UMTRI-98-42

QUANTITATIVE COMPARISONS OF FACTORS INFLUENCING THE PERFORMANCE OF LOW-BEAM HEADLAMPS

Michael Sivak
Michael J. Flannagan
Toshio Miyokawa

October 1998

QUANTITATIVE COMPARISONS OF FACTORS INFLUENCING THE PERFORMANCE OF LOW-BEAM HEADLAMPS

Michael Sivak
Michael J. Flannagan
Toshio Miyokawa

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

Report No. UMTRI-98-42
October 1998

Technical Report Documentation Page

1. Report No. UMTRI-98-42	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Quantitative Comparisons of Factors Influencing the Performance of Low-Beam Headlamps		5. Report Date October 1998 6. Performing Organization Code 302753
7. Author(s) Sivak, M., Flannagan, M.J., and Miyokawa, T.		8. Performing Organization Report No. UMTRI-98-42
9. Performing Organization Name and Address The University of Michigan Transportation Research Institute 2901 Baxter Road Ann Arbor, Michigan 48109-2150 U.S.A.		10. Work Unit no. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address The University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety		13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

The Affiliation Program currently includes Adac Plastics, BMW, Bosch, Britax International, Chrysler, Corning, Delphi Interior and Lighting Systems, Denso, Ford, GE, GM NAO Safety Center, Hella, Hewlett-Packard, Ichikoh Industries, Koito Manufacturing, LESCOA, Libbey-Owens-Ford, Magneti Marelli, North American Lighting, Osram Sylvania, Philips Lighting, PPG Industries, Reflexite, Reitter & Schefenacker, Stanley Electric, Stimsonite, TEXTRON Automotive, Valeo, Visteon, Wagner Lighting, 3M Personal Safety Products, and 3M Traffic Control Materials.
Information about the Affiliation Program is available at: http://www.umich.edu/~industry/

16. Abstract

This study compared the quantitative influence of a variety of factors on the performance of low-beam headlamps. The following factors were included: vertical aim, horizontal aim, mounting height, lateral separation, lens dirt, lamp voltage, number of functioning lamps (two vs. one), vehicle type (cars vs. light trucks and vans), beam pattern (U.S. vs. European), and light source (an unshielded 9007 vs. a shielded H4). The following aspects of headlamp performance were considered: visibility of pedestrians, visibility of road delineation, visibility of vehicle reflex reflectors, visibility of retroreflective traffic signs, visibility of targets near the road expansion point, glare directed towards oncoming drivers, glare reflected from wet pavement towards oncoming drivers, glare directed towards rearview mirrors of preceding vehicles, and foreground illumination. A market-weighted U.S. beam pattern, with lamps mounted at market-weighted locations, formed the basis for most of the analyses.

The results indicate that from among the factors studied, vertical aim is overwhelmingly the most important factor in influencing the performance of low-beam headlamps. The second most important factor is the number of functioning lamps. The main implication of this study is that major improvements in current (fixed as opposed to adaptive) low-beam headlighting could be achieved primarily by better control of vertical aim and by longer-life headlamps.

17. Key Words headlamps, headlighting, low beams, performance, visibility, glare, lamp aim, lamp life		18. Distribution Statement Unlimited	
19. Security Classification (of this report) None	20. Security Classification (of this page) None	21. No. of Pages 29	22. Price

ACKNOWLEDGMENTS

Appreciation is extended to the members of the University of Michigan Industry Affiliation Program for Human Factors in Transportation Safety for support of this research. The current members of the Program are:

Adac Plastics
BMW
Bosch
Britax International
Chrysler
Corning
Delphi Interior and Lighting Systems
Denso
Ford
GE
GM NAO Safety Center
Hella
Hewlett-Packard
Ichikoh Industries
Koito Manufacturing
LESCOA
Libbey-Owens-Ford
Magneti Marelli
North American Lighting
Osram Sylvania
Philips Lighting
PPG Industries
Reflexite
Reitter & Schefenacker
Stanley Electric
Stimsonite
TEXTRON Automotive
Valeo
Visteon
Wagner Lighting
3M Personal Safety Products
3M Traffic Control Materials

Appreciation is also extended to Kåre Rumar for many helpful suggestions on earlier drafts of this report.

CONTENTS

INTRODUCTION

The overall photometric performance of low-beam headlamps is determined by a variety of factors. Some of these factors are under the control of the designer of the lamp (e.g., the light source chosen), the vehicle manufacturer (e.g., lamp mounting height), or the driver (e.g., cleanliness of the lamp lenses). Still other factors are outside of anybody's direct control (e.g., pavement wetness).

Past studies have investigated the effects of many relevant factors. However, these studies have used a variety of methods to evaluate the importance of the factors in question. Consequently, cross-study comparisons are often difficult. For example, it is difficult to compare the effects of headlamp misaim on pedestrian detection distances derived from computer models (e.g., Bhise, Matle, and Hoffmeister, 1984) to the effects of lens dirt on light output (Sivak, Flannagan, Traube, Kojima, and Aoki, 1996b).

One notable exception is a study by Perel (1985) that used a common methodology (the CHESS model [Bhise et al., 1977]) to compare the effects of several headlamp factors (including overall intensity, aim, mounting height, and beam pattern) on three performance parameters (pedestrian detection, delineation detection, and discomfort glare). The results were presented in terms of the degree of sensitivity of the performance measures to the headlamp factors (low, moderate, and high). Perel found that "only small performance increases could be achieved by beam pattern modifications, improved aim, and increased overall intensity" (p. 225). However, Perel concluded that the method used (the CHESS model) might not be sensitive enough for the task at hand. According to Perel, "part of the difficulty in identifying performance improvements was found to be the low sensitivity of the CHESS figure of merit to changes in beam photometrics" (p. 225).

