U.S. Department
of Transportation
**National Highway
Traffic Safety
Administration**

www.nhtsa.gov

DOT HS 811 055 **December 2008**

Sensitivity Analysis of Headlamp Parameters Affecting Visibility and Glare

Technical Report Documentation Page

1. Report No. DOT HS 811 055	2. Government Accession No.
3. Recipient's Catalog No.	
4. Title and Subtitle Sensitivity Analysis of Headlamp Parameters Affecting Visibility and Glare	5. Report Date December 2008
	6. Performing Organization Code
7. Author(s) Y. Akashi, F. Hu, and J. D. Bullough	8. Performing Organization Report No.
9. Performing Organization Name and Address Lighting Research Center Rensselaer Polytechnic Institute 21 Union Street Troy, NY 12180	10. Work Unit No. (TRAIS)n code
	11. Contract of Grant No. DTNH22-05-D-01002
12. Sponsoring Agency Name and Address National Highway Traffic Safety Administration 1200 New Jersey Avenue SE. Washington, DC 20590	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code
15. Supplementary Notes Contracting Officer's Technical Representatives (COTR) were Stephanie Binder and Michael Perel.	

16. Abstract

Computer-simulated evaluations were conducted to identify the extent to which driver visibility and glare are affected by headlamp light source type (e.g., tungsten-halogen or high-intensity discharge), mounting height, optical system type, alignment type, and mis-aim. Based on the results of these simulation evaluations, this study also addressed whether further limits might be considered in photometric standards for headlamps that are addressed by Federal regulations. While there appears to be an inherent conflict between visibility and glare in the photometric design of headlamps, the analyses performed here do indicate that current photometric specifications for headlamps do not always trade off visibility and glare equally (e.g., headlamps that provide equivalent forward visibility as characterized here can result in different levels of disability or discomfort glare). The findings imply that advanced (dynamic) forward-lighting systems (AFS), if they can be made practical, might be of benefit in adjusting headlamp luminous intensity distributions in various situations to maximize visibility while controlling glare within acceptable limits.

17. Key Words headlamp glare, halogen, high-intensity discharge, headlamp aim, mounting height, headlamp optical system, headlamp photometry		18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 58	22. Price

Form DOT F1700.7 (8-72) **Reproduction of completed page authorized**

Executive Summary

As discussed in a recent report on nighttime headlamp glare from the National Highway Traffic Safety Administration (NHTSA) to the U.S. Congress, a number of factors can contribute to the extent to which drivers experience reduced visibility and discomfort from oncoming vehicle headlamps. These include the lamp type (e.g., tungsten-halogen or high-intensity discharge [HID]), lamp mounting height, headlamp optical system type (e.g., whether headlamps use reflector or projector systems), and the alignment of lamps.

Computer-simulated evaluations were conducted to identify the extent to which driver visibility and glare are affected by these factors. The degree of conformity of headlamps to current U.S. photometric regulations (both minimum and maximum intensity) for headlamps (Federal Motor Vehicle Safety Standard [FMVSS] 108) was also evaluated.

The evaluations used photometric data for 12 headlamps available in the United States, covering a sample including several headlamps with different characteristics as described above (e.g., lamp type, mounting height, etc.). These evaluations (1) examined to what extent current headlamps have luminous intensity values below the maxima and above the minima required by the FMVSS 108 photometry limits—Section 3 in this report; (2) identified the extent to which current headlamps produce disability glare and discomfort glare to oncoming drivers—Section 4; (3) investigated detection distances provided by headlamps with different characteristics—Section 5; and (4) compared the results from the glare and visibility evaluations, showing that these two factors are largely traded off in existing headlamps—Section 6.

The findings from the analyses that were performed can be summarized as follows:

- When comparing the extent to which the headlamps studied have luminous intensity values below the maximum values specified by FMVSS 108 or above the minimum values, there is a general trend that the headlamps that have luminous intensities closest to the allowable maximum values (producing close to the maximum allowable glare) tend to have luminous intensities that well exceed the allowable minimum values (producing relatively high forward visibility). Conversely, lamps that have luminous intensities much lower than the allowable maximum values (producing relatively low glare) tend to have luminous intensities just above the allowable minimum values (producing close to the minimum forward visibility). This implies that the FMVSS 108 requirements, in general, force a balance between excessive glare to oncoming drivers and too little light for forward visibility. There is, however, considerable spread among the individual headlamps studied.
- The analyses of disability glare (reduction in visibility) and discomfort glare (reduction in comfort) revealed that mounting height had a small but statistically significant effect on both disability and discomfort glare. When properly aimed, HID headlamps did not result in significantly greater disability glare but did result in slightly greater discomfort glare than halogen headlamps, even when the potential for their spectral (color) characteristics to increase discomfort is underestimated. However, upward mis-aim of headlamps resulted in the largest increases in both disability glare and discomfort glare, a statistically significant result.

- The forward-visibility evaluations showed that lamp type influences target detection distances: HID headlamps gave longer forward-visibility distances than tungsten halogen headlamps, consistent with their generally higher maximum luminous intensities. However, when headlamps were mis-aimed in the downward direction, the resulting impact on calculated detection distances was larger than for the lamp type, and detection distances were shorter if headlamps were mis-aimed down.
- Current photometric requirements limit the amount of light at certain angular locations above the horizontal and just left of center in the beam pattern. They also specify a minimum amount of light directly ahead and just below horizontal. Because these two angular locations are distinct, one could envision a headlamp with very little light above horizontal and high light levels below horizontal, which in theory would produce long detection distances and little disability or discomfort glare. Requiring lower luminous intensity values above horizontal and higher intensity values below horizontal than currently specified could be possible, but because the angular regions are close to one another, such a distribution would require a very sharp cutoff gradient. Presently, FMVSS 108 standards require a minimum gradient sharpness to allow for visual aiming, but there is no limit on the maximum sharpness. However, there is evidence that beam patterns with very sharp gradients are seen as less desirable, and such patterns would be susceptible to small changes in vertical aim. The effects of sharp gradients on driving performance are not presently known.

The variety of roadway geometries that can be experienced in the real world is large. One can envision situations where a portion of the headlamp beam pattern usually thought to contribute to forward visibility might be directed toward an oncoming driver's eyes, or when a portion normally desired to be as dark as possible (to avoid creating glare) might be needed to detect a potential roadway hazard. For this reason, dynamic adaptive forward-lighting systems (AFS) might be of benefit in future lighting systems if these can be shown to be able to adapt the distribution of light from headlamps to maximize forward visibility while controlling glare within acceptable limits.

1. Background and Objectives

As discussed in a recent report on nighttime headlamp glare from the National Highway Traffic Safety Administration (NHTSA) to the U.S. Congress (NHTSA, 2007), a number of factors can contribute to the extent to which drivers experience reduced visibility and discomfort from oncoming vehicle headlamps. These include the lamp type (e.g., tungsten-halogen or high-intensity discharge [HID]), lamp mounting height, headlamp optical system type (e.g., whether headlamps use reflector or projector systems), and the alignment of lamps.

Many studies have investigated the degree to which visibility and glare are impacted by headlamp characteristics such as intensity (Bullough et al., 2003; Clark et al., 2005; Flannagan et al., 2000), spatial distribution of the beam pattern (Van Derlofske et al., 2001, 2002; Clark et al., 2005), and spectral power distribution (Flannagan, 1999; Bullough et al., 2003). A difficulty in interpreting these disparate studies as a body is the different ways in which both independent variables (i.e., headlamp characteristics) and dependent variables (i.e., visibility or glare) are operationally defined in each of these studies. For this reason, the present study was performed to provide comparative data for some representative headlamp types using a consistent set of independent and dependent measures.

The objectives of the present study were to:

- Compare the photometric characteristics of a wide range of headlamps to determine the extent to which driver visibility might be affected by the range of photometric distributions of these headlamps; and
- Identify whether further limits may be needed in the relevant U.S. headlamp regulation FMVSS 108 by examining the impact of this range on metrics of visibility and glare.

Toward this end, the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute conducted the following evaluations by using photometric data for several headlamps covering a large variety of categories that are available in the U.S. marketplace. In these evaluations, the LRC attempted to:

- Examine how headlamps conform to the maximum and minimum photometric requirements of Federal Motor Vehicle Safety Standard (FMVSS) 108 (Section 3 of this report);
- Identify the extent to which current headlamps produce disability glare and discomfort glare (Section 4);
- Identify how long the detection distances are that current headlamps provide (Section 5); and
- Finally, compare the evaluation results based on the FMVSS 108 requirements with the results of the glare and visibility evaluations (Section 6).

It should be emphasized that all of the evaluations performed for the current study were computational in nature, based on the photometric data obtained by the research team and the analytical methods described in subsequent chapters of this report. No new experimental visibility or glare data were collected for this study.

2. Headlamps Used in This Study

The LRC collected a variety of headlamp photometric data from the U.S. market to cover the following categories:

- Lamp type (high-intensity discharge [HID] and tungsten halogen [TH] lamps): These are the two most common lamp types used in vehicle headlamps, and the presence of HID headlamps is a commonly cited source of complaints about glare from the driving public (Singh and Perel, 2003). Differences between HID and halogen headlamp distributions have also been cited as reasons for differences in forward visibility with different lamps (Van Derlofske et al., 2001, 2002), and these are generally related to the "broader" distribution of light produced by many HID headlamps compared to many halogen headlamps (Jost, 1995).
- Optical system (reflector or projector type): Most headlamps on current vehicles use one of these two optical systems to form the beam shape. In general, projector type headlamps have smaller light-emitting areas, which have been suggested as being related to increased glare (Rosenhahn and Lampen, 2004).
- Mounting height (passenger and sport utility vehicle [SUV]/light truck): Headlamp distribution requirements do not change within a wide range of mounting heights encompassing passenger cars and larger light trucks and SUVs, but this factor has been shown to influence discomfort glare (Akashi et al., 2005).
- Cut-off alignment (visually optically aimable-right [VOR] and -left [VOL]): In recent years, vehicle headlamps in the United States have moved from the mechanically aimed type to visually aimed type, set by projecting the beam pattern onto a vertical surface and aligning either the left- or right-side portion of the beam pattern to a specific vertical height (different for each side). Control of the left and right sides of the beam pattern might have different implications for glare and visibility.

The logic behind the categories and characteristics used in the present study was to use unambiguous, easily grouped factors that could be hypothesized to impact glare or visibility (or both). Other approaches have been used in other studies. For example, Clark et al. (2005) selected the angular width between which a headlamp's luminous intensity distribution exceeded 12,000 cd as a criterion for assessing width.

The LRC collected 45 headlamp photometric reports from manufacturers and research organizations and categorized each of those headlamps into 16 groups (each of the four factors listed above with two options for each factor results in 2^4 or 16 groups). Table 1 summarizes the collected headlamps of both right and left sides; only one side was available for a few headlamps. Obviously, in an automotive market with hundreds of vehicle models available, a sample of a few dozen will not capture all of the variability inherent in different types of headlamps. Rather, the present study focuses on the 16 groups created by considering the four factors outlined above in order to provide a sense of the differences in visibility and glare that can be found among these groups, but it should be recognized that the results of the study cannot be generalized to all headlamps and that the headlamps studied do not necessarily compose a statistically representative sample of vehicle headlamps in the present market. As described above, all data are based on measurements performed by manufacturers or by other research organizations; no new photometry was performed for the present study.

Table 1 summarizes the headlamp types addressed in this study. However, because photometric data for 4 of the 16 headlamp types (marked as not available [NA] in Table 1) were unavailable (these types are infrequently if ever found in the vehicle market), only 12 of the 16 groups are represented in the present study. For each headlamp group type, one representative headlamp system was selected for use in further calculation analyses. When data for multiple headlamps were available within one of the 16 groups, the criterion for selection of headlamps to represent a group was based on the likelihood of the vehicle being representative in the U.S. vehicle market (e.g., a domestic mid-price passenger car would be selected before a high-end imported sports car). If different headlamps had been used in the analyses, the specific results of the analyses would probably be affected but the general degree of differences among types would probably not change greatly because multiple headlamps still were included within each category type (HID versus halogen, projector versus reflector, etc.). Because of the limited sample, the variability within types of headlamps cannot be assessed in the present study. In this report and in all graphs describing the results, the following graphical conventions are used to identify each headlamp type:

- Lamp (color): TH (black; ▲) or HID (gray; ▲)
- Optics (shape): Reflector (triangle; ▲) or projector (circle; ●)
- Mounting height (size): passenger car (small; ▴) or SUV/light truck (large; ▲)
- Cutoff alignment (fill): VOL (filled; ▲) or VOR (unfilled; △)

Table 1: Graphical representation of the 12 headlamp types used in the study

		Projector		Reflector	
		VOL	VOR	VOL	VOR
Passenger	HID	• (gray)	○ (gray)	▴ (gray)	▵ (gray)
	TH	•	○	▴	▵
SUV	HID	● (gray)	NA	▲ (gray)	△ (gray)
	TH	NA	◯	NA	NA

Appendix 1 shows the luminous intensity distributions of the twelve headlamps used in the study.

3. Comparison of Measured Photometric Distributions With FMVSS Requirements

To regulate the luminous intensity distributions of automotive forward headlamps for minimizing glare to oncoming drivers and improving drivers' forward visibility, NHTSA issued FMVSS No. 571.108: Lamps, reflective devices, and associated equipment (FMVSS 108). This regulation states that headlamps should be designed to conform to specific photometric values. The FMVSS 108 requirements include two sets of photometry values for headlamp luminous intensity; the first set are minimum luminous intensity values, presumably to maintain good forward visibility, and the second set are maximum luminous intensity values, presumably to avoid (or at least reduce) glare. When these standards were originally developed, only TH headlamps were available; however, recent developments of HID headlamps may affect those lamps' conformity to the photometric standards. Because HID headlamps usually produce greater luminous flux than conventional TH headlamps, they can easily achieve the minimum photometry limitations for forward visibility. In regions of the photometric distribution that are not limited by maximum allowable luminous intensities, HID headlamps might produce significantly higher luminous intensities than TH headlamps, possibly increasing glare to oncoming drivers. In fact, many drivers have complained of glare from HID headlamps, as reported in NHTSA public comment dockets 8885 and 13957 (http://dms.dot.gov).

As a preliminary analysis, the present study addressed questions of how current headlamps conform to the FMVSS 108 photometric requirements.

3.1. Headlamp photometric standards

Headlamps should be designed to facilitate forward visibility while minimizing glare to oncoming drivers. To achieve these potentially conflicting requirements, manufacturers carefully select headlamp optics. To restrict glare and enhance forward visibility, the FMVSS photometric requirements regulate maximum luminous intensity limitations and minimum limitations, respectively.

Appendix 2 summarizes the photometric performance requirements for low-beam vehicle headlamps from FMVSS 108. Among the measurement points in these requirements, this study focused on 5 data points at or above the horizontal direction for the maximum limitations and on 12 data points at or below the horizontal direction for the minimum limitations and compared resulting headlamp luminous intensities with the FMVSS photometric requirements. Table 2 summarizes these photometry data points.

Table 2: FMVSS 108 photometric standards for low beams used in this study

Maximum luminous intensities				Minimum luminous intensities			
No.	Horizontal (deg.)	Vertical (deg.)	Limit (cd)	No.	Horizontal (deg.)	Vertical (deg.)	Limit (cd)
1	1	1.5	1400	1	-8	0	64
2	-1.5	1	700	2	-4	0	135
3	-1.5	0.5	1000	3	1.3	-0.6	10000
4	1	0.5	2700	4	-3.5	-0.86	1800
5	3	0.5	2700	5	0	-0.86	4500
				6	2	-1.5	15000
				7	-15	-2	1000
				8	-9	-2	1250
				9	9	-2	1250
				10	15	-2	1000
				11	-20	-4	300
				12	20	-4	300

3.2. Conditions and procedure

Data sampling intervals of headlamp luminous intensity distributions obtained for this study varied, depending on the source of information. Some headlamps are photometered at very small intervals (e.g., 0.1 degrees) to precisely characterize luminous intensity gradients, particularly near the center of the headlamp beam pattern. To compare each set of luminous intensities with the standard values specified in FMVSS 108, the original data were interpolated when necessary to estimate the luminous intensity at a particular angle. Evaluations were undertaken for the 12 headlamp types listed in Table 1.

3.3. Conformity of current headlamps to the FMVSS 108 requirements

Appendix 3 shows the results of the analyses. In Appendix 3, figures show differences of reported headlamp luminous intensities from the FMVSS 108 requirements. Note that in those figures corresponding to minimum required intensities, the higher the difference, the better the forward visibility is presumed to be. Although it is predicted that glare might occur if the luminous intensity is much higher than the minimum limitations, the FMVSS 108 requirements do not take into account such limitations.

Figure 1 shows the relationship between the mean differences of reported (from the photometric data) headlamp luminous intensities from the maximum FMVSS 108 values (horizontal axis: below-maximum, presumably for glare) and the mean difference from the minimum FMVSS 108 values (vertical axis: above-minimum, presumably for visibility). Values of zero for each would represent a headlamp that just meets the minimum or maximum requirements. The higher each of these values, the better the headlamps might be presumed to be in terms of forward visibility and low glare. Headlamps in the top right area of Figure 1 would be most desirable in that they would have the highest intensity values where a minimum luminous intensity is called for and the lowest intensity values where a maximum is called for. However, there is generally a negative correlation between the ordinate and abscissa values in Figure 1, such that low glare headlamps tend to provide lower forward visibility (e.g., symbols in the lower right quadrant of

Figure 1), and high forward visibility headlamps usually provide high glare (e.g., symbols in the upper left quadrant).

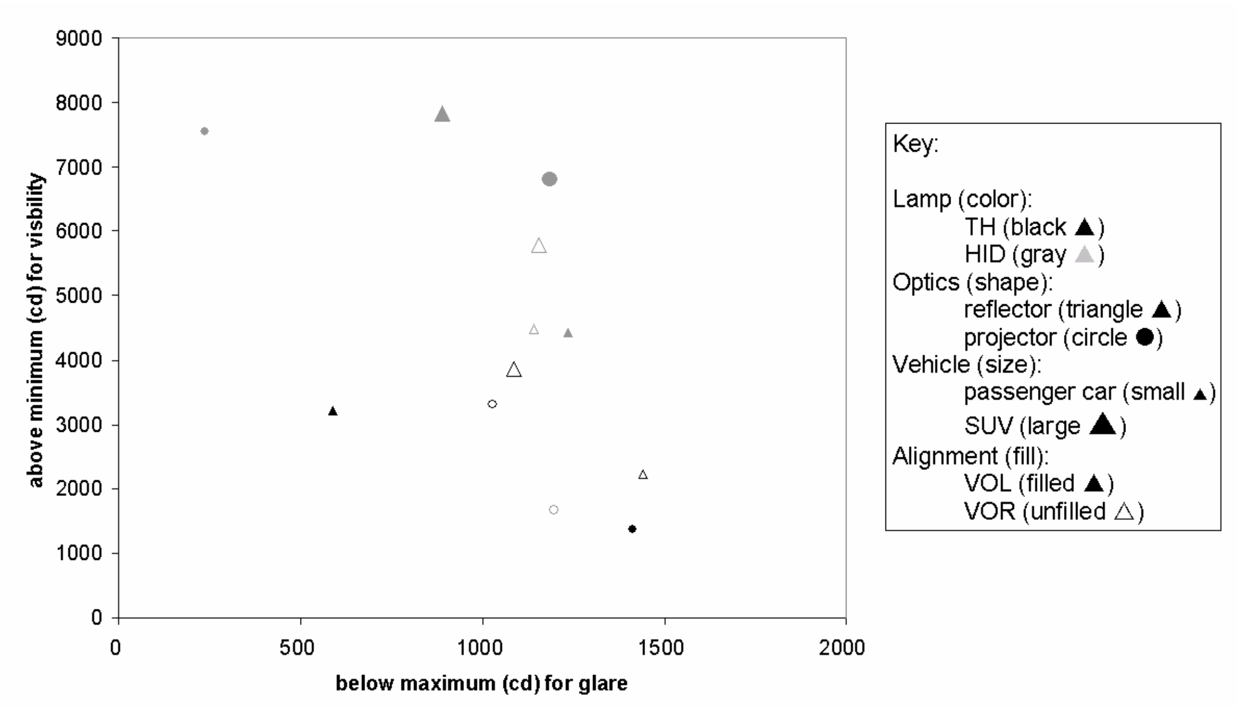


Figure 1: Mean differences of headlamp luminous intensities from the FMVSS 108 requirements.

