate that for either the U.S. or the European beams, adjusting the vertical aim upward results in increased visibility illuminance for a variety of relevant targets. The benefits are already present with a shift of 0.25°, and they increase with a shift of 0.5°.

At the same time, increased vertical aim increases the direct glare for oncoming traffic. However, these increases are rather small, especially for the 0.25° shift (28% for the U.S. beam and 18 % for the European beam). Furthermore, the glare simulations assumed that the opposing vehicle was two lanes over, but that there was no median barrier to minimize the effects of glare illuminance. Having a median barrier or wider lateral separation between the opposing lanes of traffic (as is the case on many motorways) further mitigates the glare concern.

At nominal aim, the U.S. beams provide more illuminance for all of the tested seeing aspects. Shifting the beam 0.25° upward decreases the advantage of the U.S. beam, and at 0.5° the European beams provide more illuminance for seeing on the left.

Because of the relatively steeper vertical gradient of the European beams, the relative visibility benefit of shifting the beam upward is greater for the European beams. Nevertheless, the European beams at the 0.25° shift (the more realistic of the two shifts tested) deliver less visibility illuminance for several seeing aspects than do the nominally aimed U.S. beams.

Summary

This analytical study examined the potential benefits of applying two embodiments of adaptive lighting to the U.S. and European beam patterns: curve lighting that involves shifting the beam horizontally into the curve, and motorway lighting that involves shifting the beam vertically upward.

The curve lighting simulations paired 80-m radius left and right curves with a horizontal beam shift of 15°, and 240-m radius curves with a shift of 10°. The motorway lighting simulations involved upward aim shifts of 0.25° and 0.5°. For both curve and motorway lighting, changes in both visibility and glare illuminance were considered. Market-weighted model year 2000 U.S. and European beam patterns were used.

We conclude that curve lighting, as simulated here, would substantially improve seeing performance on curves for both types of beams. On left curves (but not on right curves) there would be an increase in disability glare for oncoming traffic. No major discomfort-glare problems would be expected. Although the shifted U.S. beams were found to perform slightly better overall than the shifted European beams, the main difference in performance is between the shifted and nominally aimed beams.

Motorway lighting, as simulated here, would also substantially improve seeing performance, with the benefits already present at an upward shift of 0.25°. Because the increases in glare illuminance would be minor, and because motorways often incorporate median barriers or wide separations between lanes of opposing traffic, we do not expect substantial problems with increased glare. The European beams benefit more from this embodiment of motorway lighting than do the U.S. beams. (This is the case because under nominal aim the European beams provide less visibility illuminance and their vertical gradient is steeper.) Nevertheless, the nominally aimed U.S. beam tends to outperform the European beam shifted upward 0.25°.

Adaptive lighting is not the only way to improve current headlighting. For example, improving headlamp performance on curves could be achieved by wider beam patterns; analogously, the performance on motorways could be improved by beams with longer reach. The present study did not compare the relative benefits of such changes in the beam pattern to benefits of adaptive lighting.

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