The present study was designed to evaluate the effects of a variety of factors on the effective photometric performance of low-beam headlamps using a common methodology. The effective photometric performance was measured by the actual luminous intensity directed to several important points in space relative to the lamp (e.g., a pedestrian on the right shoulder at a distance of 100 m, and an oncoming driver's eyes in the adjacent lane at 50 m). The goal was to provide, for each important point in space, rank ordering of the importance of the factors in question. The baseline for this study was the recently obtained market-weighted headlamp beam pattern for U.S. cars (Sivak, Flannagan, Kojima, and Traube, 1997).

Although, conceptually, the present study was similar to that of Perel (1985), there are three major differences between these two studies. First, we examined a wider range of factors that could affect headlamp performance. Second, we considered more aspects of headlamp performance. Third, instead of using specific beam patterns, we used a market-weighted beam pattern from current U.S. vehicles.

METHOD

The approach was as follows:

(1) Use a representative U.S. low-beam pattern, with lamps mounted in representative positions, to quantify the effects of factors in (2) on the performance aspects in (3).

(2) Select a set of factors whose effects on the beam pattern are generally considered to be of importance.

(3) Select a set of points in space that represent major performance aspects of the beam pattern.

The effects of factors in (2) were quantified by calculating the percentage change in luminous intensity directed from both lamps towards the points in space in (3). As an example, let us assume that the luminous intensities from the representative low-beam pattern directed towards a relevant point in space (e.g., the eyes of an oncoming driver) were 600 cd from the left lamp and 400 cd from the right lamp. Consequently, the combined luminous intensity from the two lamps was 1,000 cd. Furthermore, let us assume that because of the factor in question (e.g., lens dirt), the combined luminous intensity directed to the same point in space has changed to 1,200 cd. Thus, for this example, the examined factor would result in a 20% increase in combined luminous intensity.

Representative U.S. low-beam pattern and lamp positions

We used the market-weighted data from Sivak, Flannagan, Kojima, and Traube (1997). That study photometered 35 low beams that were manufactured for use on 45% of all cars, light trucks, and vans sold in the U.S. for model year 1997. The photometric information for each lamp was weighted by the 1997 sales figures for the corresponding vehicle. For the basic photometry data for the present study, we used the market-weighted median data for cars only. The data extend from 45° left to 45° right, and from 5° down to 7° up (all in 0.5° steps).

Except as noted below, in all of the analyses we used representative headlamp mounting positions. Specifically, we used a mounting height of 0.62 m and a lamp separation of 1.12 m. These values are the market-weighted means from a recent survey of headlamps on cars in the U.S. (Sivak, Flannagan, Budnik, Flannagan, and Kojima, 1996a). We used the same beam pattern for both the left and the right lamps. (Sivak et al. (1997) found that left lamps and right lamps that were manufactured for the same vehicle were photometrically very similar.)

Factors

The following factors were considered: vertical aim, horizontal aim, mounting height, lateral separation (including a comparison of two lamps located in the same position vs. lamps laterally separated), lens dirt, lamp voltage, number of functioning lamps, vehicle type, beam pattern, and light-source type.

Vertical aim. A recent U.S. survey of headlamp aim in 768 in-service cars, vans, and light trucks (Copenhaver and Jones, 1992) found that the mean vertical aim was close to 0° with a standard deviation of 0.65°. The measurements were taken with the drivers, passengers (if any), and luggage (if any) in the positions they were when arriving at the test sites. We investigated the effects of ±2 standard deviations from the mean—1.3° up and 1.3° down. (The range of ±2 standard deviations is expected to cover 95% of all aims.)

Horizontal aim. Copenhaver and Jones (1992) found the mean horizontal aim to be about 0.2° left with a standard deviation of 0.55°. Following, again, the logic of using ±2 standard deviations from the mean, we considered 1.3° left and 0.9° right.

Mounting height. As indicated above, a recent study found that the market-weighted mean headlamp mounting height for cars to be 0.62 m, with a standard deviation of 0.02 m. Consequently, when examining the effects of mounting height, we considered 0.58 m and 0.66 m (±2 standard deviations from the mean).

Lateral separation. Sivak et al. (1996a) found that the market-weighted mean lateral separation between low-beam headlamps to be 1.12 m, with a standard deviation of 0.12 m. Thus, when examining the effects of lamp separation, we considered 1.36 m and 0.88 m (±2 standard deviations from the mean). Furthermore, we also included lamp separation of 0 m, corresponding to simulations that use the same (cyclopean) location for both lamps.

Lens dirt. Sivak, Flannagan, Traube, Kojima, and Aoki (1996b) evaluated changes in the light output of low-beam headlamps as a function of dirt accumulated during a 482-km route, representing a 10-day amount of driving for a typical U.S. driver. The complete route was traversed on three separate occasions, under each of the following environmental conditions: summer while dry, summer while wet, and winter with road salt. Candela matrices were obtained for a rectangular central portion of the beam, extending from 20° left to 20° right, and from 5° down to 5° up. The results showed that linear regressions provided good fits for the relationship between "clean" and "dirty" luminous intensities. We selected the most extreme situation tested by Sivak et al. (1996b) (winter with road salt) and used the corresponding regression equation (dirty luminous intensity = 0.72 * clean luminous intensity + 112).

Lamp voltage. Sivak, Flannagan, Traube, and Miyokawa (1998) found that voltage changes between 12.0 V and 13.5 V caused light output to change by the same proportion throughout the beam pattern. Therefore, for filament lamps, it is reasonable to use a single constant for all values in a beam pattern when converting photometry at one voltage to photometry at a different voltage. Furthermore, the obtained constants were in good agreement with the constants derived using the standard IES (1984) formula. In this analysis, we used the change from 12.8 V to 12.0 V (with a resulting decrease in luminous intensity of 20%) and the change from 12.8 V to 13.5 V (with a resulting increase in luminous intensity of 20%).

Number of functioning lamps. Here we evaluated the effects of having either only the left or only the right lamp functioning, as compared to having both lamps functioning. A recent U.S. survey of 102,000 moving vehicles found that 2.3% had one headlamp not functioning (Rys, Konz, and Russell, 1993).