4. Glare Evaluation

To further analyze the effects of headlamp characteristics on glare, the degree of glare was quantified by calculating glare illuminance, de Boer (1967) rating, veiling luminance, and glare dosage. To obtain those parameters, this study used a comprehensive software program, TarVIP (OPL, 2004), that is based on a Matlab platform. This program was developed at the University of Iowa and uses headlamp photometric distribution data to calculate light levels at targets and locations specified by the user. It also incorporates visibility and glare modeling to calculate the luminance contrasts of targets and compare them to the minimum contrast to see a target of its apparent size.

4.1. Definitions

Glare illuminance is vertical illuminance at an oncoming driver's eyes. Studies have reported that the degree of glare is largely determined by this quantity (Sivak et al., 1997).

The de Boer rating is a glare scale — 1: unbearable, 3: disturbing, 5: just acceptable, 7: satisfactory, and 9: just noticeable (de Boer, 1967) — that is often used for glare evaluations from headlamps and roadway lighting. Schmidt-Clausen and Bindels (1974) developed an equation relating illuminance at the eye to the degree of discomfort produced by light sources, expressed on the de Boer scale. The equation is listed below:

$$W = 5 - 2\log \sum \frac{E_i}{0.02\left(1 + \sqrt{Lb_i / 0.04}\right)\theta_i^{0.46}} \qquad (1)$$

where,

W is the de Boer scale,
Lb_i is background luminance (cd/m^2) of the *ith* glare source,
E_i is illuminance at the eye (in lx) caused by the *ith* glare source, and
θ_i is eccentricity angle (in degrees) of the *ith* glare source.

Veiling luminance is a luminance from scattered light in the eye superimposed on the retinal image that reduces its contrast (Fry, 1954). It is the effect produced by bright sources in the visual field that results in decreased visual performance and visibility by reducing the contrast of objects in the field of view, making them more difficult to see and decreasing the distance at which objects can be seen. Veiling luminance is proportional to illuminance at the eye caused by the glare sources, or the so-called glare illuminance. As glare illuminance increases and the angle of the displacement between a light source and the line of sight becomes smaller, veiling luminance is increased. This equation also takes the effect of an observer's age into account. As one ages, the amount of light scattered in the eye also increases.

Because of the veiling luminance caused by oncoming headlamps, the luminance contrast is decreased and therefore a potential target becomes less visible to the driver.

There are several equations used to calculate veiling luminance, L_v. The age-adapted Stiles-Holladay glare equation (for glare lights located between 3° and 30° from the line of sight) is given by (CIE, 2002):

$$L_v / E_{gl} = \{1 + [A/70]^4\} \cdot 10/\theta^2 \qquad (2)$$

A simple glare equation (for angles between 0.1° and 30°) is given by:

$$L_v / E_{gl} = 10/\theta^3 + \{1 + [A/62.5]^4\} \cdot 5/\theta^2 \qquad (3)$$

A general glare equation (0.1°<θ<30°) is given by:

$$L_v / E_{gl} = 10/\theta^3 + [5/\theta^2 + 0.1 \cdot p/\theta] \cdot \{1 + [A/62.5]^4\} + 2.5 \cdot 10^{-3} \cdot p \qquad (4)$$

where for all of these equations,

L_v	is veiling luminance (cd/m^2),
E_{gl}	is glare illuminance at the eye (in lx),
θ	is eccentricity angle from the line of sight in degrees,
A	is age in years, and
p	is pigmentation factor, ranging from 0 for very dark eyes, 0.5 for brown eyes, 1.0 for blue-green eyes, 1.2 for blue eyes.

Glare dosage is the product of exposure time (in seconds) and illuminance (in lx) while drivers' eyes are exposed to oncoming glare sources. A recent study found that the glare dosage had a high correlation with the recovery time after a driver's exposure to a glare source (Van Derlofske et al., 2005).

The development of the formula for discomfort glare is described extensively by Schmidt-Clausen and Bindels (1974); the development of the formulae for disability glare is described extensively in the International Illumination Commission's (CIE, 2002) report on glare models and equations.

4.2. Independent variables

The present study used the following independent variables:

- Oncoming car headlamps: the 12 headlamp types listed in Table 1. Those headlamps varied in the following parameters:
  - Lamp type: HID and halogen
  - Optics type: Reflector and projector
  - Cut-off type: VOR and VOL
  - Mounting height: Passenger and SUV (this latter category includes light trucks as well); headlamps were evaluated only for the mounting height of the vehicle for which they were designed

- Mis-aiming angle of oncoming cars – four angles as follows:
  - 0°, 0.5°, 1°, and 1.5° upward

4.3. Scenario and layout for simulation

For simulated calculations, this study used the following scenario: two opposing cars encountering one another along a local roadway with a lane width of 3.5 m. The initial distance between the two cars was 100 m. While both cars approached each other, the above-described glare parameters were calculated at intervals of 4 m. The speed of each car was set as 100 km/h, so the total time during which the driver's eyes were exposed to oncoming headlamps was 1.8 sec. The car speed and the exposure time did not affect the calculation results of the veiling luminances or de Boer ratings, but it did determine the glare dosage. Drivers were assumed to be looking at the roadway 100 m straight ahead. The simulation layout is depicted in Figure 2.

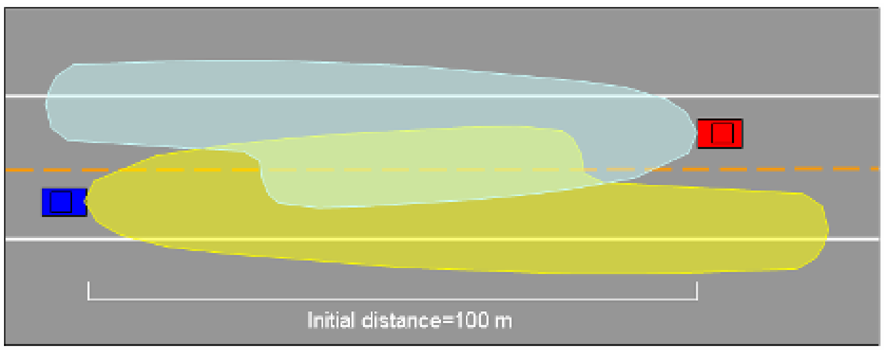


Figure 2: Layout for calculation simulation.

4.4. Results of veiling luminance and de Boer rating

Figure 3 illustrates two examples of the veiling luminance calculations for the headlamps resulting in the lowest (i.e., a TH, projector, VOL, passenger car headlamp) and highest (i.e., an HID, reflector, VOR, SUV headlamp) mean veiling luminance. Figure 3 suggests that as the distance between the two cars increases, the veiling luminance becomes higher, making objects more difficult to see and decreasing the distances at which they can be detected. This is most likely because the angular separation between a driver's line of sight and the oncoming headlamps is smallest when the oncoming vehicle is farthest away. Because the equation for veiling luminance contains terms with the angle between the glare source and the line of sight in the denominator, the veiling luminance approaches infinity as the glare separation angle approaches zero, which occurs as the oncoming vehicle is furthest away. While the relationship between the veiling luminance and glare separation angle is somewhat controversial for small glare separation angles (Boyce, 2003), and disability glare must approach zero when an oncoming vehicle is very far away, recent experimental data have confirmed that when a glare source is close to an object, that object can be very difficult to detect, even if the glare illuminance is relatively low (Bullough et al., 2003), so up to about 100 m the relationship between disability glare and distance from the line of sight is more likely to be valid. At further distances (i.e., several hundred meters) it seems this relationship would break down. While the maximum veiling luminance values are similar for each headlamp type at the farthest distance

(100 m), they differ substantially at shorter distances. In addition, as the mis-aiming angle increases the veiling luminance also increases.

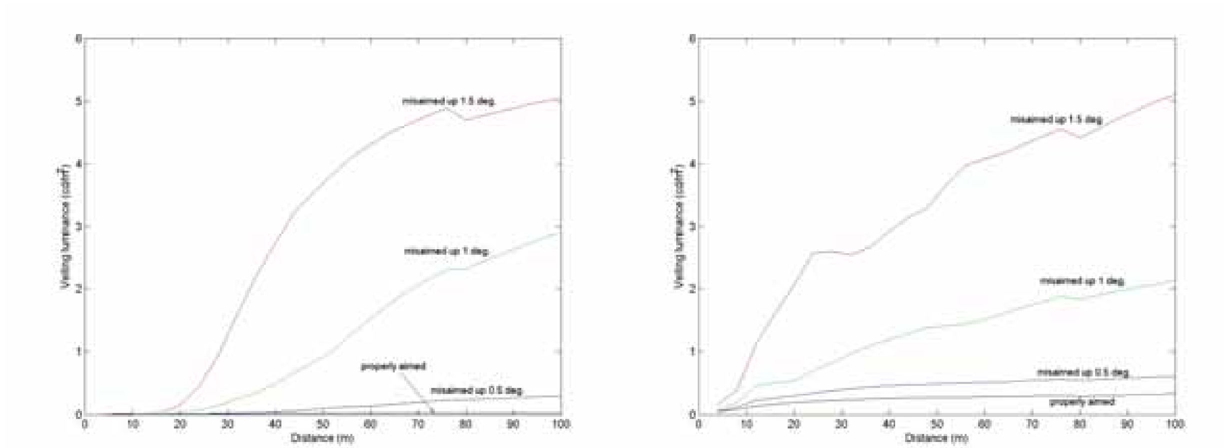


Figure 3: Veiling luminance profiles for headlamps with lowest (left) and highest (right) mean veiling luminance.

Figure 4 shows the results of the de Boer rating calculations for the same two headlamps. It should be noted that discomfort glare, as characterized by the de Boer rating, has an opposite tendency to that of disability glare for properly aimed headlamps (i.e., as the distance between the two cars becomes shorter, the degree of discomfort glare increases). The headlamp with the highest mean veiling luminance has much higher discomfort glare (i.e., smaller de Boer rating values) than the headlamp with the lowest mean veiling luminance. Another interesting feature is that as the mis-aiming angle increases, maximum values of discomfort glare appear around 10 m and 40 m for the two types, respectively.

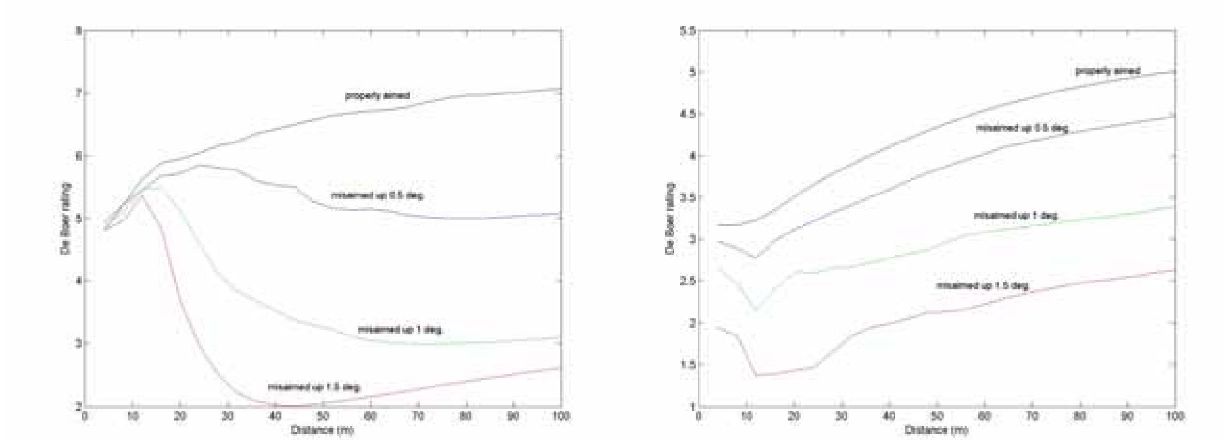


Figure 4: de Boer rating profiles for the headlamps shown in Figure 3 for different mis-aiming angles.

Beyond the data shown in Figures 3 and 4, to further analyze the effects of the independent variables on glare, analyses of variance (ANOVAs) were applied to each set of results under normal aiming conditions using a criterion probability of 0.05 for rejecting the null hypothesis.

The detailed results of the ANOVAs are shown in Table A-4(a) and Table A-4(b) for veiling luminance and de Boer rating, respectively (Appendix 4). Although there was only one headlamp in each of the 12 specific groups evaluated, for each independent variable in the ANOVA (e.g., lamp type, optics type, etc.) there were between four and eight headlamps for each variable in the analysis.

For the veiling luminances, four significant main effects and one significant interaction were found with properly aimed headlamps. Figure 5 summarizes the mean veiling luminances for each independent variable resulting in a significant main effect (Figures 5(a) - 5(d)) and for the significant interaction (Figure 5(e)). From the results of the ANOVAs and Figure 5, the following statistically significant relationships were found:

- Higher-mounted headlamps (i.e., from SUVs) produced higher veiling luminances than lower-mounted headlamps (i.e., from passenger cars).
- Reflector headlamps produced higher veiling luminances than projector headlamps.
- VOR headlamps produced higher veiling luminances than VOL headlamps.
- Headlamps from greater distances produced higher veiling luminances than those at shorter distances.

Additionally, an interaction between the mounting height and the lamp type suggested that for the lower mounting height (passenger cars), headlamps with TH lamps had higher veiling luminances than those with HID lamps. However, for higher mounting heights (SUVs), headlamps with TH lamps had lower veiling luminances than those with HID lamps. For the de Boer ratings, five significant main effects and three significant interactions were found. Figure 6 summarizes the mean de Boer ratings for each of the independent variables resulting in a significant main effect (Figures 6(a) - 6(e)) and for the significant interactions (Figures 6(f) – 6(h)). From the results of the ANOVAs and Figure 6, the following relationships were found:

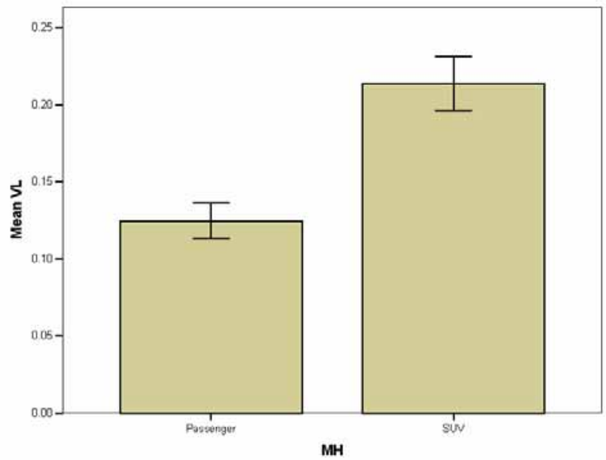
- Higher-mounted headlamps (i.e., from SUVs) resulted in greater discomfort glare (i.e., lower de Boer ratings) than lower-mounted ones (i.e., from passenger cars).
- HID headlamps resulted in greater discomfort glare than TH headlamps.
- Reflector headlamps resulted in greater discomfort glare than projector headlamps.
- VOR headlamps resulted in greater discomfort glare than VOL headlamps.
- Headlamps at shorter distances resulted in greater discomfort glare than those at longer distances.

Regarding the effect of lamp type (TH or HID) on discomfort glare, it should be recalled that the analysis method used in the present study does not take the spectral distribution into account. For the same luminous intensity, HID headlamps produce greater sensations of discomfort glare than halogen headlamps (Bullough et al., 2003). Thus, the present analyses somewhat underestimate the potential for HID headlamps to produce discomfort glare.

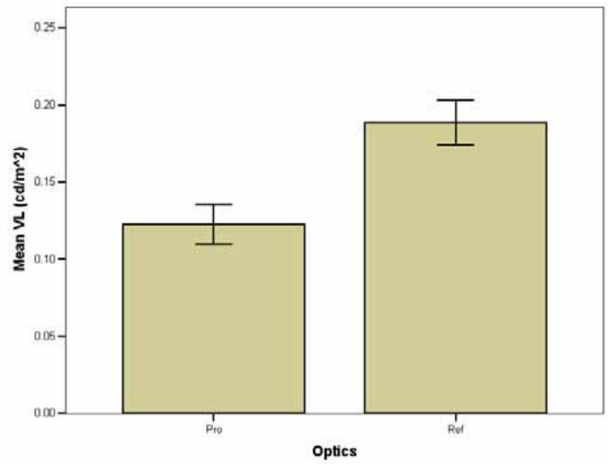
The significant interaction between the optics and the mounting height suggested that although reflector headlamps had significantly more discomfort glare (or lower de Boer ratings) than projector headlamps, this tendency was more pronounced for passenger cars than for SUVs (Figure 6(f)). From the significant interaction between the lamp and the optics, it was found that while HID headlamps had significantly higher discomfort glare than TH headlamps, this difference was even larger with projector optics than with reflector optics (Figure 6(g)). Similarly, the significant interaction between the alignment and the optics suggested that while VOR headlamps had significantly higher discomfort glare than VOL headlamps, this tendency was more pronounced with projector optics than reflector optics (Figure 6(h)).

To identify the correlation between veiling luminance and de Boer rating, Figure 7 shows calculation results of both dependent variables for the 12 headlamp types. As expected, these two representative glare indexes were generally correlated with one another ($R^2 = 0.76$), implying that although disability glare and discomfort glare are separate phenomena, conditions resulting in high levels of one type of glare are likely to elicit high levels of the other type.

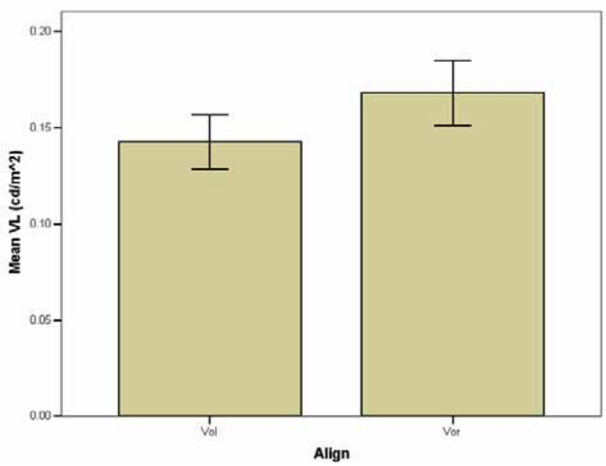
As an example of the relationship between glare (both disability glare and discomfort glare) and the luminous intensity distributions of the headlamps studied, the headlamp resulting in the highest veiling luminance (and in the lowest de Boer ratings) shown in Figure A-1(i) and the headlamp resulting in the lowest veiling luminance (and highest de Boer ratings) shown in Figure A-1(a) were compared. In the angular region just above horizontal and just to the left of 0º ahead, the higher-glare headlamp has a luminous intensity close to the maximum permissible value of 1000 cd (corresponding to the 0.5º up and 0º to 1. 5º left locations in Table A-2). The lower-glare headlamp has a luminous intensity in the same region of less than 300 cd, meaning the amount of light that could potentially reach oncoming drivers is lower for the latter headlamp, consistent with the lower glare observed in the preceding analyses.



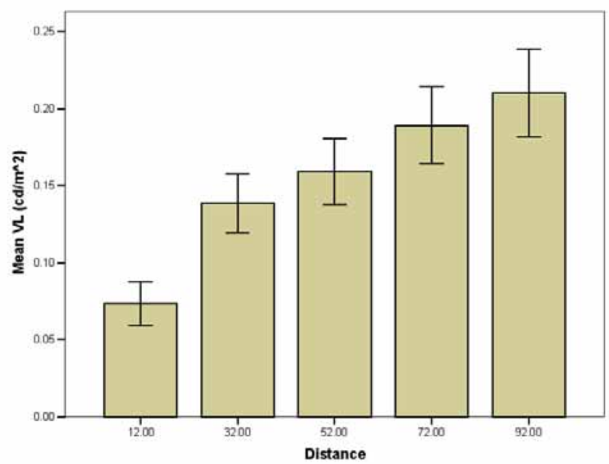
(a) Mounting height



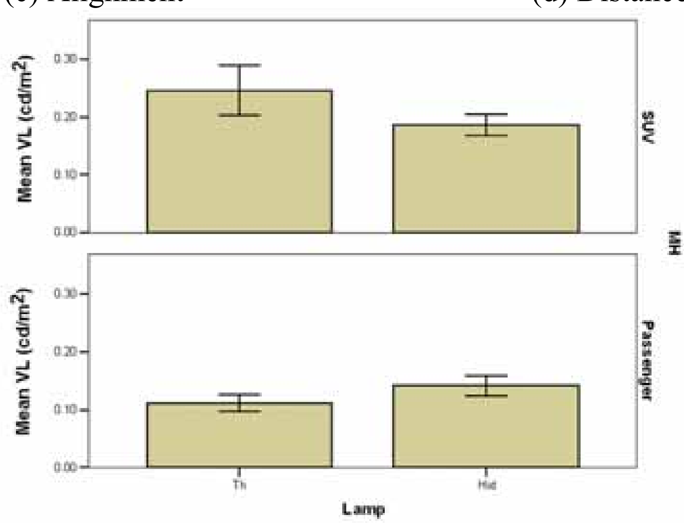
(b) Optics



(c) Alignment

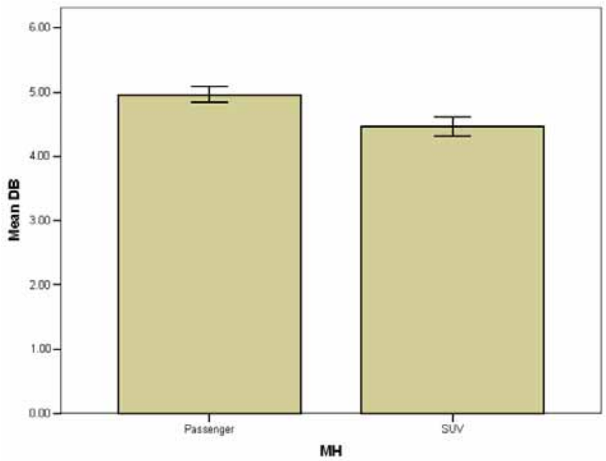


(d) Distance

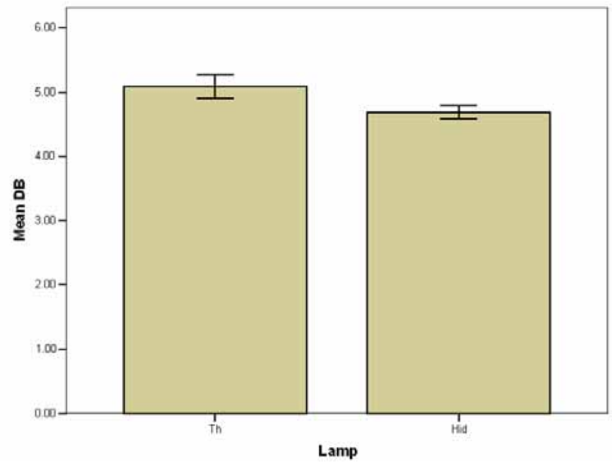


(e) Interaction between lamp and mounting height

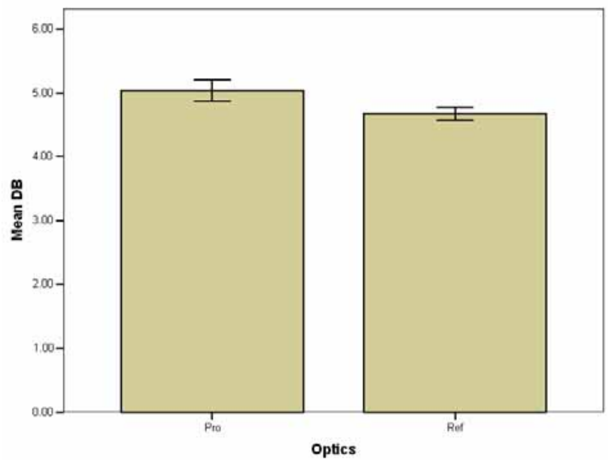
Figure 5: Results of veiling luminance (VL) calculations. Pro: projector, Ref: reflector, Th: tungsten halogen lamp, Hid: HID lamp, and MH: mounting height.



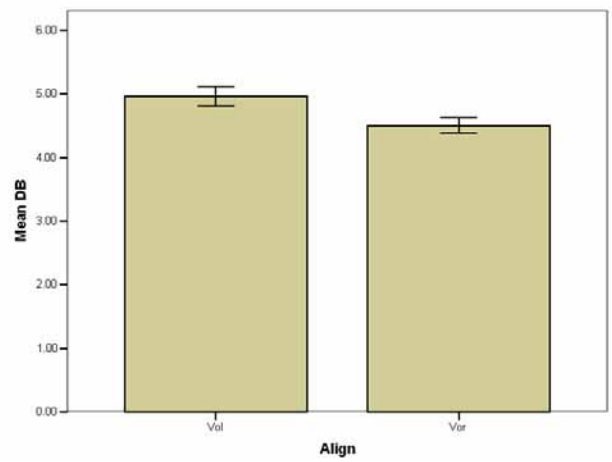
(a) Mounting height



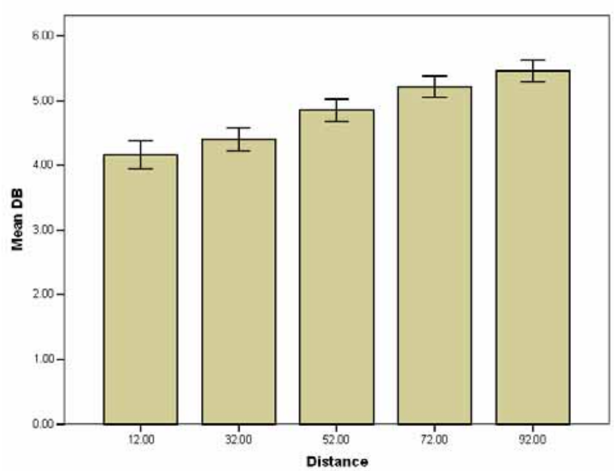
(b) Lamp



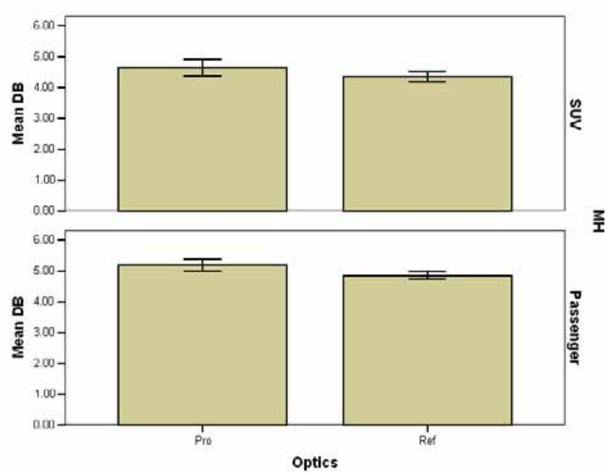
(c) Optics



(d) Alignment

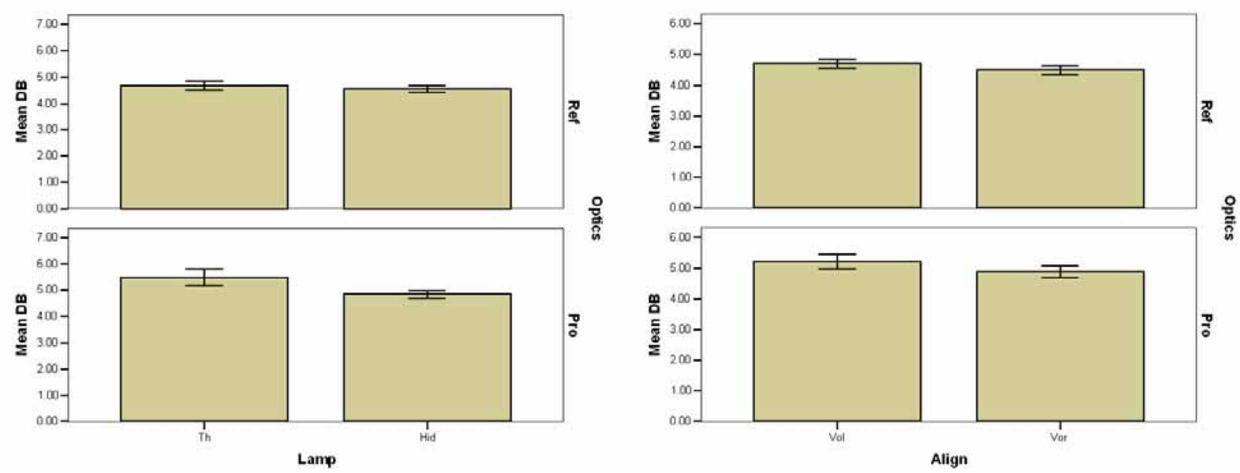


(e) Distance



(f) Interaction between optics and mounting height

Figure 6: Results of de Boer (DB) rating calculations. Pro: projector, Ref: reflector, Th: tungsten halogen lamp, Hid: HID lamp, and MH: mounting height.



(g) Interaction between lamp and optics (h) Interaction between alignment and optics

Figure 6 (cont.): Results of de Boer (DB) rating calculations. Pro: projector, Ref: reflector, Th: tungsten halogen lamp, Hid: HID lamp, and MH: mounting height.

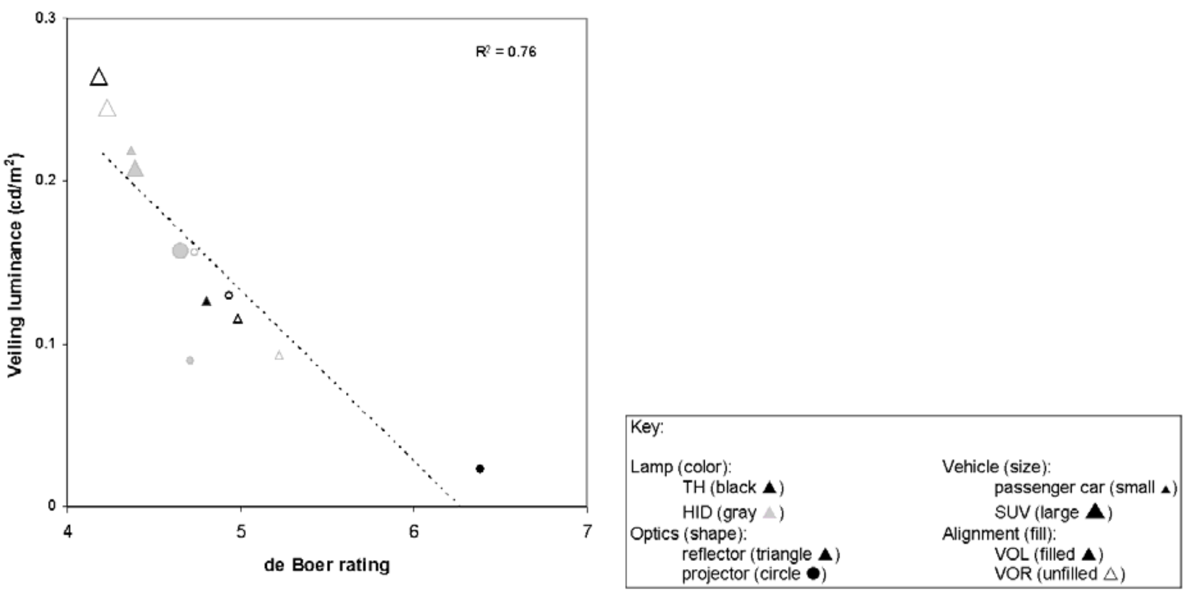


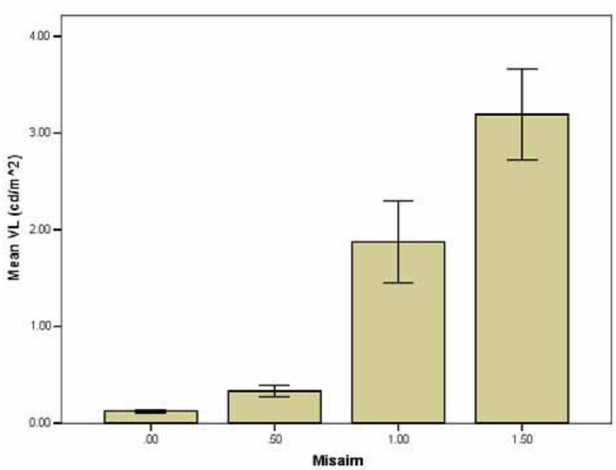
Figure 7: Correlation between veiling luminance and de Boer rating for each headlamp type.

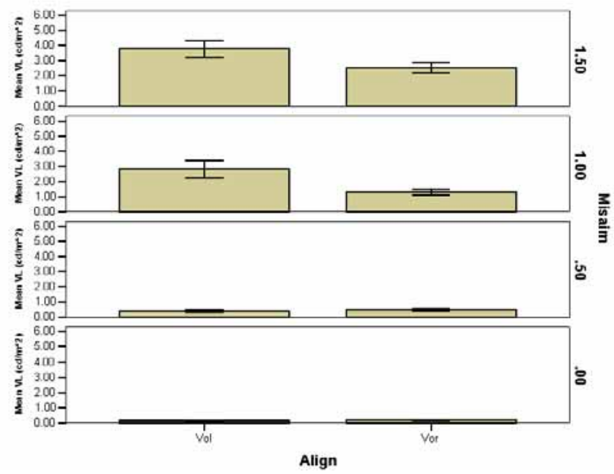
For <u>mis-aiming conditions</u>, the results of the ANOVAs are shown in Table A-4(c) and Table A-4(d). Since these tables suggest similar general tendencies as those for normal aiming headlamps, here we focus on the effect of mis-aiming angles.

Figure 8 shows the results of veiling luminance calculations in terms of mis-aiming angles: (a) the significant main effect of mis-aiming angles on detection distances, suggesting that as the mis-aiming angle increased, veiling luminance was also increased, (b) a significant interaction between mis-aiming angle and alignment, and (c) another significant interaction between mis-aiming angle and distance. Figure 8(b) suggests that although the VOL alignment headlamp type provided lower veiling luminances than the VOR alignment headlamp type when normally aimed, this headlamp type might cause significantly higher veiling luminances if mis-aimed. As Figures 3 and 5(d) show, veiling luminance increased as distance increased. This tendency was more pronounced when the mis-aiming angle became larger, as seen in Figure 8(c).

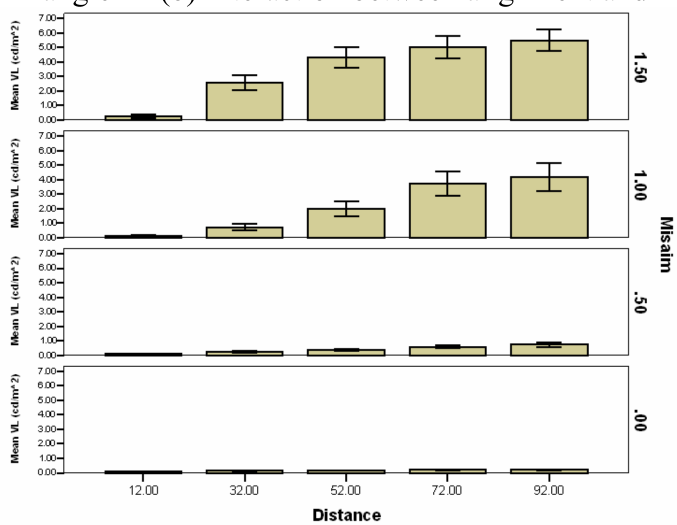
A similar tendency can be seen for de Boer ratings, as summarized below:

- As the mis-aiming angle increased, the de Boer rating was reduced, that is, was more glaring (Figure 9(a)).
- When headlamps were normally aimed, the projector headlamp types provided higher de Boer ratings (less glare) than the reflector headlamp types. However, when these headlamps were mis-aimed, both headlamp types had similar degrees of glare in terms of the de Boer rating (Figure 9(b)).
- Although VOL alignment headlamp types provided significantly higher ($p<0.05$) de Boer ratings (less glare) than the VOR alignment headlamp types when they were normally aimed, they resulted in significantly lower ($p<0.05$) de Boer ratings (more severe glare) than the VOR headlamp types when they were mis-aimed (Figure 9(c)).
- As Figures 4 and 6(e) show, the de Boer ratings increased (or the degree of discomfort glare was reduced) as the distance increased. However, this tendency changed when the mis-aiming angle became larger. As the mis-aiming angle increased, the maximum discomfort glare (troughs in Figure 9(d)) appeared at distances between 30 to 50 m approximately.