Vehicle type. As indicated above, all of the previous analyses used the market-weighted car photometry from Sivak et al. (1997), while assuming a lamp mounting height of 0.62 m and a lamp separation of 1.12 m. In these analyses we compared the effect of changing from the market-weighted car photometry data to the market-weighted photometry for light trucks and vans (also from Sivak et al., 1997). Importantly, the light truck/van lamps were assumed to be mounted at 0.83 m, with a lateral separation of 1.30 m. (The locations of headlamps both for cars and for light trucks/vans were based on the market-weighted data from Sivak et al. (1996a).)

Beam pattern. Sivak, Flannagan, and Sato (1993) provided detailed photometry information on 37 lamps manufactured for sale in Europe. We used the median data (that were not market-weighted) from that study and the median market-weighted U.S. data from Sivak et al. (1997) to compare the effects of changing from the U.S. to the European beam pattern. The European lamps were assumed to be positioned at the same mounting height and lateral separation as the U.S. lamps.

Light-source type. In addition to the aggregate information, Sivak et al. (1997) also provide photometric data broken down by light source. We used the data from that study to compare a light source without an internal shield (9007) to a light source with an internal shield (H4). Each light source created a beam pattern designed to meet the current U.S. specifications.

Major performance aspects of low-beam headlamps

The following performance aspects were considered: visibility of pedestrians, visibility of road delineation, visibility of reflex reflectors, visibility of retroreflective traffic signs, visibility of targets near the road expansion point, glare directed towards oncoming drivers, glare reflected from wet pavement towards oncoming drivers, glare directed towards rearview mirrors of preceding vehicles, and foreground illumination. For each of the performance aspects, a typical geometric situation was specified in terms of the longitudinal, lateral, and vertical positions (see Table 1), and the corresponding visual angles from each of the two lamps 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.)

Performance aspect	*x*	*y*	*z*
Visibility of right pedestrians and road delineation at 100 m	100	1.85	0
Visibility of right pedestrians and road delineation at 50 m	50	1.85	0
Visibility of left pedestrians and road delineation at 100 m	100	-5.55	0
Visibility of left pedestrians and road delineation at 50 m	50	-5.55	0
Visibility of right reflex reflectors at 20 m; mounting height 0.5 m	20	0.60	0.50
Visibility of right reflex reflectors at 20 m; mounting height 1.0 m	20	0.60	1.00
Visibility of left reflex reflectors at 20 m; mounting height 0.5 m	20	-0.60	0.50
Visibility of left reflex reflectors at 20 m; mounting height 1.0 m	20	-0.60	1.00
Visibility of retroreflective traffic signs; right shoulder at 150 m	150	6.15	2.10
Visibility of retroreflective traffic signs; center overhead at 150 m	150	0	6.10
Visibility of retroreflective traffic signs; left shoulder at 150 m	150	-8.85	2.10
Visibility of targets near the road expansion point	∞	0	0.62
Glare directed towards oncoming drivers at 50 m	50	-3.35	1.11
Glare reflected from wet pavement towards oncoming drivers at 50 m	17.9	-1.20	0
Glare directed towards a left mirror in the right adjacent lane at 20 m	20	2.83	0.98
Glare directed towards center mirror in the same lane at 20 m	20	0	1.24
Glare directed towards a right mirror in the left adjacent lane at 20 m	20	-2.83	0.98
Foreground illumination at 15 m	15	0	0
Foreground illumination at 25 m	25	0	0

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

Performance aspect	Left lamp	Right lamp
Visibility of right pedestrians and road delineation at 100 m	1.4R, 0.4D	0.7R, 0.4D
Visibility of right pedestrians and road delineation at 50 m	2.8R, 0.7D	1.5R, 0.7D
Visibility of left pedestrians and road delineation at 100 m	2.9L, 0.4D	3.5L, 0.4D
Visibility of left pedestrians and road delineation at 50 m	5.7L, 0.7D	7.0L, 0.7D
Visibility of right reflex reflectors at 20 m; mounting height 0.5 m	3.3R, 0.3D	0.1R, 0.3D
Visibility of right reflex reflectors at 20 m; mounting height 1.0 m	3.3R, 1.1U	0.1R, 1.1U
Visibility of left reflex reflectors at 20 m; mounting height 0.5 m	0.1L, 0.3D	3.3L, 0.3D
Visibility of left reflex reflectors at 20 m; mounting height 1.0 m	0.1L, 1.1U	3.3L, 1.1U
Visibility of retroreflective traffic signs; right shoulder at 150 m	2.6R, 0.6U	2.1R, 0.6U
Visibility of retroreflective traffic signs; center overhead at 150 m	0.2R, 2.1U	0.2L, 2.1U
Visibility of retroreflective traffic signs; left shoulder at 150 m	3.2L, 0.6U	3.6L, 0.6U
Visibility of targets near the road expansion point	0, 0	0, 0
Glare directed towards oncoming drivers at 50 m	3.2L, 0.6U	4.5L, 0.6U
Glare reflected from wet pavement towards oncoming drivers at 50 m	3.2L, 2.0D	4.5L, 2.0D
Glare directed towards a left mirror in the right adjacent lane at 20 m	9.6R, 1.0U	6.5R, 1.0U
Glare directed towards center mirror in the same lane at 20 m	1.6R, 1.8U	1.6L, 1.8U
Glare directed towards a right mirror in the left adjacent lane at 20 m	6.5L, 1.0U	9.6L, 1.0U
Foreground illumination at 15 m	2.1R, 2.4D	2.1L, 2.4D
Foreground illumination at 25 m	1.3R, 1.4D	1.3L, 1.4D

Visibility of pedestrians. Pedestrians walking on the right edge line and on the left edge line of the left adjacent lane were considered. In these and all subsequent analyses the lane width was set at 3.7 m. Two distances were included (assuming two different approaching speeds): 100 m and 50 m. Feet were selected as the relevant location on the pedestrians (i.e., vertical position was set at 0 m above the roadway).