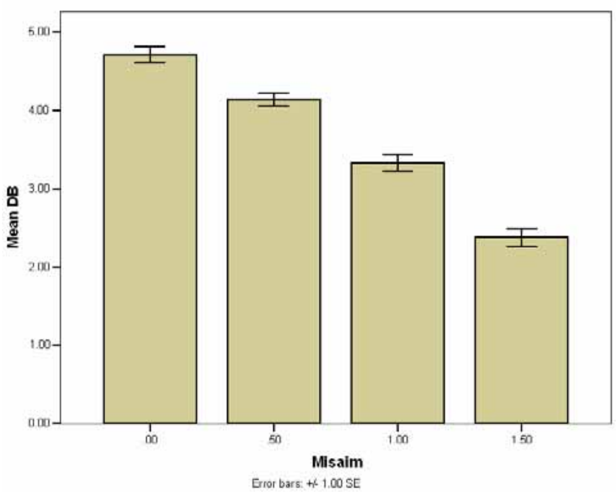


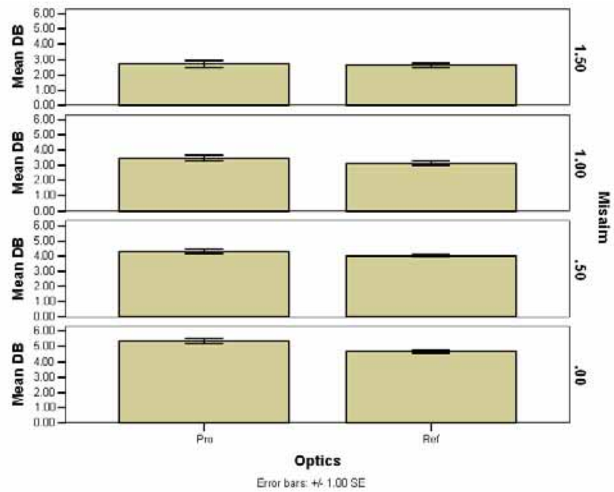
(a) Mis-aim angle (b) Interaction between alignment and mis-aim angle (degrees)



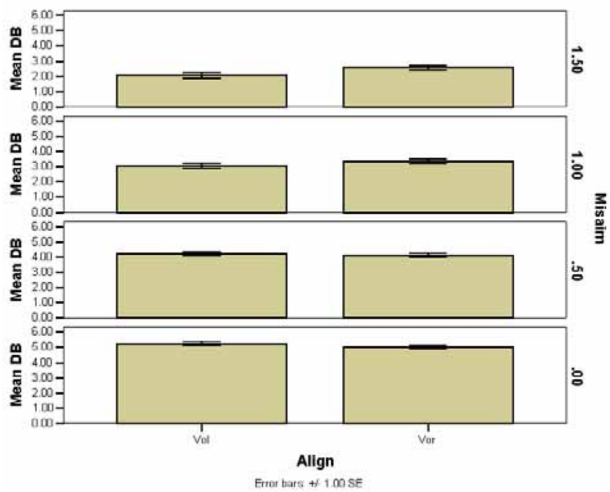
(c) Interaction between distance (in meters) and mis-aiming angle (degrees)

Figure 8: Results of veiling luminance (VL) calculations regarding mis-aiming angle (in degrees), interaction between mis-aiming angle and alignment (Vol: VOL, Vor: VOR), and interaction between mis-aiming angle and distance (in meters).

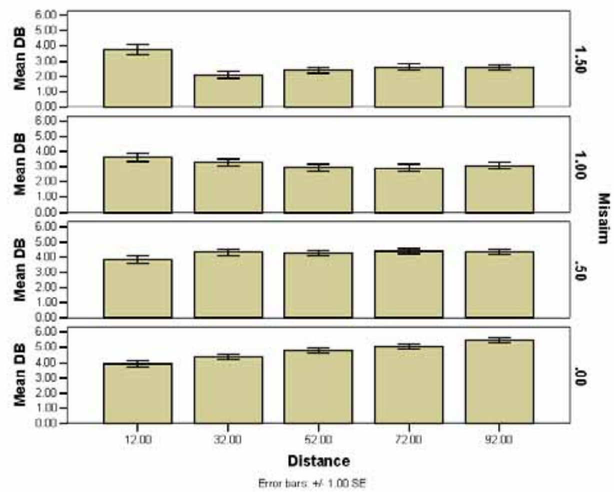




(a) Mis-aiming angle (degrees) (b) Interaction between optics and mis-aiming angle (degrees)



(c) Interaction between alignment and mis-aiming angle (in degrees)



(d) Interaction between distance (in meters) and mis-aiming angle (in degrees)

Figure 9: Results of de Boer rating calculations regarding mis-aiming angle (in degrees), interaction between optics and mis-aiming angle, interactions between mis-aiming angle and alignment, and interaction between mis-aiming angle and distance. Pro: projector, Ref: reflector, Vol: VOL, and Vor: VOR.

4.5. Results of glare dosage

As described and defined above, glare dosage was calculated as the product of glare illuminance (in lx) and total exposure time (in seconds) during which drivers' eyes were exposed to light from oncoming headlamps. As described in the scenario section, the total exposure time of 1.8 seconds was used for the glare dosage calculations. In addition, as another glare index, the exposure time to glare sources was addressed for each headlamp type. To this end, the period of time during which the driver's eyes were exposed to oncoming glare headlamps that produced glare illuminance over 1 lx was calculated. The glare illuminance of 1 lx was used as the glare threshold illuminance because Rumar (2000) suggested, based on a literature review, that this illuminance was the upper limit that drivers would accept while driving at night from oncoming headlamps.

Figure 10 shows the 12 headlamp types with different mis-aiming angles on the coordinates of the exposure time to glare headlamps (in seconds) and the glare dosage (in lx*seconds). In Figure 10(a) for normal aiming, all headlamps with a mounting height of a passenger car congregate along the y-axis at the zero exposure time to glare sources. This means that those headlamps did not exceed the 1 lx threshold in glare illuminance. In contrast, all headlamps with higher mounting heights (SUVs) exceeded the 1 lx threshold, regardless of lamp type. The SUV, halogen, reflector VOR headlamp resulted in the highest glare dosage and the longest exposure time of all of oncoming glare sources evaluated.

As the mis-aiming angles increased, the glare dosages and the exposure times to glare sources for all headlamps increased. At any mis-aiming angle, the higher-mounted (i.e., SUV) headlamps tended to maintain the highest glare dosages and the longest exposure time to glare sources.

To further analyze the data, a five-way ANOVA was applied to the glare dosage data. The ANOVA results found significant main effects for the mounting height, lamp type, and mis-aiming angle, and a significant interaction between the mis-aiming angle and the mounting height, as shown in Table A-5 in Appendix 5. Figure 11 summarizes the mean glare dosages for each independent variable resulting in a significant main effect (Figures 11(a) to 11(c)) and for the significant interaction (Figure 11(d)). From the results of the ANOVA and Figure 11, the following relationships were found:

- The higher mounted headlamps (i.e., from SUVs) tended to have larger glare dosages than the lower-mounted headlamps (i.e., from passenger cars).
- The HID headlamps had larger glare dosages than the TH headlamps.

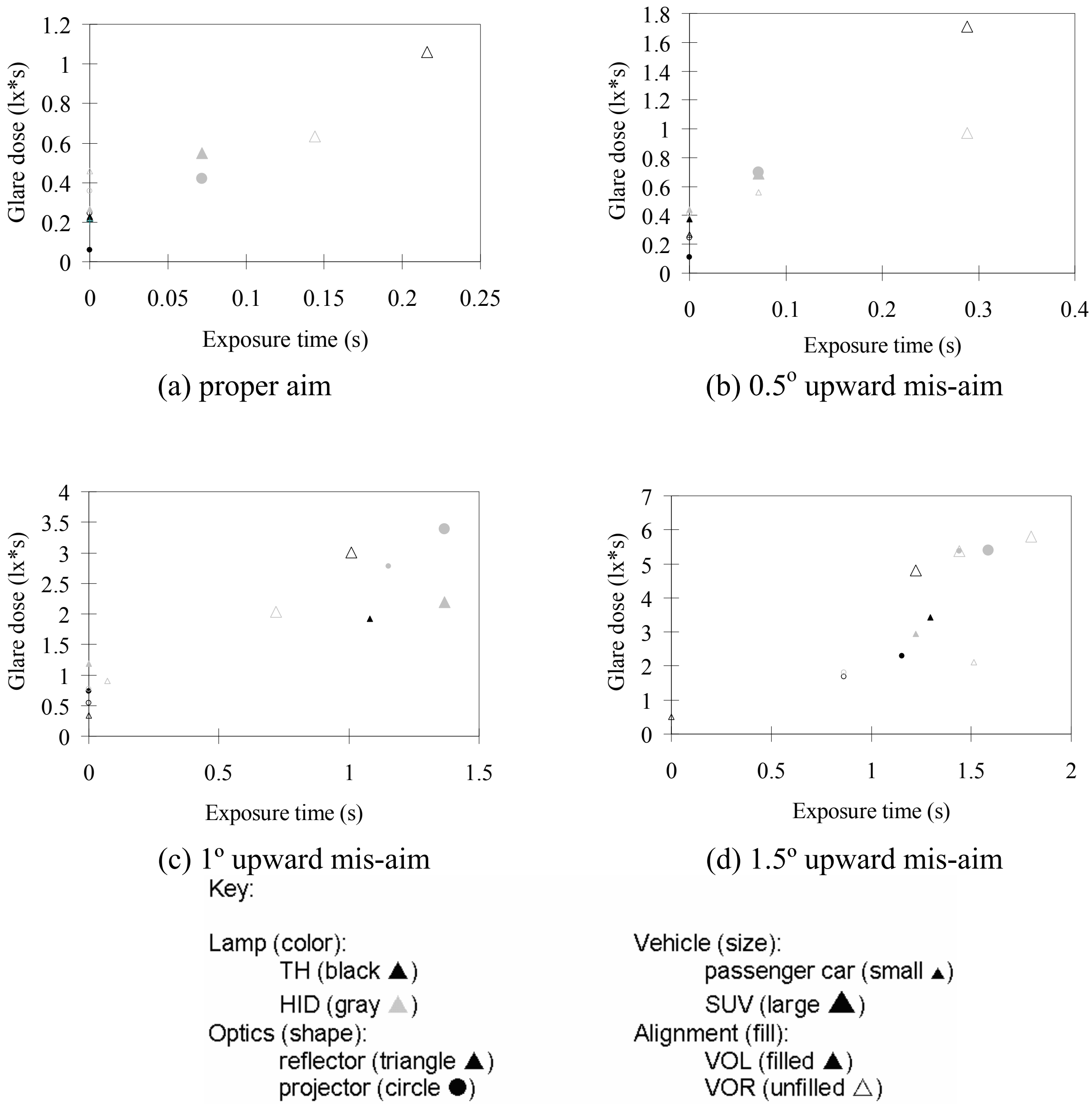


Figure 10: Glare dosage and exposure time to glare sources.

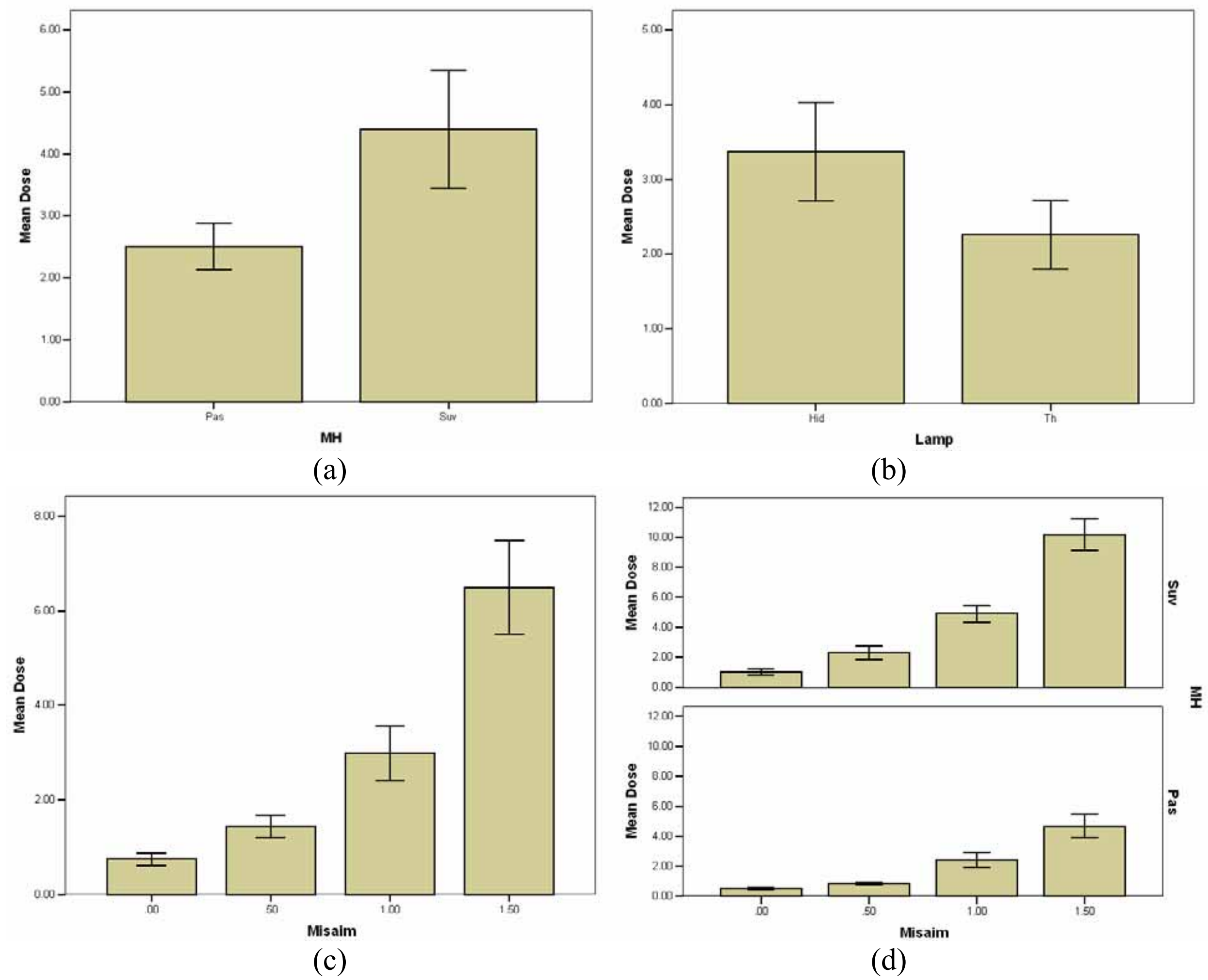


Figure 11: Glare dosage results for different headlamp mounting heights, lamp types, and extent of mis-aim (in degrees). Pas: passenger car, Suv: SUV, Th: tungsten halogen lamp, Hid: HID lamp, and MH: mounting height.

4.6. Conclusions

The preceding analyses yield the following conclusions:

- According to the disability glare (veiling luminance) evaluations:
  - Most independent variables related to headlamp characteristics, including mounting height, optics, and alignment, had statistically significant effects on veiling luminances or disability glare as described above. Lamp type was not among the impact factors having significant influences on disability glare.
  - As the distance of oncoming headlamps increased, veiling luminance was increased. At the longest distance (100 m) within the study range, the highest veiling luminance occurred, because the assumed angle between the driver's line of sight and the oncoming headlamps was smallest for this distance.

    - HID headlamps resulted in higher veiling luminances than TH headlamps only when the mounting height was high.
- Regarding the discomfort glare (de Boer rating) evaluations:
    - All independent variables, including mounting height, lamp type, optics, and alignment, had significant effects on discomfort glare as described above.
    - In contrast to disability glare (veiling luminance), as the distance of oncoming headlamps increased, discomfort glare was decreased. At the shortest distance, the highest discomfort glare occurred.
    - The de Boer rating correlated well with the veiling luminance evaluation when comparing means across all conditions except oncoming headlamp distance.
- Regarding both disability glare and discomfort glare, the angular region just above horizontal and just to the left of 0º appears to be related to glare for oncoming drivers.
- The glare dosage analyses found that mounting height, lamp type, and the mis-aiming angle of oncoming headlamps had significant effects on glare dosage as described above.

5. Detection Distance Evaluation

To analyze the effects of headlamp distribution on forward visibility, this study used detection distance as a dependent variable in the analysis method. Greater detection distances allow drivers more time when identifying whether collisions with obstacles on the roadway can be avoided. Many studies have measured detection distances of targets moving toward subjects (e.g., Akashi et al., 2005). Detection distances can be estimated by calculations based on visibility threshold by determining the distance at which an object's size and contrast characteristics place it above the visual threshold.

5.1. Definition of detection distance

Blackwell (1946) and Blackwell and Blackwell (1971) obtained numerous visibility threshold data for various sizes and luminance contrasts of targets under different background luminance conditions and for different age groups. A standardized threshold contrast was defined as a luminance contrast for a reference task, namely detecting the presence of a luminous disk with a 4 min arc diameter presented against a uniform luminance field for 0.2 seconds. This standard threshold can be used to evaluate whether the illuminance provided by a headlamp system is sufficient to see the target under a given condition.

However, the size and reflectance of the target are subject to change depending on roadway contexts and the distance of a driver to the target. Therefore, the standard threshold *per se* is not useful as an index for headlamp performance evaluations. What is more important for headlamp evaluations is to explore at how far of a distance a driver can see a target in each direction. The same visibility threshold data can be more efficiently applied to such evaluations, identifying detection distances of targets. Thus, in the present study, detection distances are utilized as one of the metrics of headlamp performance.

Based on the visibility thresholds measured by Blackwell and Blackwell (1971), a visibility threshold model was developed (Adrian, 1989). The ANSI/IESNA standards simplified the original equations by predetermining several parameters (ANSI/IESNA, 2000). The equations from the ANSI/IESNA standards are listed below. In equation 6, visibility threshold is expressed by luminance difference threshold, $\Delta L_{threshold}$, representing the difference in luminance between a target and the background to detect the target.

$$\Delta L_{threshold} = 2.6\left(\frac{\sqrt{F}}{\alpha} + \sqrt{L}\right)^2 \qquad (5)$$

where,

$\Delta L_{threshold}$ =luminance difference threshold in cd/m^2,
F =luminous flux function related to Ricco's law,
L =luminance function related to Weber's law,
L_b =adaptation luminance (background luminance) in cd/m^2,
α =target size in min of arc.

$$\text{If} \quad L \geq 0.6 \quad \text{cd/m}^2$$
$$\text{then} \quad F = \{\log_{10}(4.2841 \times L_b{}^{0.1556}) + (0.1684 \times L_b{}^{0.5867})\}^2 \qquad (6)$$
$$\text{and} \quad L = (0.05946 \times L_b{}^{0.466})^2 \qquad (7)$$

$$\text{If} \quad 0.00418 < L < 0.6 \quad \text{cd/m}^2$$
$$\text{then} \quad F = 10^{(0.346 \times \log_{10} L_b + 0.056)} \qquad (8)$$
$$\text{and} \quad L = 10^{\left[(0.0454 \times (\log_{10} L_b)^2) + (1.055 \times \log_{10} L_b) - 1.782)\right]} \qquad (9)$$

$$\text{If} \quad L < 0.00418 \quad \text{cd/m}^2$$
$$\text{then} \quad F = 10^{\{2 \times \left[\left(0.0866 \times (\log_{10} L_b)^2\right)\right] + (0.3372 \times \log_{10} L_b) - 0.072)} \qquad (10)$$
$$\text{and} \quad L = 10^{[2 \times (0.319 \times \log_{10} L_b - 1.256)]} \qquad (11)$$

To simplify the original $\Delta L_{threshold}$ equations, ANSI/IESNA assumed these standard conditions:

- The observer is an adult at the age of 60 with normal eyesight whose fixation time is 0.2 seconds.
- The target is brighter than the background (positive contrast).
- In equation 5, the first constant of 2.6 is adjusted for a condition under which 99.93 percent of people detect targets. (For lower probability, a smaller constant is used—e.g., 1.0 for 50% probability.)

The visual task of a driver at night is complex and cannot be specified comprehensively by a single criterion. In experiments on visibility under nighttime driving conditions, however, some criterion has to be assumed that describes at least one aspect of the visual task. To this end, the target size of 10 minutes of arc and the luminance contrast of 0.2-0.3 were chosen. This is an approximately 18 cm square that is located about 86 m in front of the driver. This is the height of an obstacle that a passenger car can clear when running over it. The distance relates to a safe stopping distance within which a car can stop before the reaching the object when the driver's reaction time and the deceleration of the car are considered. It was assumed that the driver should be able to perceive such an object in order to ensure safe driving.

The observation period of 0.2 seconds is based on results obtained from eye movement studies while driving. Zwahlen found that drivers fixated on particular points in front of the car for 0.2 seconds as a minimum, and usually up to 0.4-0.5 seconds (Zwahlen, 1993).

The development of the detection distance model is described in detail by Adrian (1989) and in the Illuminating Engineering Society of North America's recommended practice for roadway lighting (ANSI/IESNA, 2000).

5.2. Scenario and layout for simulation

Like the scenario used for the glare evaluation in Section 4, an encounter between two opposing cars was simulated along a local roadway with a lane width of 3.5 m. Figure 12 illustrates the layout of the two cars in this scenario. The question was at what distances three different targets—on the roadway center line and on each roadway shoulder— can be detected by the driver. For this calculation, the three targets were initially placed at a distance of 70 m from the driver's car. Keeping the distance between the two cars constant at 50 m, both cars moved toward the targets. Thus, while the model simulated the movement of the first car toward the targets, the relative position of the second (glare-producing) car was always kept at a distance of 50 m.

Figure 13 illustrates how detection distance was determined. The solid line represents the actual luminance contrast of one of the three targets as a function of distance driven by the car. This diagram suggests that the luminance contrast of the target is very low at a distance of 70 m from the target. However, the luminance contrast of the target gradually increases as the car approaches to the target. The dashed line represents the luminance contrast threshold for the target as a function of driving distance. Therefore, the driver can first detect the target with a probability of 50 percent at the location where both the blue line and the red line cross each other. In this case, this happens after the car drives 38 m (32 m from the targets). So, the detection distance is defined as 32 m. It should be noted that the detection distance calculation procedure outlined here does not take into account the possible creation of shadows that might be seen against a lighted background; only the target and background luminances are considered.

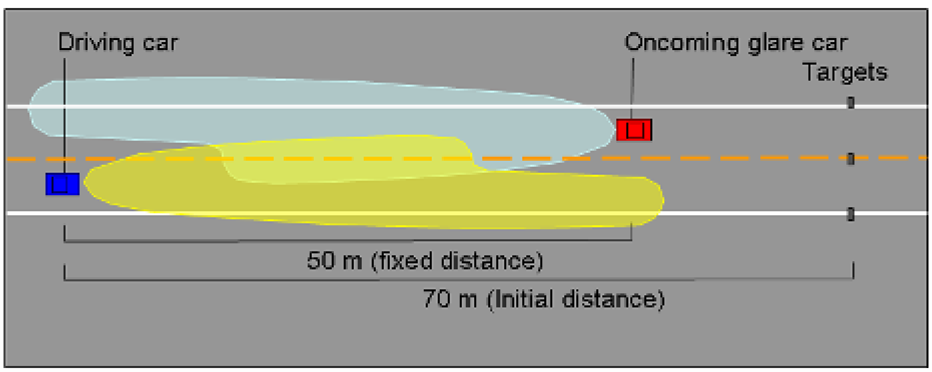


Figure 12: Layout for calculation simulation.

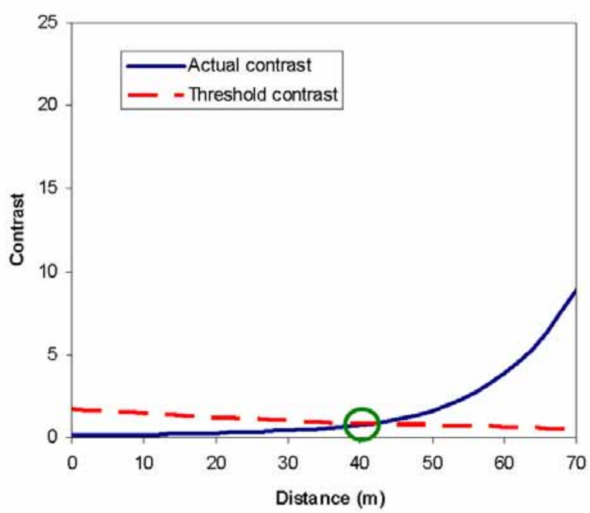
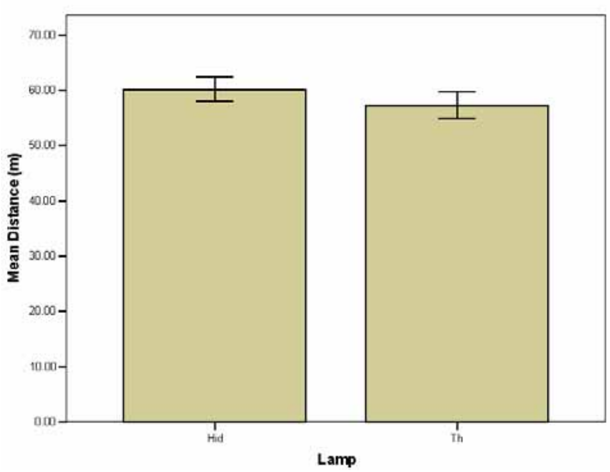


Figure 13: Procedure of detection distance calculation.

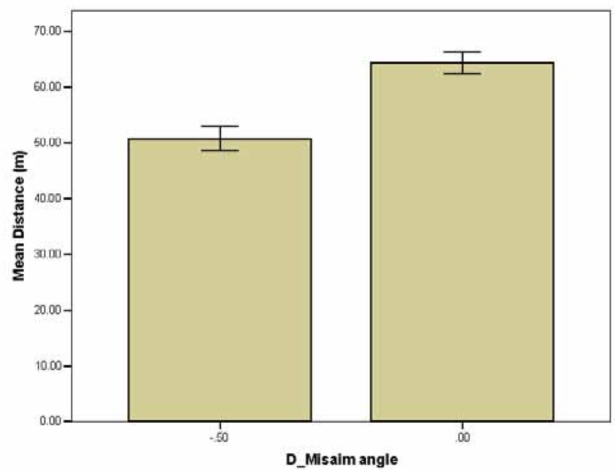
5.3. Results

An ANOVA was applied to detection distances for the 12 headlamp types without oncoming glare headlamps while considering main effects and two-way interactions. Appendix 5 summarizes the results of the ANOVA. Based on the ANOVA results, Figure 14 summarizes the effects of independent variables that had significances. Generally, mis-aiming angle of forward headlamps had the most powerful influence on detection distances, followed by lamp type. More detailed findings can be summarized as follows:

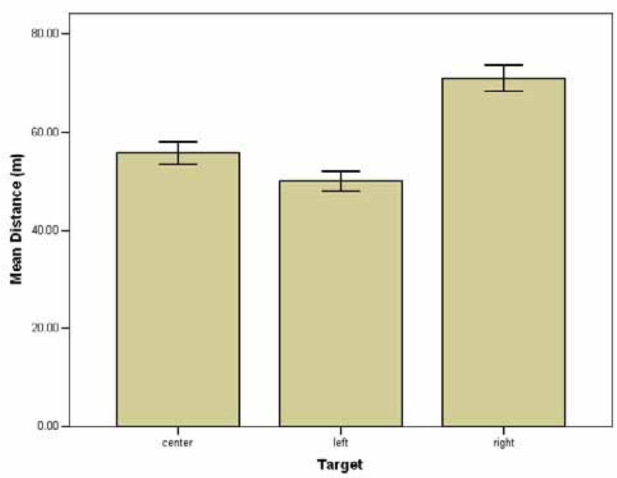
- As Figure 14(a) suggests, the HID headlamps evaluated had significantly longer ($p<0.001$) detection distances than the TH headlamps evaluated.
- If the forward headlamps were mis-aimed downward by 0.5 degrees, the detection distance became significantly shorter ($p<0.001$) than properly aimed forward headlamps (see Figure 14(b)).
- There was a significant ($p<0.001$) main effect of target location on the detection distance (see Figure 14(c)). A two-tailed t-test suggested that central targets had significantly longer detection distances ($p<0.001$) than left targets, and central targets had significantly shorter detection distances ($p<0.001$) than right targets.
- There was a significant ($p<0.001$) interaction between mounting height and lamp type. As Figure 14(d) shows that differences in detection distances between the two lamp types were larger for higher mounting heights (i.e., the SUV conditions) than for lower mounting heights (i.e., the passenger car conditions).
- As Figure 14(e) suggests, there was also a significant interaction between mounting height and alignment. The VOR alignment types had significantly shorter ($p<0.001$) detection distances than the VOL types only for the lower mounting height (i.e., passenger cars).
- Figure 14(f) suggests another significant ($p<0.001$) interaction between lamp type and alignment. In this case, the detection distances became longer with the VOL alignment than with the VOR alignment only when HID headlamps were used. This was not the case for TH headlamps.



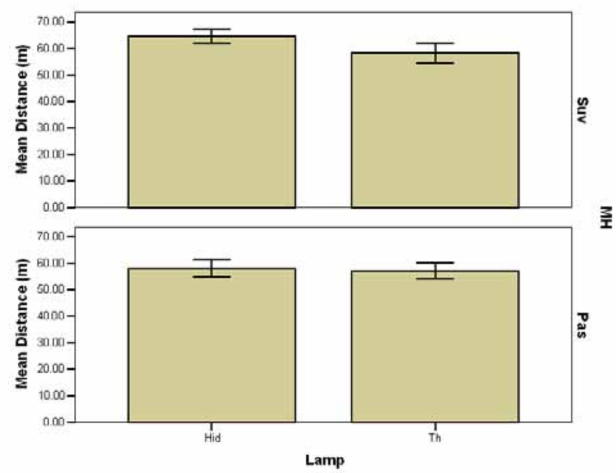
(a) Lamp type



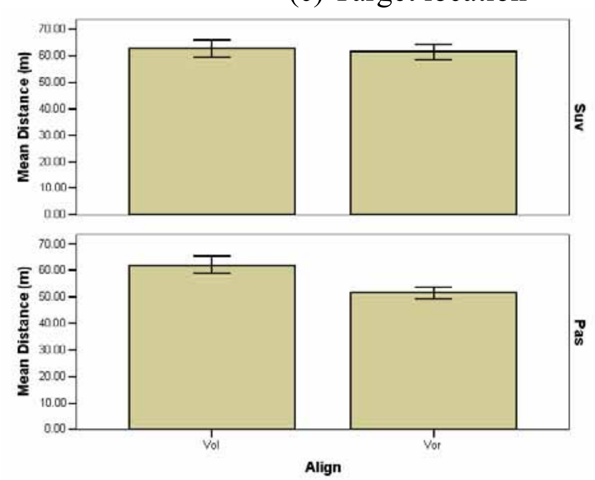
(b) Mis-aim angle of forward headlamp



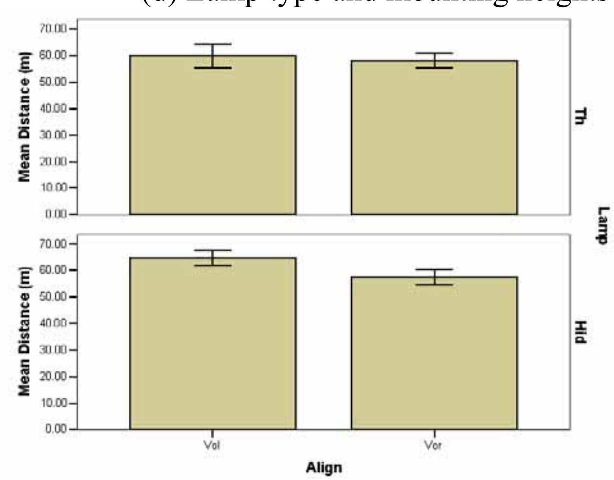
(c) Target location



(d) Lamp type and mounting heights



(e) Alignment and mounting height



(f) Lamp type and alignment

Figure 14: Results of detection distances. Pro: projector, Ref: reflector, Th: tungsten halogen lamp, Hid: HID lamp, Vol,: VOL, Vor: VOR, Pas: passenger car, Suv: SUV and MH: mounting height.

Beyond the identification of the effects of forward headlamps on detection distances, what is more important may be how oncoming headlamps affect the detection distances. Figure 15 shows a comparison in detection distance with oncoming glare and without oncoming glare. A single headlamp type (an HID, reflector, VOR SUV headlamp) was used as the source of oncoming for all calculations shown in Figure 15. As expected, a two-tailed t-test found that oncoming glare significantly reduced detection distances relative to the no-oncoming-glare condition ($p<0.001$).

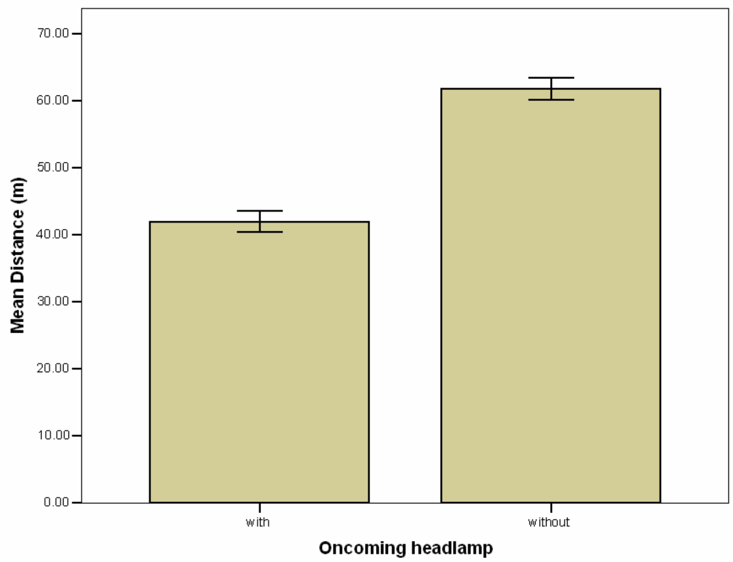


Figure 15: Detection distances with and without oncoming headlamps.

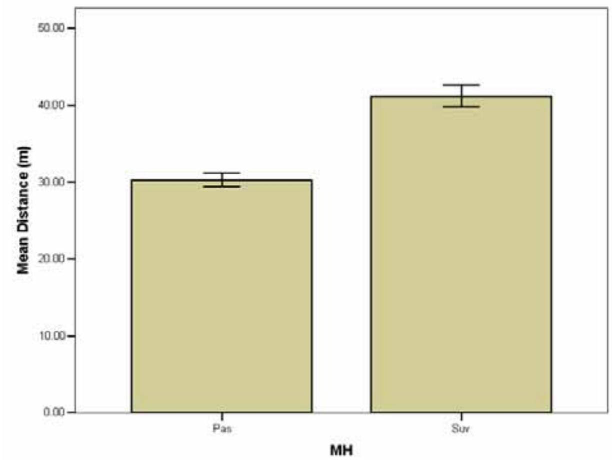
Once a driver has oncoming headlamps as glare sources, it is worthwhile to identify how mis-aiming angles of oncoming headlamps affect the detection distance of the driver. This is because a large proportion of vehicles have headlamps that are somewhat mis-aimed, as a recent survey suggested (Copenhaver and Jones, 1992; LRC, 2005). In addition, uneven roadway surfaces might presumably make normally aimed headlamps behave as mis-aimed headlamps. To identify the effects of mis-aiming angles of oncoming headlamps on detection distances, another calculation was conducted with three different upward mis-aiming angles compared to normally aimed headlamps (i.e., 0, 0.5, 1.0, and 1.5 degrees). For oncoming glare, only a single headlamp type was used in this calculation as described above.

An ANOVA was applied to the results of the detection distance calculations while considering main effects and two-way interactions. Appendix 6 summarizes the results of the ANOVA. The results suggest that significant main effects were found for mounting height ($p<0.001$), lamp type ($p<0.05$), optics ($p<0.001$), mis-aiming angle of forward headlamps ($p<0.001$), target location ($p<0.001$), and mis-aiming angle of oncoming headlamps ($p<0.001$). Figure 16 shows those main effects and suggests the following tendencies.

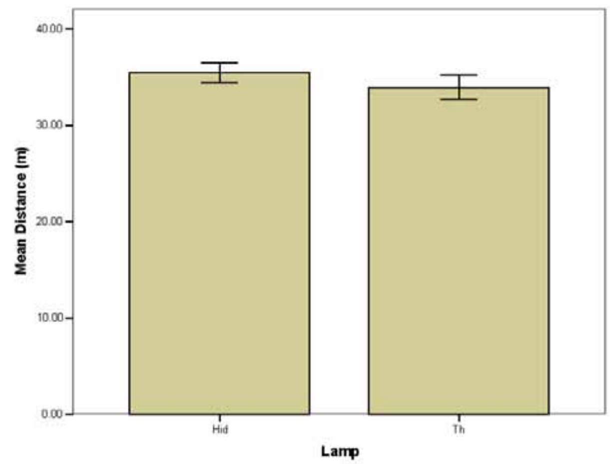
- Headlamps with higher mounting heights had longer detection distances (Figure 16(a)).
- With HID headlamps, a driver's detection distance was longer than that with TH lamps (Figure 16(b)). Interestingly, the effect of lamp type on detection distances became smaller with oncoming headlamps than without oncoming headlamps ($p<0.05$).

- Headlamps with reflectors had better forward visibility than ones with projectors (Figure 16(c)).
- As the mis-aiming angle of oncoming headlamps increased, the detection distance was reduced (Figure 16(d)).
- Targets on the right shoulder were easier for drivers to detect than ones in the center and on the left shoulder (Figure 16(e)).
- As mis-aiming angles of oncoming headlamps increased, drivers' detection distances were reduced (Figure 16(f)).

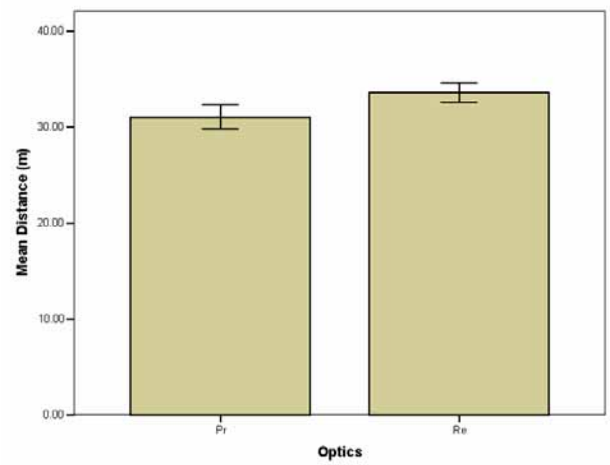
There are significant interactions between mounting height and optics ($p<0.001$), between mounting height and alignment ($p<0.01$), between mounting height and target locations ($p<0.001$), between lamp type and optics ($p<0.001$), between lamp type and alignment ($p<0.001$), between lamp type and mis-aiming angle of forward headlamps ($p<0.001$), between lamp type and target position ($p<0.001$), between lamp type and mis-aiming angle of oncoming headlamps ($p<0.05$), between optics and alignment ($p<0.001$), between alignment and target position ($p<0.001$), and between mis-aiming angle of forward headlamps and target location ($p<0.001$).