Visibility of road delineation. Two distances were selected for road delineation: 100 m and 50 m. Both the right edge line and the left edge line of the adjacent lane were included. (An alert reader will notice that the delineation locations and pedestrian locations were identical.)

Visibility of reflex reflectors on the rear of vehicles. Two sets of mounting-height locations were considered: 0.5 m and 1.0 m. Both left and right reflectors were included, at a separation of 1.2 m. The mounting heights chosen approximately represent the range found in an informal survey of 61 cars, light trucks, and vans belonging to the staff of UMTRI. The separation chosen corresponds to the mean value from that survey.

Visibility of retroreflective traffic signs. Three locations of retroreflective traffic signs were included: right shoulder-mounted, center overhead, and left shoulder-mounted—all at 150 m.

Visibility of targets near the road expansion point. The longitudinal distance here is infinity, the lateral offset is zero, and the vertical height is the same as that of the lamps.

Glare directed towards oncoming drivers. The oncoming driver was assumed to be in the left adjacent lane at a distance of 50 m. The oncoming driver's eye location was selected based on the market-weighted data in Sivak et al. (1996a).

Glare reflected from wet pavement towards oncoming drivers. The oncoming driver was, again, assumed to be in the left adjacent lane at a distance of 50 m. The corresponding location on the pavement was calculated by assuming that the angle of reflection is equal to the angle of incidence.

Glare directed towards rearview mirrors of preceding cars. All three mirrors were considered. For the center mirror, the preceding car was in the same lane. For the left mirror, the preceding car was in the right adjacent lane, while for the right mirror it was in the left adjacent lane. The distance between the headlamps and the mirrors was set at 20 m. The mounting position of the mirrors was based on a late-model sedan.

Foreground illumination. Two locations were used: pavement 15 m and 25 m ahead (both at the centerline of the vehicle).

Simplifying assumptions concerning retroreflective materials

This study investigated the changes in the combined luminous intensities from both lamps that were directed toward certain points in space. An explicit assumption was made that a given amount of luminous intensity is equally effective whether it originated from the left lamp or the right lamp. This assumption is valid for diffusely reflecting materials. However, because the driver is not seated at the centerline of the vehicle, this assumption is not strictly correct when dealing with retroreflective materials (e.g., retroreflective traffic signs or vehicle reflex reflectors). Because of the offset of the driver toward the left side of the vehicle (for the right-hand traffic), the observation angle (the angle between the headlamp, the retroreflective material, and the driver eye point) is smaller for the left lamp than for the right lamp. Consequently, a given amount of luminous intensity directed towards retroreflective objects is more effective if it originates from the left lamp than from the right lamp, because more light will be reflected back to the driver's eyes from the incident illumination that originated from the left lamp.

The observation angle is affected by several of our factors, such as lamp separation, lamp mounting height, and vehicle type. (Vehicle-type manipulation involved changes in both lamp location and driver eye point location.) Again, the effects of the changes in observation angle were not included in the calculations.

RESULTS

The results are presented in Tables 3 through 8 in terms of the percentage changes in luminous intensity directed towards the points in space representing the important performance aspects of headlamps.

Table 3.
The effects of the selected factors on the visibility of pedestrians and road delineation. The candela values in the column headings are the combined luminous intensities from the two lamps directed towards the relevant points in space. The entries are percentage changes in the luminous intensities. (Negative numbers are undesirable changes.)

Factor	Pedestrians and delineation			
	Right, 100 m (23,428 cd)	Right, 50 m (35,959 cd)	Left, 100 m (3,864 cd)	Left, 50 m (3,731 cd)
Lamp misaim 1.3° up	+43	-15	+205	+128
Lamp misaim 1.3° down	-91	-86	-80	-79
Lamp misaim 1.3° left	+12	-14	+22	+23
Lamp misaim 0.9° right	-34	-8	-18	-17
Lamp mounting height 0.58 m	-4	-3	-3	-8
Lamp mounting height 0.66 m	+4	+3	+3	+8
Lamp separation 1.36 m	-1	-3	0	0
Lamp separation 0.88 m	+1	+2	0	+1
Lamp separation 0 m	+2	+6	0	+3
Lens dirt (after 482 km in winter)	-27	-27	-22	-22
Lamp voltage 12.0 V	-20	-20	-20	-20
Lamp voltage 13.5 V	+20	+20	+20	+20
Right lamp only	-55	-50	-51	-57
Left lamp only	-45	-50	-49	-43
Light trucks/vans instead of cars	+6	+10	-8	+12
European instead of U.S. pattern	-56	-42	-40	+2
H4 light source instead of 9007*	-13	-19	-31	-5

* The specific candela values listed in the column headings do not apply to these analyses.

Table 4.
The effects of the selected factors on the visibility of vehicle reflex reflectors. The candela values in the column headings are the combined luminous intensities from the two lamps directed towards the relevant points in space. The entries are percentage changes in the luminous intensities. (Negative numbers are undesirable changes.)

Factor	Right reflex reflectors at 20 m, height of		Left reflex reflectors at 20 m, height of	
	0.5 m (18,703 cd)	1.0 m (1,667 cd)	0.5 m (8,020 cd)	1.0 m (862 cd)
Lamp misaim 1.3° up	+69	+835	+131	+670
Lamp misaim 1.3° down	-88	-64	-87	-44
Lamp misaim 1.3° left	+13	+10	+77	+23
Lamp misaim 0.9° right	-10	-23	-42	-14
Lamp mounting height 0.58 m	-18	-12	-18	-7
Lamp mounting height 0.66 m	+18	+15	+18	+10
Lamp separation 1.36 m	-12	+3	+21	+4
Lamp separation 0.88 m	+14	-9	-18	-5
Lamp separation 0 m	+40	-11	-41	-10
Lens dirt (after 482 km in winter)	-27	-15	-25	-2
Lamp voltage 12.0 V	-20	-20	-20	-20
Lamp voltage 13.5 V	+20	+20	+20	+20
Right lamp only	-61	-66	-77	-63
Left lamp only	-39	-34	-23	-37
Light trucks/vans instead of cars	+60	+99	+95	+115
European instead of U.S. pattern	-60	-62	-32	-43
H4 light source instead of 9007*	-23	-54	-34	-54

* The specific candela values listed in the column headings do not apply to these analyses.