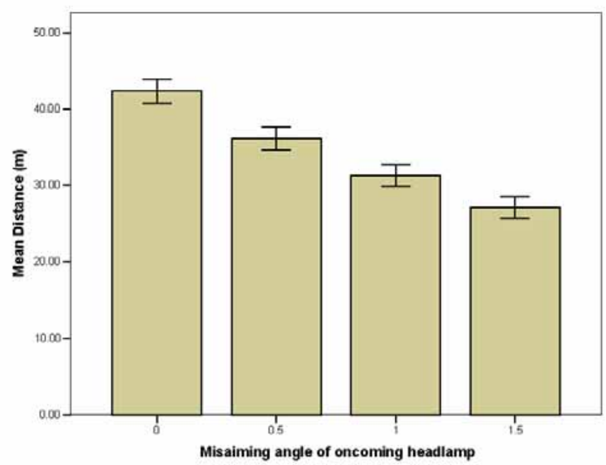
(a) Mounting heights



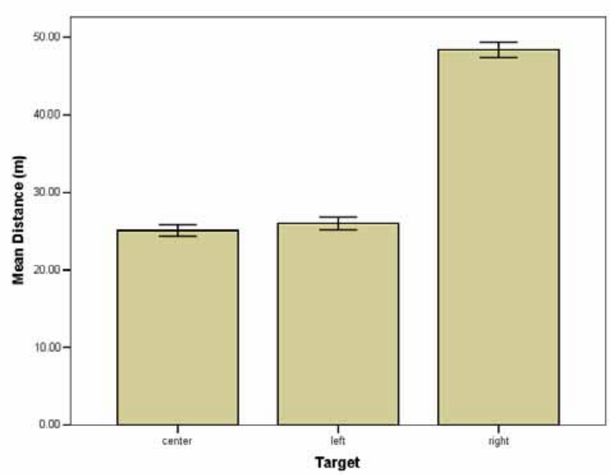
(b) Lamp type



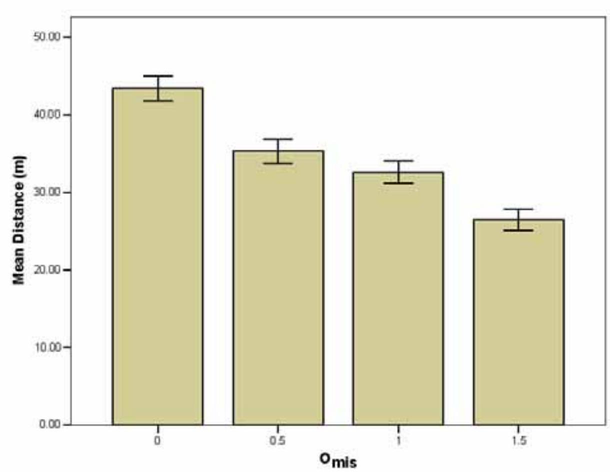
(c) Optics



(d) Mis-aiming angle of oncoming headlamp (degrees)



(e) Target location



(f) Mis-aiming angle of oncoming headlamp (degrees)

Figure 16: Results of detection distances. Pas: passenger car, Suv: SUV, Pr: projector, Ref: reflector, Th: tungsten halogen lamp, Hid: HID lamp, and MH: mounting height.

5.4. Conclusions from detection distance evaluation

Without oncoming glare present, the mis-aiming angle of forward headlamps and the lamp type had greater influence on detection distances than the other factors (mounting height, optics, and alignment) examined in the present analyses. The HID headlamp types evaluated gave drivers better forward visibility (defined in terms of detection distances) than the TH headlamps evaluated. However, when oncoming glare was present with some mis-aim, mounting height and optics became important in addition to the mis-aiming angle of forward headlamps, while the effect of lamp type on detection distances was reduced.

One of the headlamps with a longer calculated detection distance was the passenger car, halogen, reflector, VOL headlamp shown in Figure A-1(c). In comparison, the passenger car, halogen, reflector, VOR headlamp in the sample, shown in Figure A-1(d), resulted in a shorter calculated distance. Comparison of the luminous intensity distributions shows that the area just below horizontal and at the center of the beam pattern (0º) for the longer-distance headlamp had a higher luminous intensity than the shorter-distance headlamp. The minimum luminous intensity at the angular location corresponding to 0.86º down and 0º left or right is 4500 cd according to Table A-2. The headlamp producing the shorter distance has a luminous intensity close to this value, whereas the longer-distance headlamp has a luminous intensity more than twice this minimum value, consistent with the longer detection distances it provides in the preceding analyses.

Other findings were, as expected:

- Oncoming glare shortens detection distance.
- As the mis-aiming angle of oncoming headlamps increases in an upward direction, detection distance is reduced.

6. Discussion

Headlamps are designed to satisfy antithetical requirements: improving forward visibility while minimizing glare. Regarding the glare and visibility measures used in this study, an ideal headlamp should have a long detection distance and low glare illuminance. By using the same calculation results in previous sections, all 12 headlamp types in this study were compared. Figure 17 illustrates the relationship between mean de Boer rating and mean detection distance for these 12 headlamp types. The higher the de Boer rating and detection distance, the better the general headlamp performance. Fortunately, the mean de Boer ratings of all 12 headlamps are above the threshold of "4," a value often used as a threshold for acceptability of discomfort glare (Bhise et al., 1977). However, as expected, it can be difficult for any headlamp to achieve both glare and visibility requirements of the driver. For instance, the lowest-glare headlamp did not have a long detection distance, while the best visibility headlamp was just an average headlamp in terms of glare.

A comparison of Figure 17 with Figure 1 may allow us to discuss to what extent the FMVSS 108 photometric requirements standards control forward visibility and glare. There do not appear to be any headlamps that simultaneously result in low glare and long detection distances (the upper right corner of Figure 17), implying that there is an inherent conflict between visibility and glare with respect to headlamp design. However, there are several headlamps that produce similar levels of discomfort glare (e.g., between 4 and 5 for mean de Boer ratings) but have a large variation in detection distances. In Figure 1, the headlamps with the greatest margin of conformance to the "visibility" points in the FMVSS 108 specification tend to have the smallest margin of conformance to the "glare" points in the specification, similar to the trend seen in Figure 17.

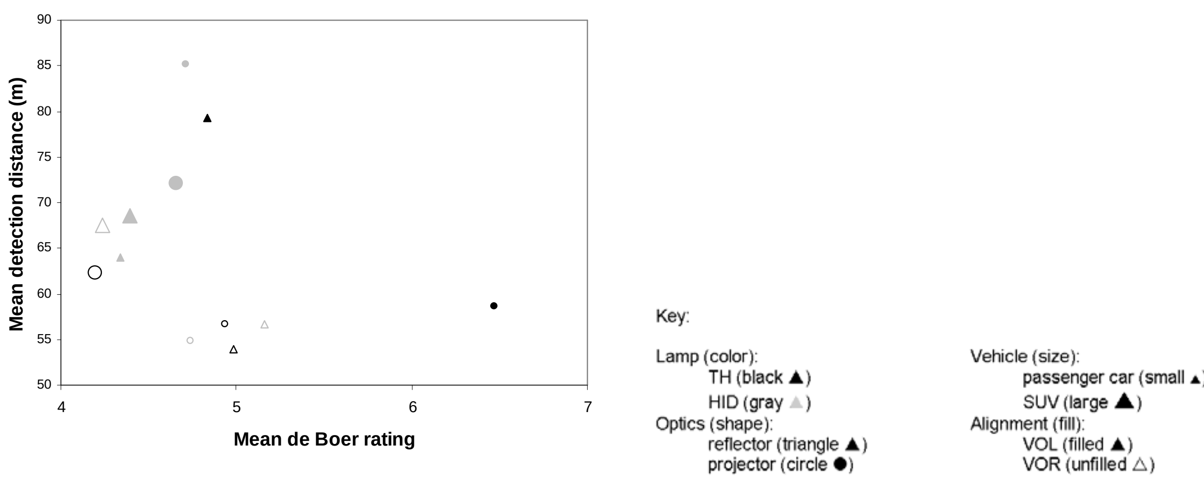


Figure 17: Relationship between mean de Boer rating and mean detection distance.

Another way to investigate the potential for the headlamps under study in terms of visibility and glare is to assess the maximum luminous intensity from the headlamp, regardless of the angular location at which this occurs (it is always near the center and slightly downward and to the right). This provides some indication of the maximum illuminance that can be produced onto an object, as well as the maximum illuminance that can be produced onto the eyes of oncoming drivers or their mirrors. Figure 18 illustrates the range of maximum luminous intensity values for the HID and TH headlamps investigated in the present study. While the range is generally higher for HID headlamps, there is substantial overlap, indicating that there can be large variability in specific photometric values even among headlamps of the same type.

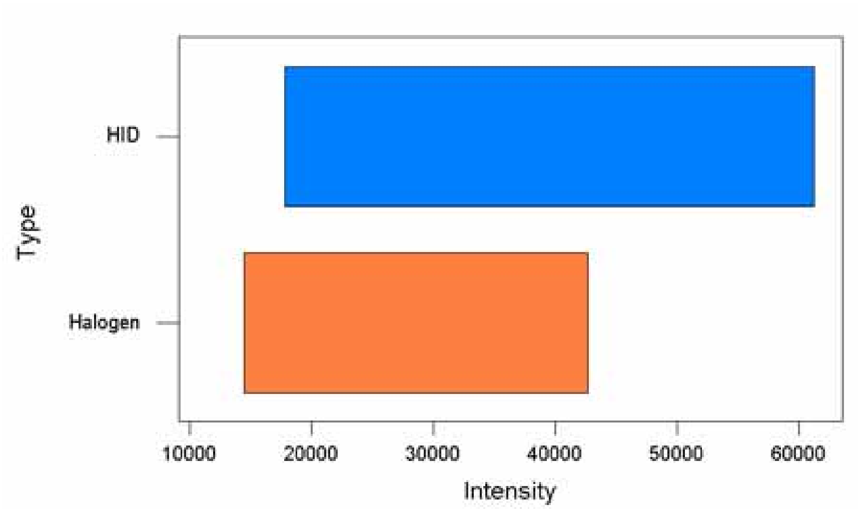


Figure 18: Range of maximum luminous intensities from HID and halogen headlamps.

7. Conclusions

The present study conducted evaluations on disability glare (veiling luminance) and discomfort glare (de Boer rating) for a representative sample of headlamps and driving conditions.

The analyses revealed that for the driving conditions studied (corresponding to driving along straight, flat, two-lane highways), higher mounting heights and HID headlamps tended to result greater calculated levels of glare to oncoming drivers than headlamps with lower mounting heights and than TH headlamps. Headlamp mis-aim was more influential than either of these factors at affecting both disability and discomfort glare.

The present study also included forward visibility evaluations. The results suggested that lamp type is an influential factor on detection distances. Overall, the HID headlamps studied would be expected to give drivers better forward visibility than the TH headlamps, but this finding must be tempered by the large degree of overlap between HID and TH headlamps in terms of maximum luminous intensity. As with the glare analyses, the analyses of forward visibility found that headlamp aim could have very large and statistically significant effects on detection distances.

The current photometric requirements for headlamps do appear to provide a balance between forward visibility and glare. While there appears to be an inherent conflict between visibility and glare in the photometric design of headlamps, the analyses performed here do indicate that this tradeoff is not necessarily inherent in every situation. The amount of light in distinct angular locations appears to influence visibility and glare, so further limits on light allowed above horizontal, and increasing the minimum needed light levels below horizontal, could simultaneously improve visibility and glare control. However, because these angular locations are close, further changes in such requirements would be likely to increase the sharpness of the cutoff gradient. Although current photometric requirements for headlamps do not have an upper limit on the allowed sharpness of the cutoff, increased cutoff sharpness is seen as undesirable by drivers (Manz, 2000), and the implications of sharp cutoffs on driving performance are not presently known. It would appear that sharper cutoffs would be more likely to result in large changes in the light levels toward oncoming drivers during conditions of headlamp mis-aim and when roadway geometries differ from the straight, flat roadway scenarios investigated in the present study.

Thus, the precise locations of the desirable high-intensity and low-intensity angular regions will depend upon the specific roadway geometry associated with a specific situation, implying that no single low-beam headlamp pattern is optimal for all situations. This implies that advanced (dynamic) forward-lighting systems (AFS) might be of benefit in adjusting headlamp luminous intensity distributions in various situations to maximize visibility while controlling glare within acceptable limits, although such systems were not evaluated using the methods developed for the present study and might be expensive to implement on vehicles.

Acknowledgments

This study was performed with support from NHTSA under the supervision of Stephanie Binder and Michael Perel, and through a subcontract managed by Neil Lerner of Westat, Inc. Headlamp photometric data were generously provided through the assistance of Carl Andersen of FHWA, Paul Carlson of the Texas Transportation Institute, Thomas Schnell and Fuat Aktan of the University of Iowa, Ronald Gibbons of the Virginia Tech Transportation Institute, and members of the Society of Automotive Engineers Road Illumination Devices Standards Committee. Valuable input was provided by John Van Derlofske, Mark Rea, Nicholas Skinner, Jennifer Taylor, and Keng Chen of the Lighting Research Center.

References

Akashi, Y., Dee, P., Chen, J., Van Derlofske, J., & Bullough, J. D. (2003). Interaction between fixed roadway lighting and vehicle forward lighting, *2003 Progress in Automobile Lighting,* Darmstadt, Germany, 11-22.

Akashi, Y., Van Derlofske, J., & Bullough, J. D. (2005). Recommendations for dimming headlamps through AFS, *International Symposium on Automotive Lighting*, Darmstadt, Germany, 890-899.

Adrian, W. (1989). Visibility of targets: model for calculation. *Lighting Research and Technology*, *21*(4), 181-188.

ANSI/IESNA. (2000). *American National Standard Practice for Roadway Lighting* (RP-8-00).

Bhise, V. D. et al. (1977). Modeling vision with headlights in a system context (*SAE Technical Paper* #770238), 247-295.

Blackwell, H. R. (1946). Contrast thresholds of the human eye. *Journal of the Optical Society of America*, *36*(11), 624-643.

Blackwell, O. M., & Blackwell, H. R. (1971). Visual performance data for 156 normal observers of various ages. *Journal of the Illuminating Engineering Society of America*, *1*(1), 3-13.

Boyce, P. R. (2003). *Human Factors in Lighting* (2nd Edition). New York, NY: Taylor and Francis.

Bullough, J. D., Van Derlofske, J., Dee, P., Chen, J., & Akashi, Y. (2003). *An Investigation of Headlamp Glare: Intensity, Spectrum and Size* [report to the National Highway Traffic Safety Administration]. Washington, DC, National Highway Traffic Safety Administration.

CIE 146. (2002). *TC 1-50 report: CIE equations for disability glare*. Wien, Austria: Commission Internationale de L'Eclairage.

Clark, J., Gibbons, R. B., & Hankey, J. M. (2005). *Enhanced Night Visibility Series Vol. XV: Influence of Beam Characteristics on Discomfort and Disability Glare* [report to the Federal Highway Administration]. Washington, DC: Federal Highway Administration.

Copenhaver, M. M., & Jones, R. E. (1992). *Measurement of Headlamp Aim and the Electrical and Photometric Performance Characteristics of Rear Lighting Systems* (DOT HS 807 930). Washington, DC: National Highway Traffic Safety Administration.

De Boer, J. B. (1967). *Public Lighting*. Eindhoven, The Netherlands: Philips Technical Library.

Flannagan, M. J. (1999). *Subjective and Objective Aspects of Headlamp Glare: Effects of Size and Spectral Power Distribution* (Report UMTRI-99-36). Ann Arbor, MI, University of Michigan.

Flannagan, M. J., Sivak, M., Traube, E. C., & Kojima, S. (2000). Effects of overall low-beam intensity on seeing distance in the presence of glare. *Transportation Human Factors 2*(4), 313-330.

Fry, G. A. (1954). A re-evaluation of the scatter theory of glare. *Illuminating Engineering*, *49*, 98-102.

Jost, K. (1995). Anatomy of high intensity discharge headlamps. *Automotive Engineering*, November, 38-42.

Lighting Research Center (LRC), Rensselaer Polytechnic Institute. (2005). *Assessment of Headlamp Glare and Potential Countermeasures: New Methodology for the Assessment of Headlamp Aim* [report submitted to NHTSA]. Troy, NY: Rensselaer Polytechnic Institute.

National Highway Traffic Safety Administration. (2003). *Glare from Headlamps and Other Front-Mounted Lamps: Adaptive Frontal-Lighting Systems Federal Motor Vehicle Safety Standard No. 108; Lamps, Reflective Devices, and Associated Equipment*.

National Highway Traffic Safety Administration. (2007). *Nighttime Glare: Report to Congress*. Washington, DC: National Highway Traffic Safety Administration.

Operator Performance Laboratory. (2004). *Target Visibility Predictor Version 4.x*. Iowa City, IA: The University of Iowa.

Rosenhahn, E. O., & Lampen, M. (2004). New investigation of the subjective glare effect of projection type headlamps (SAE paper 2004-01-1281). In *Lighting*, SP-1875. Warrendale, PA: Society of Automotive Engineers.

Rumar, K. (2000). *Relative Merits of the U.S. and ECE High-Beam Maximum Intensities and of Two- and Four-Headlamp Systems*, UMTRI 2000-41. Ann Arbor, MI: University of Michigan.

Schmidt-Clausen H-J, Bindels J-Th-H, 1974, Assessment of discomfort glare in motor vehicle lighting. *Lighting Research and Technology*, *6*(2), 79-88.

Singh, S., & Perel, M. (2003). *Drivers' Perceptions of Headlight Glare from Oncoming and Following Vehicles* (DOT HS 809 669). Washington, DC: National Highway Traffic Safety Administration.

Sivak, M., Flannagan, M. J., Traube, E. C., & Kojima, S. (1997). *The influence of stimulus duration on discomfort glare for persons with and without visual correction (UMTRI-97-23)*. Ann Arbor, MI: University of Michigan Transportation Research Institute.

Van Derlofske, J., Bullough, J. D., & Hunter, C. M. (2002). Visual benefits of high-intensity discharge forward lighting (SAE paper 2002-01-0259). In *Advanced Lighting Technology for Vehicles* (SP-1668), pp. 51-56. Warrendale, PA: Society of Automotive Engineers.

Van Derlofske, J., Bullough, J. D., & Hunter, C. M. (2001). Evaluation of high-intensity discharge automotive forward lighting (SAE paper 2001-01-0298). In *Lighting Technology Developments for Automobiles* (SP-1595), pp. 1-7. Warrendale, PA: Society of Automotive Engineers.

Van Derlofske, J., Chen, J., Bullough, J. D., & Akashi, Y. (2005). Headlight glare exposure and recovery (SAE paper 2005-01-1573). *Society of Automotive Engineers 2005 World Congress*, 235-242.

Zwahlen, H. T. (1993). Eye scanning rules for drivers: How do they compare with actual observed eye scanning behavior? *Transportation Research Record*, 1403, 14-22.

Appendix 1: Headlamp Luminous Intensity Distributions

Figure A-1(a): Passenger Car - Halogen - Projector - VOL

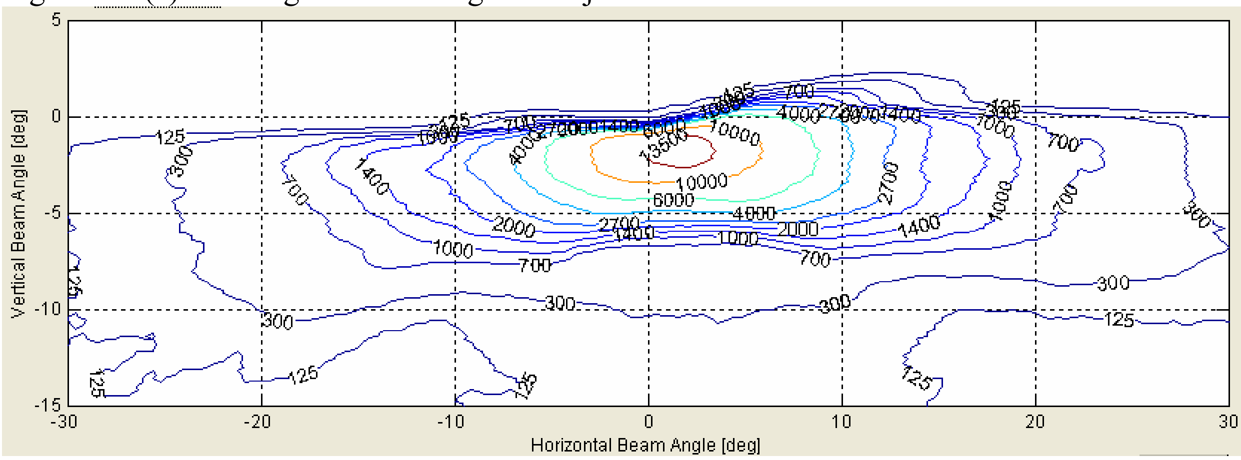


Figure A-1(b): Passenger Car - Halogen - Projector - VOR

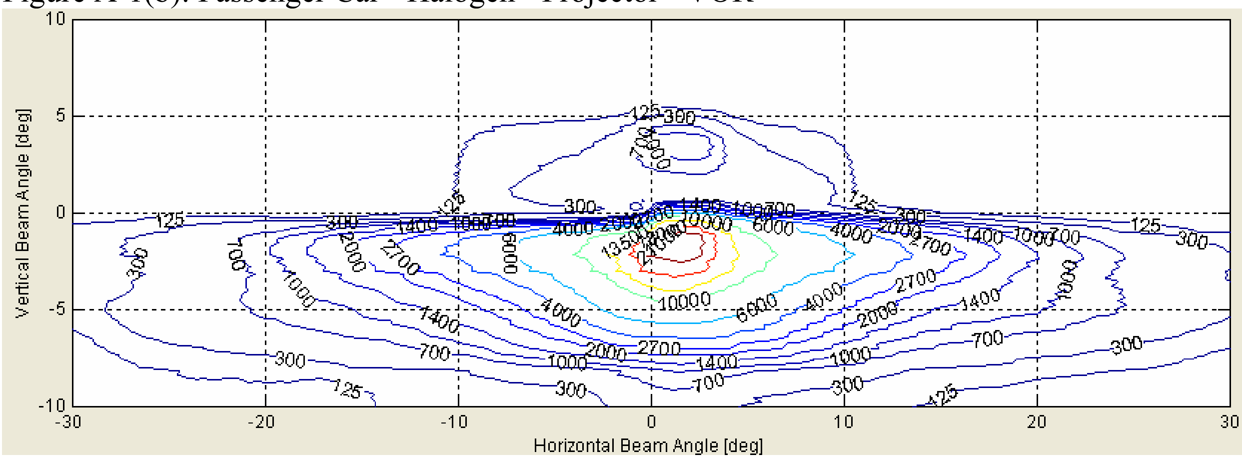


Figure A-1(c): Passenger Car - Halogen - Reflector - VOL

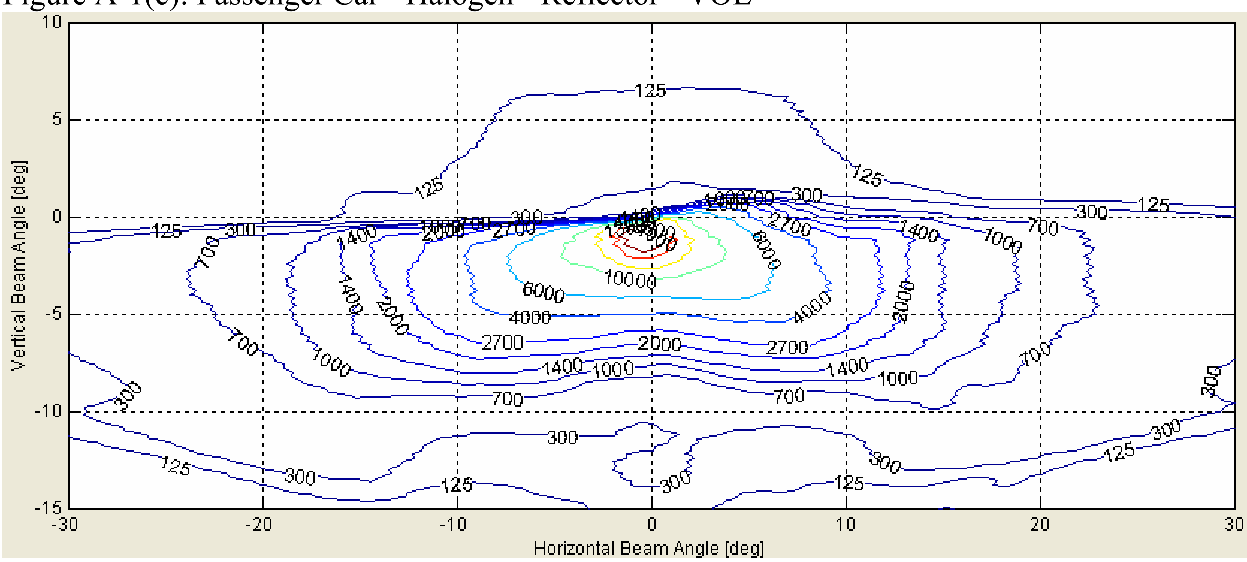


Figure A-1(d): Passenger Car - Halogen - Reflector - VOR

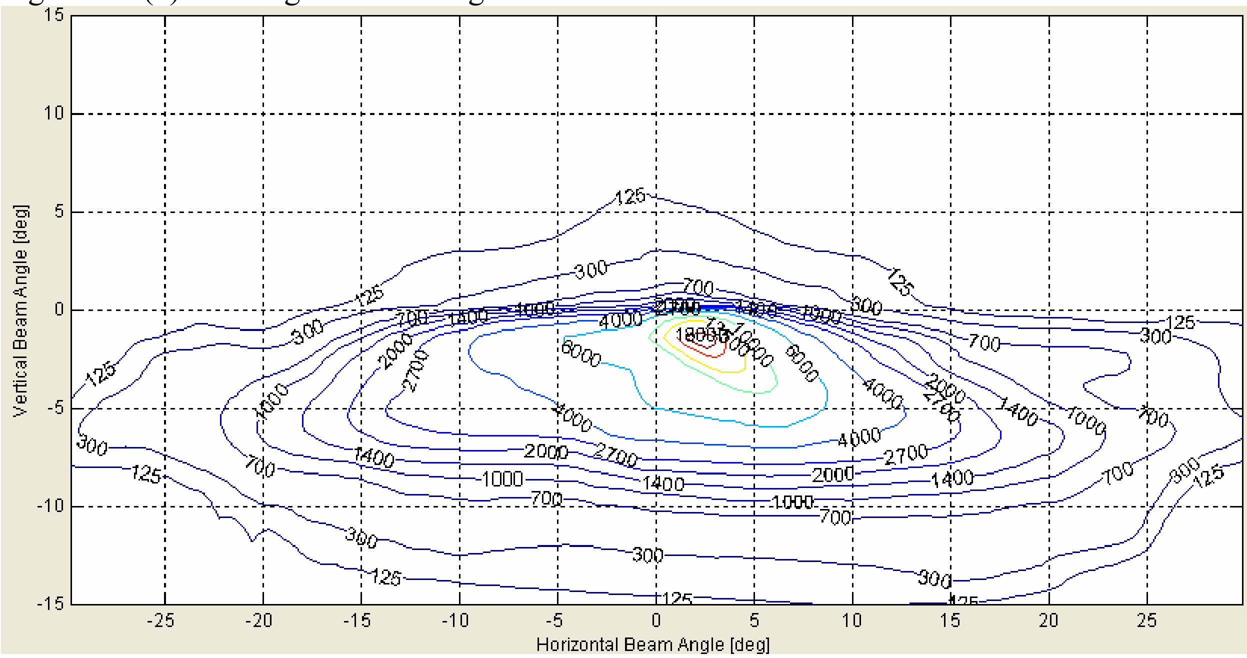


Figure A-1(e): Passenger Car - HID - Projector - VOL

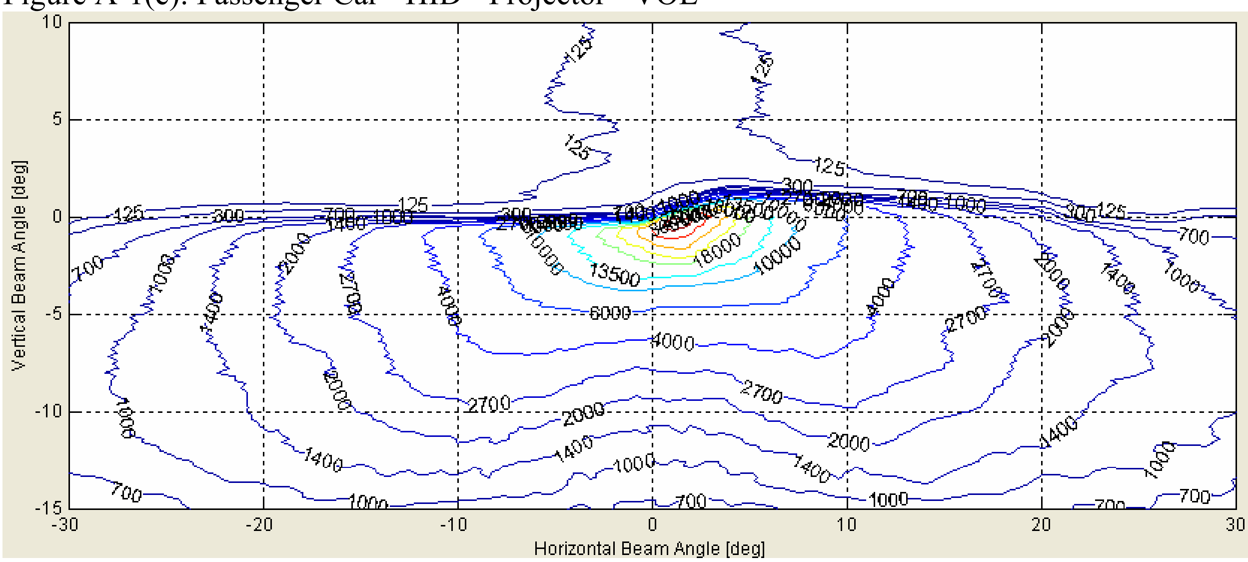


Figure A-1(f): Passenger Car - HID - Projector - VOR

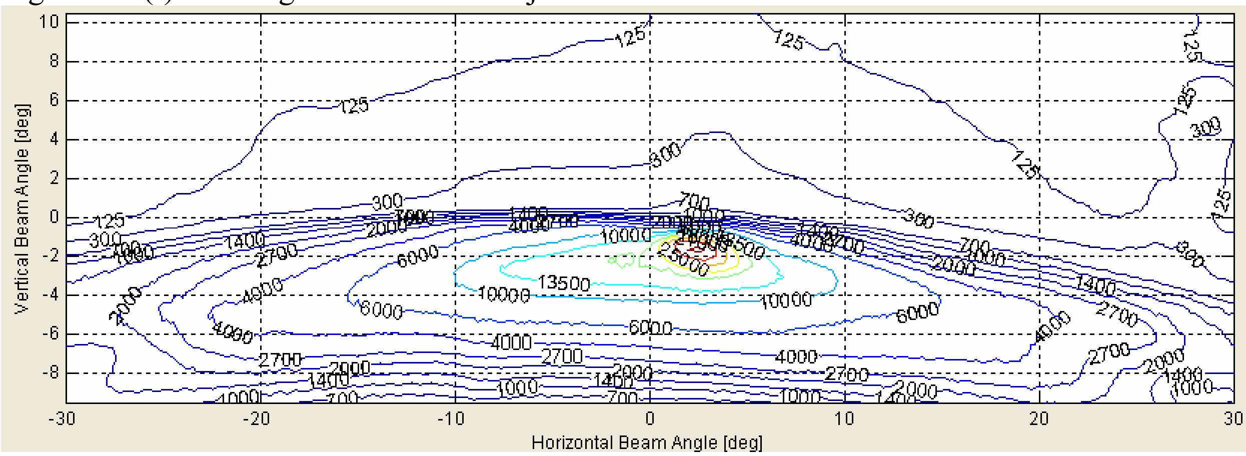


Figure A-1(g): Passenger Car - HID - Reflector - VOL

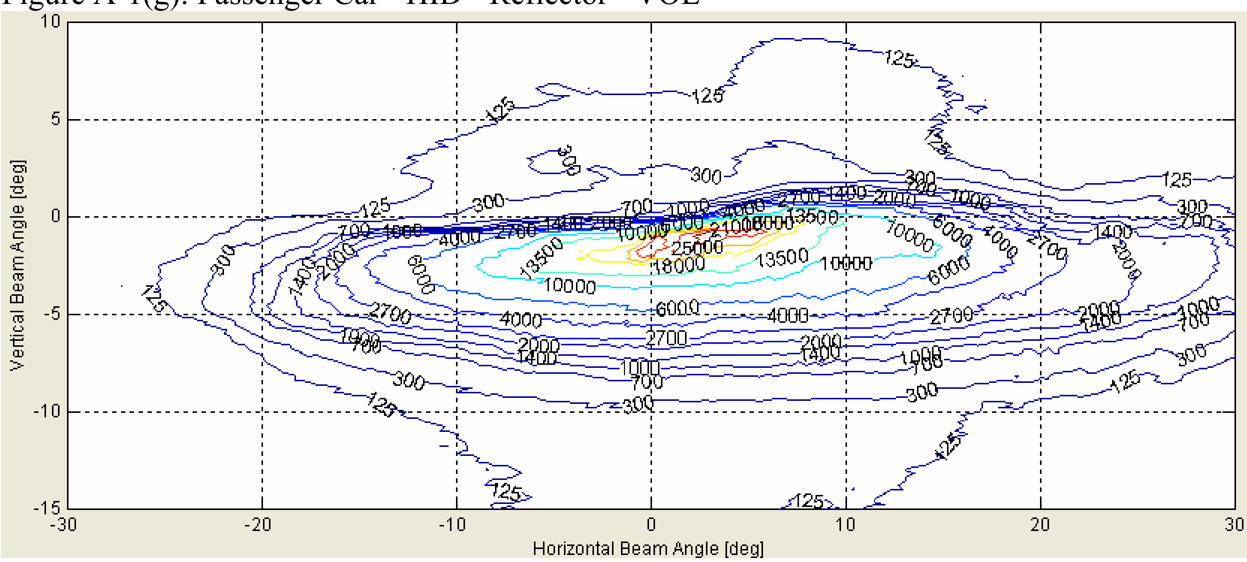


Figure A-1(h): Passenger Car - HID - Reflector - VOR

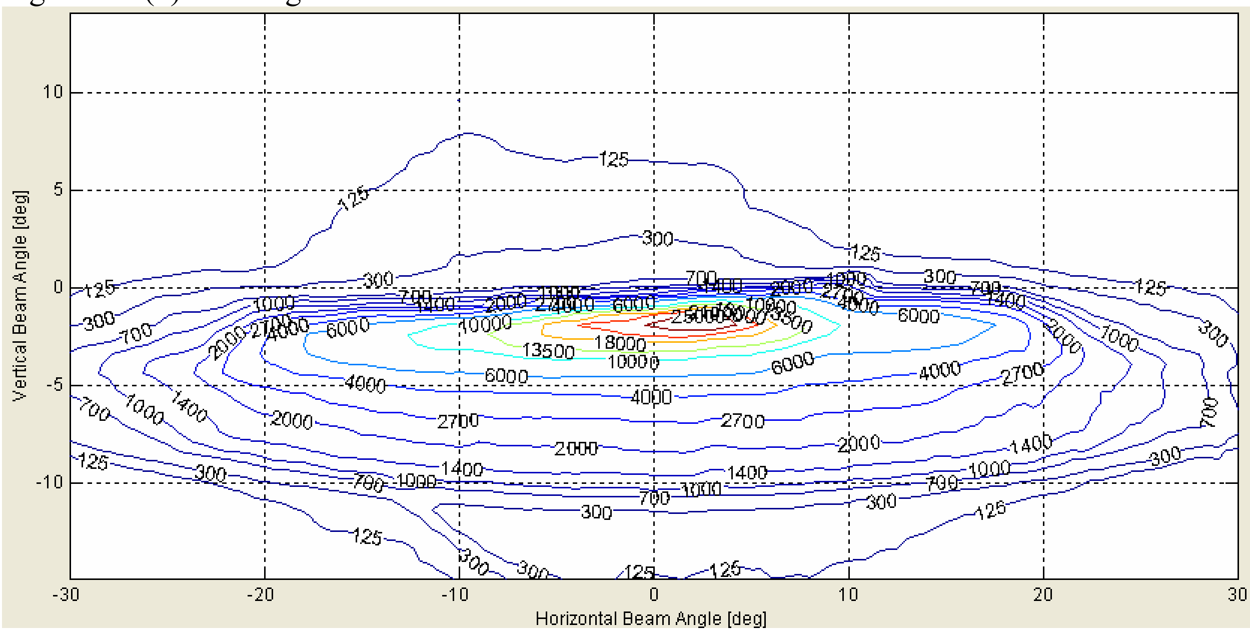


Figure A-1(i): SUV - Halogen - Reflector - VOR

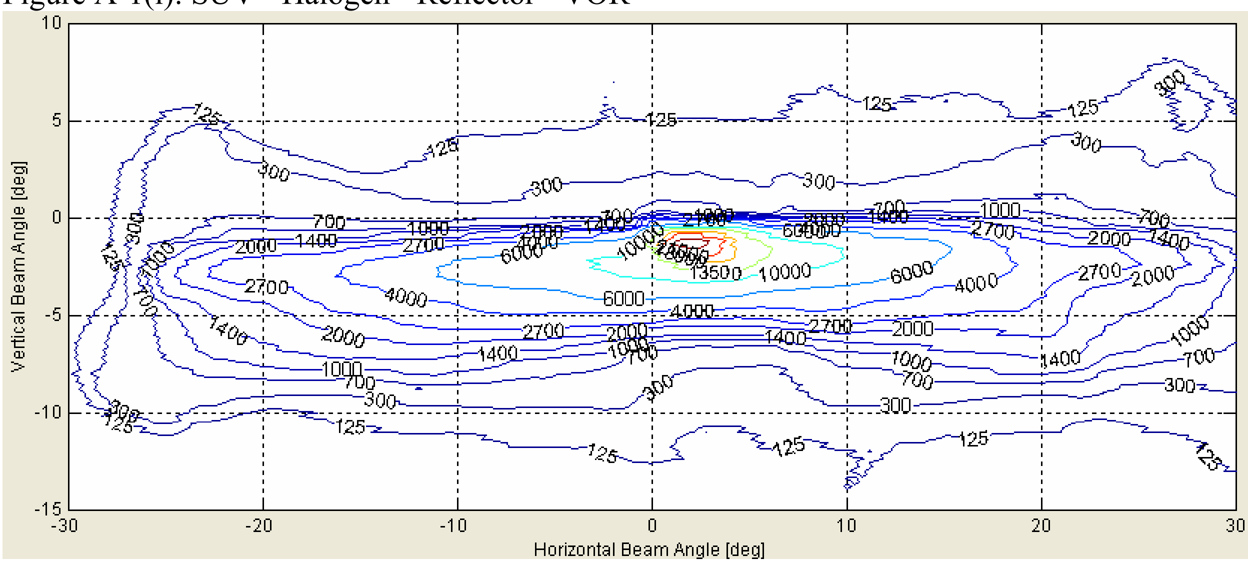


Figure A-1(j): SUV - HID - Projector - VOL

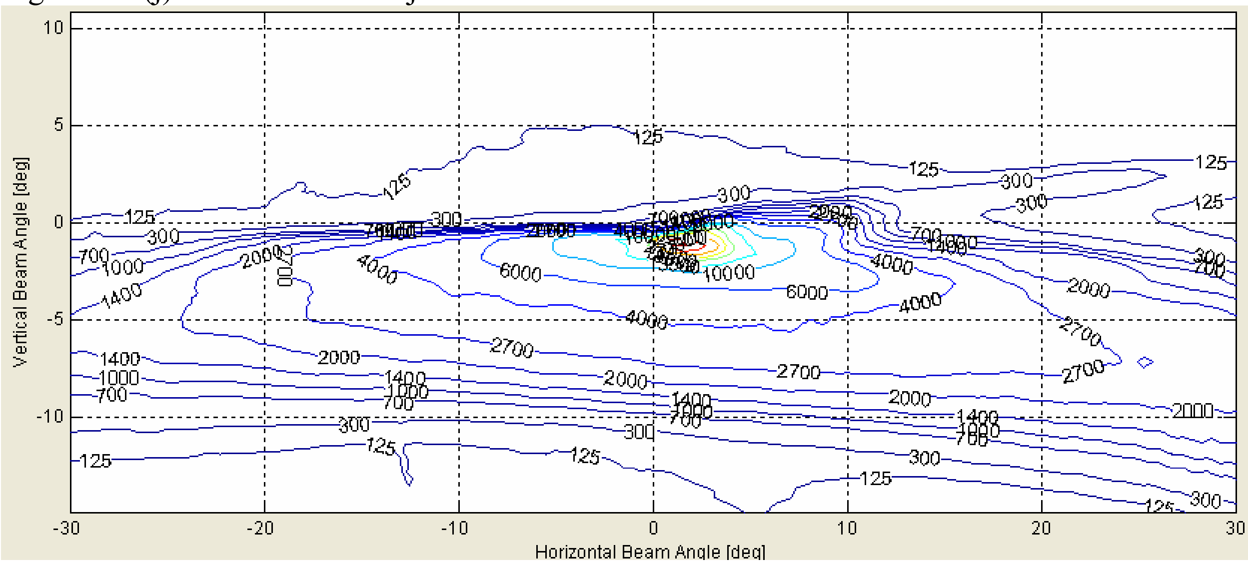


Figure A-1(k): SUV - HID - Reflector - VOL

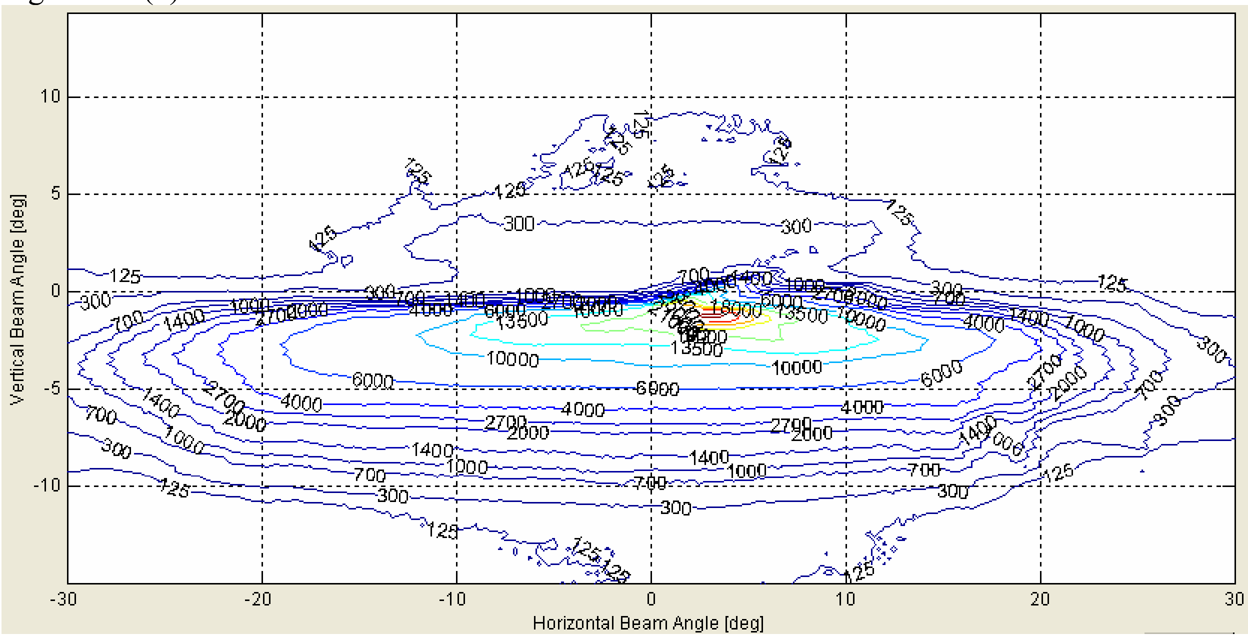
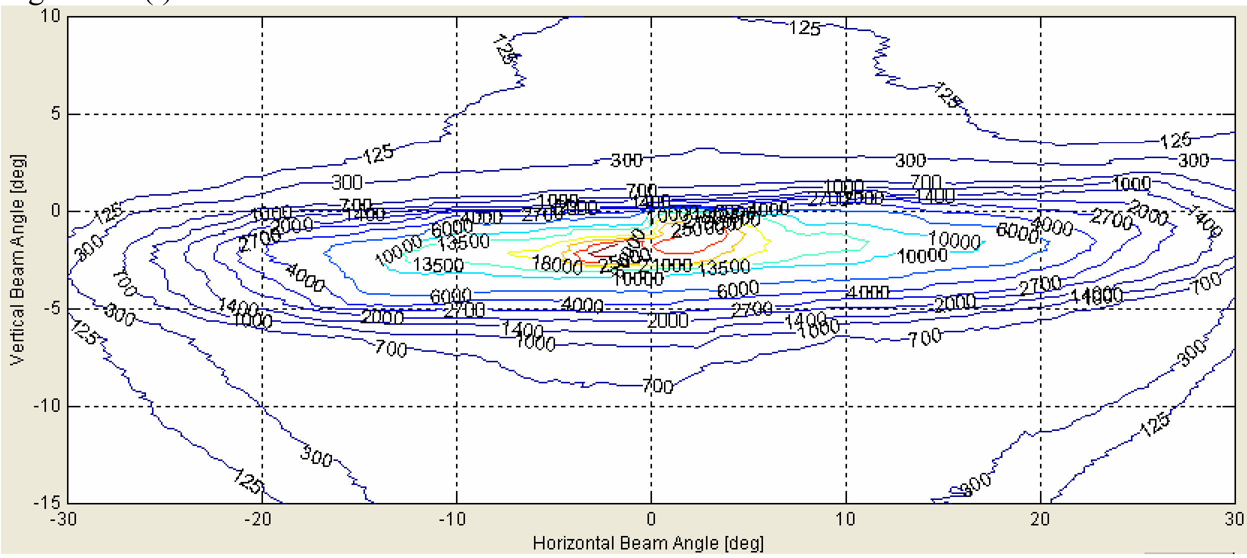


Figure A-1(l): SUV - HID - Reflector - VOR



Appendix 2: FMVSS 108 photometry standards

Table A-2: Photometry requirements for headlamps from FMVSS 108.

UPPER BEAM

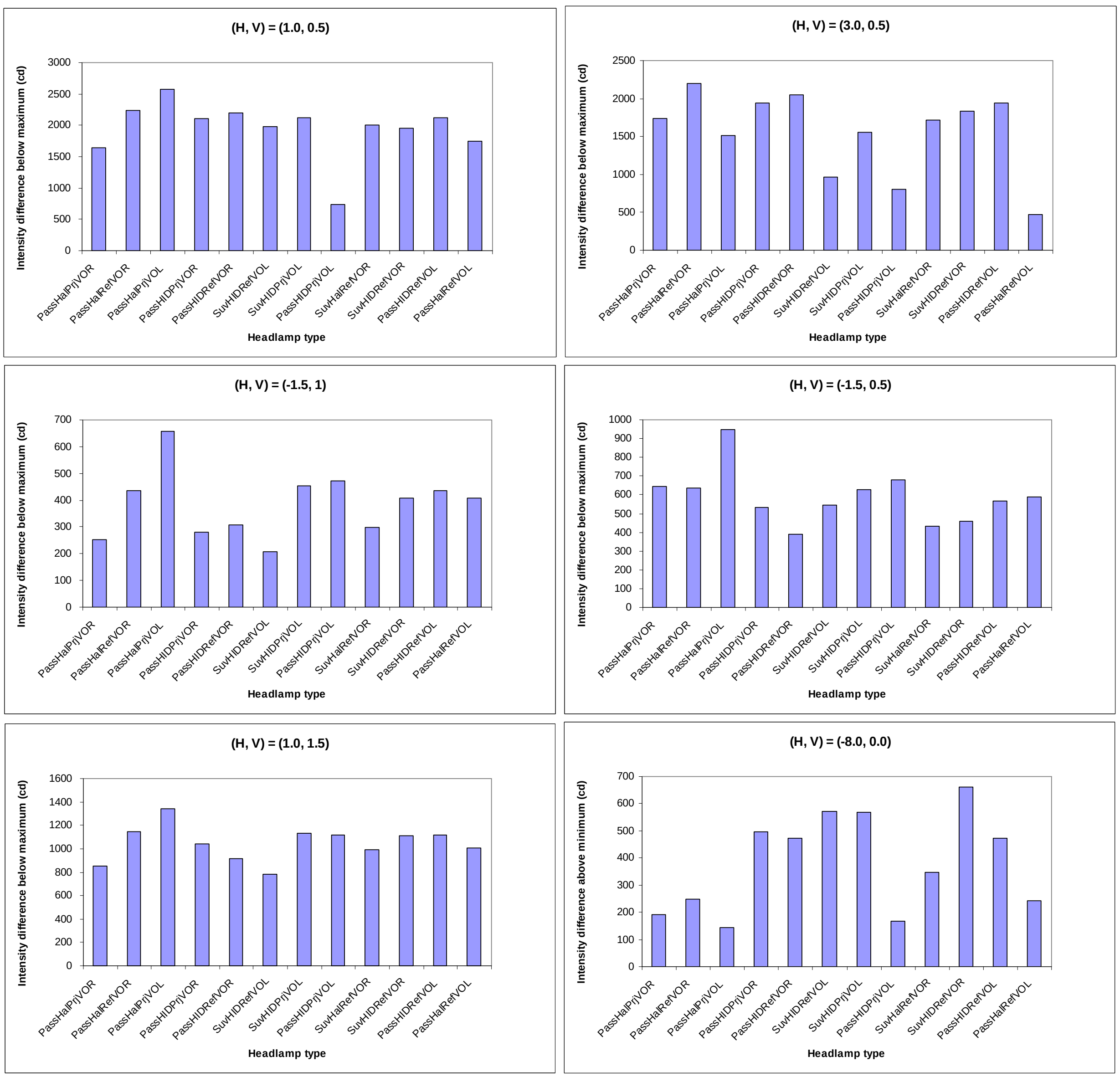
Test Points (degrees)	Candela maximum	Candela minimum
2U-V	–	1,500
1U-3L and 3R	–	5,000
H-V	75,000	40,000
H-3L and 3R	–	15,000