Table 5.
The effects of the selected factors on the visibility of retroreflective traffic signs and on the visibility of objects near the road expansion point. The candela values in the column headings are the combined luminous intensities from the two lamps directed towards the relevant points in space. The entries are percentage changes in the luminous intensities. (Negative numbers are undesirable changes.)

Factor	Retroreflective traffic signs			Road expansion point (5,345 cd)
	Right, 150 m (5,078 cd)	Center, 150 m (615 cd)	Left, 150 m (1,015 cd)	
Lamp misaim 1.3° up	+645	+192	+522	+416
Lamp misaim 1.3° down	-84	-31	-55	-82
Lamp misaim 1.3° left	-11	+1	+14	+124
Lamp misaim 0.9° right	-19	-3	-5	-31
Lamp mounting height 0.58 m	-2	0	-1	0
Lamp mounting height 0.66 m	+2	0	+1	0
Lamp separation 1.36 m	0	0	0	0
Lamp separation 0.88 m	0	0	0	0
Lamp separation 0 m	+1	0	0	0
Lens dirt (after 482 km in winter)	-24	+8	-6	-24
Lamp voltage 12.0 V	-20	-20	-20	-20
Lamp voltage 13.5 V	+20	+20	+20	+20
Right lamp only	-51	-50	-50	-50
Left lamp only	-49	-50	-50	-50
Light trucks/vans instead of cars	-8	+8	+12	-6
European instead of U.S. pattern	-82	-49	-47	-77
H4 light source instead of 9007*	-43	-43	-52	-53

* The specific candela values listed in the column headings do not apply to these analyses.

Table 6.
The effects of the selected factors on direct glare and reflected glare from wet pavement. The candela values in the column headings are the combined luminous intensities from the two lamps directed towards the relevant points in space. The entries are percentage changes in the luminous intensities. (Positive numbers are undesirable changes.)

Factor	Oncoming driver glare at 50 m	
	Direct (990 cd)	Wet pavement (11,340 cd)
Lamp misaim 1.3° up	+490	-21
Lamp misaim 1.3° down	-55	-53
Lamp misaim 1.3° left	+12	+16
Lamp misaim 0.9° right	-8	-7
Lamp mounting height 0.58 m	-4	0
Lamp mounting height 0.66 m	+4	0
Lamp separation 1.36 m	0	0
Lamp separation 0.88 m	0	+1
Lamp separation 0 m	+2	+3
Lens dirt (after 482 km in winter)	-5	-26
Lamp voltage 12.0 V	-20	-20
Lamp voltage 13.5 V	+20	+20
Right lamp only	-52	-52
Left lamp only	-48	-48
Light trucks/vans instead of cars	+34	0
European instead of U.S. pattern	-46	+9
H4 light source instead of 9007*	-50	-25

* The specific candela values listed in the column headings do not apply to these analyses.

Table 7.
The effects of the selected factors on rearview mirror glare. The candela values in the column headings are the combined luminous intensities from the two lamps directed towards the relevant points in space. The entries are percentage changes in the luminous intensities. (Positive numbers are undesirable changes.)

Factor	Glare directed towards a rearview mirror at 20 m		
	Left mirror (2,225 cd)	Center mirror (699 cd)	Right mirror (483 cd)
Lamp misaim 1.3° up	+146	+463	+186
Lamp misaim 1.3° down	-71	-38	-33
Lamp misaim 1.3° left	-12	+14	+9
Lamp misaim 0.9° right	-5	-13	-5
Lamp mounting height 0.58 m	-11	-7	-4
Lamp mounting height 0.66 m	+11	+7	+7
Lamp separation 1.36 m	-2	-1	0
Lamp separation 0.88 m	+1	0	0
Lamp separation 0 m	-2	+1	0
Lens dirt (after 482 km in winter)	-18	+4	+18
Lamp voltage 12.0 V	-20	-20	-20
Lamp voltage 13.5 V	+20	+20	+20
Right lamp only	-45	-57	-55
Left lamp only	-55	-43	-45
Light trucks/vans instead of cars	-37	+91	+52
European instead of U.S. pattern	-30	-49	-27
H4 light source instead of 9007*	+86	-44	-10

* The specific candela values listed in the column headings do not apply to these analyses.

Table 8.
The effects of the selected factors on foreground illumination. The candela values in the column headings are the combined luminous intensities from the two lamps directed towards the relevant points in space. The entries are percentage changes in the luminous intensities. (There is not a complete consensus whether high levels of foreground illumination are desirable or not.)

Factor	Foreground at	
	15 m (18,475 cd)	25 m (27,682 cd)
Lamp misaim 1.3° up	-50	-40
Lamp misaim 1.3° down	+45	-61
Lamp misaim 1.3° left	+12	+26
Lamp misaim 0.9° right	-6	-17
Lamp mounting height 0.58 m	+10	+1
Lamp mounting height 0.66 m	-9	-1
Lamp separation 1.36 m	-3	+2
Lamp separation 0.88 m	+2	-2
Lamp separation 0 m	+7	-1
Lens dirt (after 482 km in winter)	-27	-27
Lamp voltage 12.0 V	-20	-20
Lamp voltage 13.5 V	+20	+20
Right lamp only	-63	-70
Left lamp only	-37	-30
Light trucks/vans instead of cars	+9	+32
European instead of U.S. pattern	-19	-22
H4 light source instead of 9007*	-62	-44

* The specific candela values listed in the column headings do not apply to these analyses.

DISCUSSION

Sensitivity of the headlamp performance aspects

Visibility of pedestrians and delineation. The amount of light directed towards the pedestrians and road delineation was most influenced by vertical aim. The changes in luminous intensity due to vertical misaim exceeded 100% for the left-side targets, and were just below 100% for the right-side targets. Number of functioning lamps was the second most important factor, with the changes hovering around 50%. The third most important factor was beam pattern.

Visibility of reflex reflectors on the rear of vehicles. Vertical aim was, by far, the most important factor. The changes in the incident illumination on the reflectors mounted at a height of 1.0 m were 835% and 670% (for the right and left reflectors, respectively). The analogous changes for the reflectors at 0.5 m were 69% and 131%. Vehicle type (cars vs. light trucks and vans) was the second most important factor, with the effects for the four conditions of interest ranging between 60% and 115%. Presumably, the influence of vehicle type was primarily due to the differences in lamp mounting height (0.62 m vs. 0.83 m). The third most important factor was number of functioning lamps.

Notably, the amount of incident light was about 10 times greater at a mounting height of 0.5 m than at 1.0 m (see the column headings in Table 4). Furthermore, as indicated above, the effect of the principal factor (vertical aim) was less severe for a mounting height of 0.5 m than 1.0 m. These two findings suggest that it would be desirable if the mounting height of reflex reflectors were below the mounting height of headlamps, so that the headlamp high intensity zone is projected on the reflector. (The observation angle—the angle between the headlamp, the reflex reflector, and the driver eye point—is, at 20 m distance, approximately the same for the two mounting heights.)

However, it is unrealistic to expect the highest headlamp intensity to be directed towards the reflex reflectors. That is the case because the hot spot in the U.S. low beams is near 1.5° down (Sivak et al., 1997). Given that the current average mounting height of cars headlamps in the U.S. is 0.62 m, at 20 m following distance the hot spot is projected at a position that is about 0.1 m above the ground. (If the distance were less than 20 m, that position would be more than 0.1 m above the ground. Conversely, if the distance were more than 20 m, that position would be less than 0.1 m, reaching the ground at the distance of 23.7 m.) The main problem with very low mounting heights of reflex reflectors is that they are more susceptible to dirt than higher mounting heights. Thus, a reasonable mounting height for reflex reflectors appears to be near 0.5 m.

Reflex reflectors mounted at 0.5 m would fall nearer the low-beam hot spot of light trucks and vans (with an average headlamp mounting height of 0.83 m). That is desirable, because the higher driver eye position in light trucks and vans (and the consequent increase in the observation angle) results in a lower proportion of the incident light being returned to the driver's eyes in light trucks and vans than in cars.

Visibility of retroreflective traffic signs. Vertical aim was, again, the most important factor. The changes in the incident illumination ranged from 192% to 645% (depending on the sign location). The next most important factors were beam pattern (between 47% and 82%) and number of functioning lamps (about 50%).

Visibility of targets near the road expansion point. The greatest effects were for vertical aim (416%), horizontal aim (124%), and beam pattern (77%).

Glare directed towards oncoming drivers. The most important factor was vertical aim (490%), followed by number of functioning lamps and light source (both about 50%).

Glare reflected from wet pavement towards oncoming drivers. The greatest effects were for vertical aim (53%), number of functioning lamps (about 50%), and lens dirt (26%). Interestingly, however, the wet-road reflected glare illumination is more than 10 times *greate*r than the direct glare illumination (see the column headings in Table 6). Thus, a given percentage change in reflected glare will have more influence on total (reflected plus direct) glare than the same percentage change in direct glare.

Glare directed towards rearview mirrors of preceding vehicles. The effects of the strongest factor—vertical aim—ranged from 146% to 463%. The effects due to vehicle type ranged from 37% to 91%, while those of number of functioning lamps were around 50%.

Foreground illumination. None of the effects were over 70%, with the most potent factors being number of functioning lamps, light source, and vertical aim.

The most important factors

Table 9 lists, for each performance aspect, the three factors with the greatest effects. Overall, the most potent factor was, by far, vertical aim. It was the factor with the greatest influence on 17 of the 19 performance aspects that were included in Table 9, and it had the second and third greatest effects, respectively, on the remaining two performance aspects. The second most important factor was number of functioning lamps; this factor was the most important factor twice, and it was either the second or the third most important factor 15 times. Other factors represented among the top three factors were beam pattern (featured

7 times as either the second or the third most important factor), light source (5 times as either the second or the third), vehicle type (5 times as either the second or the third), horizontal aim (3 times as either the second or the third), and lens dirt (once as the third).

Table 9.
Rank ordering of the factors by the size of the effects on the performance aspects.

Performance aspect	Rank ordering of factors by the size of the effect		
	First	Second	Third
Right pedestrians and delineation at 100 m	Vertical aim	Beam pattern	One lamp only
Right pedestrians and delineation at 50 m	Vertical aim	One lamp only	Beam pattern
Left pedestrians and delineation at 100 m	Vertical aim	One lamp only	Beam pattern
Left pedestrians and delineation at 50 m	Vertical aim	One lamp only	Horizont. aim
Right reflectors at 20 m and height of 0.5 m	Vertical aim	One lamp only	Beam pattern
Right reflectors at 20 m and height of 1.0 m	Vertical aim	Vehicle type	One lamp only
Left reflectors at 20 m and height of 0.5 m	Vertical aim	Vehicle type	Horizont. aim
Left reflectors at 20 m and height of 1.0 m	Vertical aim	Vehicle type	One lamp only
Right shoulder-mounted traffic signs at 150 m	Vertical aim	Beam pattern	One lamp only
Center overhead traffic signs at 150 m	Vertical aim	One lamp only	Beam pattern
Left shoulder-mounted traffic signs at 150 m	Vertical aim	Light source	One lamp only
Targets near the road expansion point	Vertical aim	Horizont. aim	Beam pattern
Direct oncoming glare at 50 m	Vertical aim	One lamp only	Light source
Wet-pavement reflected glare at 50 m	Vertical aim	One lamp only	Lens dirt
Left rearview mirror glare at 20 m	Vertical aim	Light source	One lamp only
Center rearview mirror glare at 20 m	Vertical aim	Vehicle type	One lamp only
Right rearview mirror glare at 20 m	Vertical aim	One lamp only	Vehicle type
Foreground illumination at 15 m	One lamp only	Light source	Vertical aim
Foreground illumination at 25 m	One lamp only	Vertical aim	Light source

Vertical aim. As indicated above, a criterion of ±2 standard deviations (which should be exceeded about 5% of the time) was used for investigating the effects of factors for which such information was available. These factors included vertical aim, horizontal aim, lamp mounting height, and lamp separation. Furthermore, number of functional lamps could be, conceptually, placed into the same category, because the likelihood of one lamp not being functional is similar to the likelihood of an event that is two standard deviations or more from the mean. Specifically, the most recent estimate is that in the U.S. the likelihood of one headlamp not being functional is about 2.3% (Rys et al., 1993). Furthermore, the lens dirt condition that was included was also rather extreme (after 482 km in snow and road salt), as were the levels selected for vehicle type (cars vs. light trucks and vans), beam pattern (U.S. vs. European), and light source (an unshielded 9007 vs. a shielded H4). Consequently, a criterion of two standard deviations for vertical misaim appears to be reasonably comparable.

Nevertheless, because vertical aim so dominated all other factors, we also examined the consequences of vertical misaim of only one standard deviation from the mean (±0.65°). Almost a third (32%) of lamps would exceed this criterion. A comparison of the effects of one and two standard deviations of vertical misaim are shown in Table 10, in relation to the effects of the second most important factor—number of functioning lamps. The findings are that even at ±0.65° of misaim (at one standard deviation) the effects are generally greater than those of the next most important factor.

Number of functioning lamps. As indicated above, the second most influential factor was the number of functioning lamps; this factor was the most important factor twice, and it was either the second or the third most important factor 15 times (see Table 9).

Beam pattern and light source. The light-source manipulation can be considered as a weaker version of the beam-pattern manipulation. The two light sources selected (9007 and H4) create beam patterns that tend to differ along the same lines as do U.S. and European beam patterns. However, both light sources needed to produce beam patterns consistent with current U.S. specifications. The effects of beam pattern and light source are summarized in Table 11. As expected, the U.S. beam pattern and the 9007 light source were superior from the visibility points of view, while the European beam pattern and the H4 light source were superior from the glare points of view.

Table 10.
The effects of vertical misaim of ±1.30° and ±0.65°, compared with the effects of number of functioning lamps. The entries are percentage changes in the luminous intensities.

Performance aspect	Vertical misaim		One lamp only
	Up 1.3° (Up 0.65°)	Down 1.3° (Down 0.65°)	Right (Left)
Right pedestrians and delineation at 100 m	+43 (+56)	-91 (-70)	-55 (-45)
Right pedestrians and delineation at 50 m	-15 (+12)	-86 (-53)	-50 (-50)
Left pedestrians and delineation at 100 m	+205 (+122)	-80 (-60)	-51 (-49)
Left pedestrians and delineation at 50 m	+128 (+89)	-79 (-60)	-57 (-43)
Right reflectors at 20 m and height of 0.5 m	+69 (+65)	-88 (-67)	-61 (-39)
Right reflectors at 20 m and height of 1.0 m	+835 (+191)	-64 (-50)	-66 (-34)
Left reflectors at 20 m and height of 0.5 m	+131 (+101)	-87 (-68)	-77 (-23)
Left reflectors at 20 m and height of 1.0 m	+670 (+139)	-44 (-31)	-63 (-37)
Right shoulder-mounted traffic signs at 150 m	+645 (+244)	-84 (-71)	-51 (-49)
Center overhead traffic signs at 150 m	+192 (+40)	-31 (-16)	-50 (-50)
Left shoulder-mounted traffic signs at 150 m	+522 (+153)	-55 (-41)	-50 (-50)
Targets near the road expansion point	+416 (+278)	-82 (-61)	-50 (-50)
Direct oncoming glare at 50 m	+490 (+142)	-55 (-41)	-52 (-48)
Wet-pavement reflected glare at 50 m	-21 (-7)	-53 (-12)	-52 (-48)
Left rearview mirror glare at 20 m	+146 (+61)	-71 (-53)	-45 (-55)
Center rearview mirror glare at 20 m	+463 (+84)	-38 (-25)	-57 (-43)
Right rearview mirror glare at 20 m	+186 (+55)	-33 (-22)	-55 (-45)
Foreground illumination at 15 m	-50 (-27)	+45 (+39)	-63 (-37)
Foreground illumination at 25 m	-40 (-19)	-61 (-14)	-70 (-30)

Table 11.
The effects of beam pattern and light source. The entries are percentage changes in the luminous intensities. The changes in the desirable directions are in parentheses.

Performance aspect	Beam pattern (European instead of U.S.)	Light source (H4 instead of 9007)
Right pedestrians and delineation at 100 m	-56	-13
Right pedestrians and delineation at 50 m	-42	-19
Left pedestrians and delineation at 100 m	-40	-31
Left pedestrians and delineation at 50 m	(+2)	-5
Right reflectors at 20 m and height of 0.5 m	-60	-23
Right reflectors at 20 m and height of 1.0 m	-62	-54
Left reflectors at 20 m and height of 0.5 m	-32	-34
Left reflectors at 20 m and height of 1.0 m	-43	-54
Right shoulder-mounted traffic signs at 150 m	-82	-43
Center overhead traffic signs at 150 m	-49	-43
Left shoulder-mounted traffic signs at 150 m	-47	-52
Targets near the road expansion point	-77	-53
Direct oncoming glare at 50 m	(-46)	(-50)
Wet-pavement reflected glare at 50 m	+9	(-26)
Left rearview mirror glare at 20 m	(-30)	+86
Center rearview mirror glare at 20 m	(-49)	(-44)
Right rearview mirror glare at 20 m	(-27)	(-10)
Foreground illumination at 15 m	-19*	-62*
Foreground illumination at 25 m	-22*	-44*

* There is not a complete consensus whether high levels of foreground are desirable or not.

Horizontal aim. As expected, horizontal misaim had substantially weaker effects than did vertical misaim. The greatest effects were on the targets near the road expansion point (124%), followed by left-mounted reflex reflectors at 0.5 m (77%), and pedestrians and delineation (averaging 18%).

Lateral separation. The effects of changing the lateral separation from the current mean value of 1.12 m to either 1.36 m or 0.88 m (±2 standard deviations) were small. (None of the changes were greater than 21%.) Interestingly, assuming a cyclopean position of both lamps (a separation of 0 m) also had only small effects (11% or less), with one exception. Specifically, for both the right and left vehicle reflex reflectors mounted at 0.5 m (near the mounting height of the lamps), using a cyclopean position reduced the incident illumination by about 40%. Overall, the present analyses indicate that using a cyclopean approximation to lamp separation does not introduce major errors, except if the target in question is both at a near distance and at a mounting height near that of the headlamps.

Mounting height. The effects of changing the lamp mounting height from the current mean value of 0.62 m to either 0.66 m or 0.58 m (±2 standard deviations) ranged from negligible to small (18% or less). The greatest effects were on vehicle reflex reflectors and rearview mirror glare.

Vehicle type. This manipulation was primarily a more extreme manipulation of mounting height (from 0.62 m to 0.83 m), coupled with a modest beam-pattern change. The effects ranged from negligible (averaging 8% for traffic signs) to major (averaging 92% for vehicle reflex reflectors).

Lens dirt. The effects of dirt were generally moderate, with a maximum of 27%.

Lamp voltage. The values investigated (12.0 V and 13.5 V) result in 20% changes in luminous intensity (down and up, respectively) for all performance aspects.

Relative vs. absolute effects

The primary focus of this study was on the relative effects of a variety of factors. However, the present data can also be used for making inferences about the absolute effects of these factors. To do that, we recommend as a reasonable criterion the magnitude of the effects due to one lamp not being functional. According to this recommendation, any effects that exceed this criterion (near 50% for all performance functions) should be considered substantial.

CONCLUSIONS

This study compared the quantitative influence of a variety of factors on the performance of low-beam headlamps. The goal was to derive a rank ordering of the importance of these factors for improving low-beam headlighting.

The following factors were included: vertical aim, horizontal aim, mounting height, lateral separation (including a comparison of two lamps located in the same position vs. lamps laterally separated), lens dirt, lamp voltage, number of functioning lamps (two vs. one), vehicle type (cars vs. light trucks and vans), beam pattern (U.S. vs. European), and light source (an unshielded 9007 vs. a shielded H4). Whenever the information on the distribution of the factors was available, a range of ±2 standard deviations was used in the calculations.

The following performance aspects were considered: visibility of pedestrians, visibility of road delineation, visibility of vehicle reflex reflectors, visibility of retroreflective traffic signs, visibility of targets near the road expansion point, glare directed towards oncoming drivers, glare reflected from wet pavement towards oncoming drivers, glare directed towards rearview mirrors of preceding vehicles, and foreground illumination. A market-weighted U.S. beam pattern, with lamps mounted at market-weighted locations, formed the basis for most of the analyses.

For each of the performance aspects, typical geometric situations (points in space) were specified in terms of the longitudinal, lateral, and vertical positions, and the corresponding visual angles from each of the two lamps were calculated. The effects of the factors were quantified by calculating the percentage change in luminous intensity directed from both lamps towards the points in space representing the performance aspects.

The results indicate that from among the factors studied, vertical aim is overwhelmingly the most important factor in influencing the performance of low-beam headlamps. The second most important factor was the number of functioning lamps.

The main implication of this study is that major improvements in current (fixed as opposed to adaptive) low-beam headlighting could be achieved primarily by better control of vertical aim and by longer-life headlamps (be they longer-life incandescent or high-intensity discharge headlamps).

REFERENCES

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 systems context* (SAE Technical Paper Series No. 770238). Warrendale, PA: Society of Automotive Engineers.

Bhise, V.D., Matle, C.C., and Hoffmeister, D.H. (1984). *CHESS model applications in headlamp systems evaluation* (SAE Technical Paper Series No. 840046). Warrendale, PA: Society of Automotive Engineers.

Copenhaver, M.M. and Jones, E. (1992). *Measurement of headlamp aim and the electrical and photometric performance characteristics of rear lighting systems* (Report No. DOT HS 807 930). Washington, D.C.: U.S. Department of Transportation.

Perel, M. (1985). Evaluation of headlamp beam patterns using the Ford CHESS program. In *The Proceedings of the Tenth International Technical Conference on Experimental Safety Vehicles* (pp. 225-229). Washington, D.C.: U.S. Department of Transportation.

Rys, M., Konz, S., and Russell, E. (1993). *Headlight outages.* Presented at the 1993 SAE Congress, Detroit, March 1-5.

Sivak, M., Flannagan, M.J., and Sato, T. (1993). *Light output of U.S., European, and Japanese low-beam headlamps* (Report No. UMTRI-93-26). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Budnik, E., Flannagan, C., and Kojima, S. (1996a). *The locations of headlamps and driver eye positions in vehicles sold in the U.S.* (Report No. UMTRI-96-36). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Traube, E.C., Kojima, S., and Aoki, M. (1996b). *Effects of realistic dirt levels on light distribution of low-beam headlamps* (Report No. UMTRI-96-10). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak, M., Flannagan, M.J., Kojima, S., and Traube, E.C. (1997). *A market-weighted description of low-beam headlighting patterns in the U.S.* (Report No. UMTRI-97-37). Ann Arbor: The University of Michigan Transportation Research Institute.

Sivak., M., Flannagan, M.J., Traube, E.C., and Miyokawa, T. (1998). *Do changes in voltage result in proportional changes throughout headlamp beam patterns?* (Report No. UMTRI-98-27). Ann Arbor: The University of Michigan Transportation Research Institute.