H-6L and 6R	–	5,000
H-9L and 9R	–	3,000
H-12L and 12R	–	1,500
1.5D-V	–	5,000
1.5D-9L and 9R	–	2,000
2.5D-V	–	2,500
2.5D-12L and 12R	–	1,000
4D-V	12,000	–

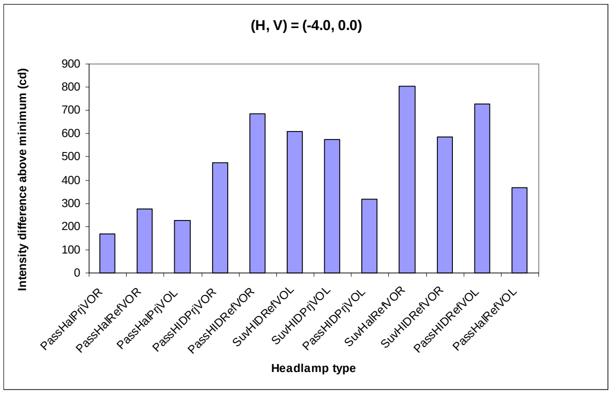
LOWER BEAM

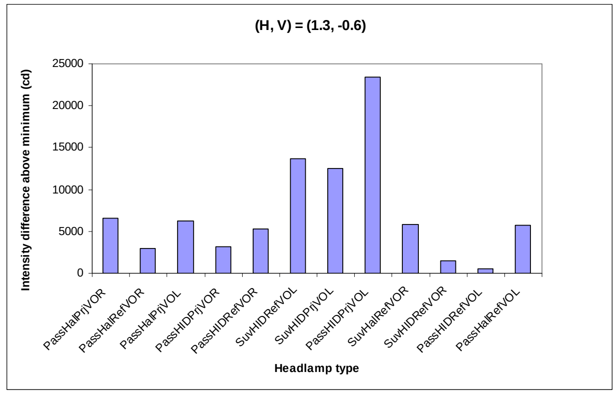
Test Points (degrees)	Candela maximum	Candela minimum
10U-90U	125	–
4U-8L and 8R	–	64
2U-4L	–	135
1.5U-1R to 3R	–	200
1.5U-1R to R	1,400	–
1U-1.5L to L	700	–
0.5U-1.5L to L	1,000	–
0.5U-1R to 3R	2,700	500
H-4L	–	135
H-8L	–	64
0.6D-1.3R	–	10,000
0.86D-V	–	4,500
0.86D-3.5L	12,000	1800
1.5D-2R	–	15,000
2D-9L and 9R	–	1,250
2D-15L and 15R	–	1,000
4D-4R	12,500	–
4D-20L and 20R	–	300

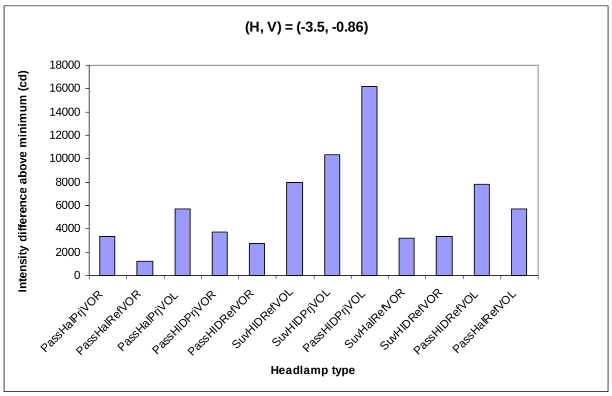
Appendix 3: Conformity of headlamps in the present study (reported data) to FMVSS 108 requirements.

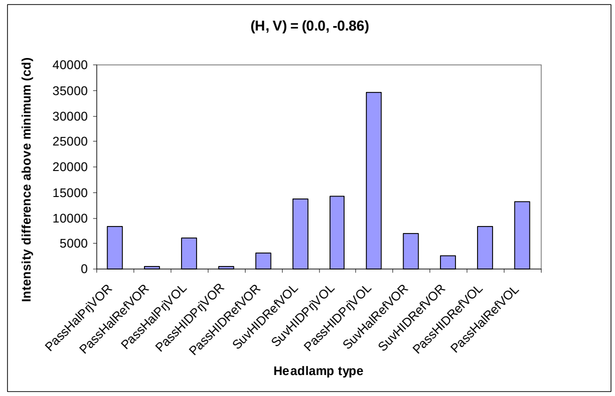
Key - Pass: passenger car, Suv: SUV, HID: HID lamp, Hal: halogen, Prj: projector headlamp, Ref: reflector headlamp, VOL: VOL alignment, VOR: VOR alignment.

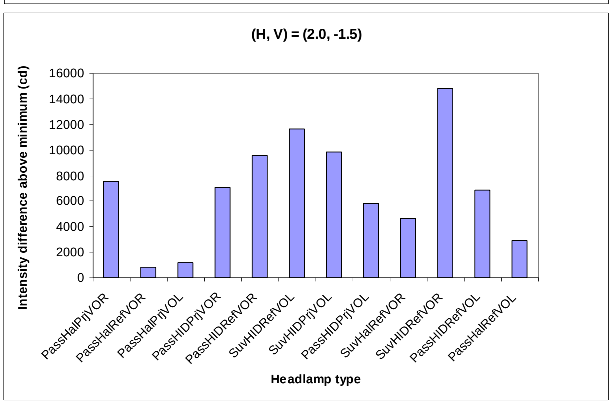


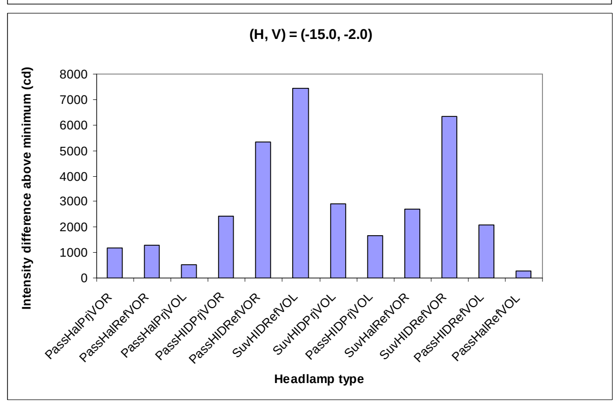

(H, V) = (-4.0, 0.0)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type

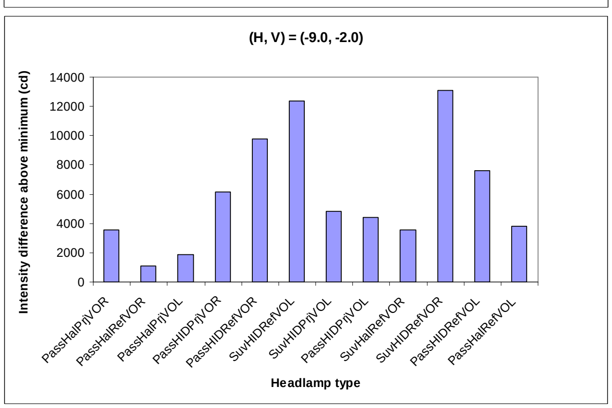

(H, V) = (1.3, -0.6)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type

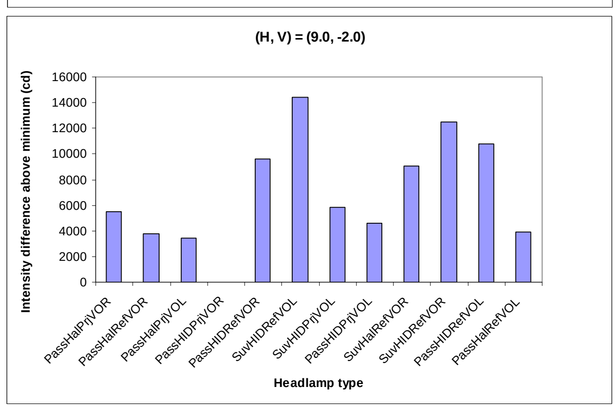

(H, V) = (-3.5, -0.86)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type

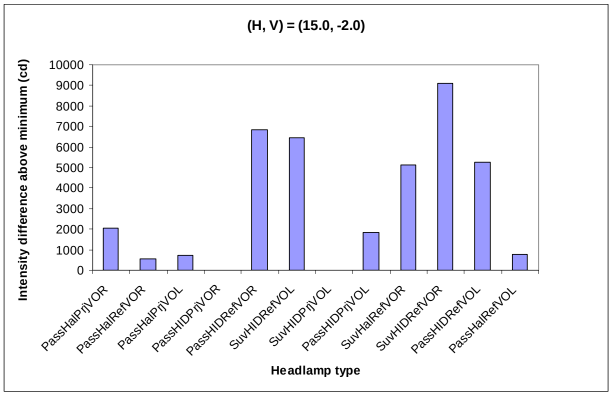

(H, V) = (0.0, -0.86)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type

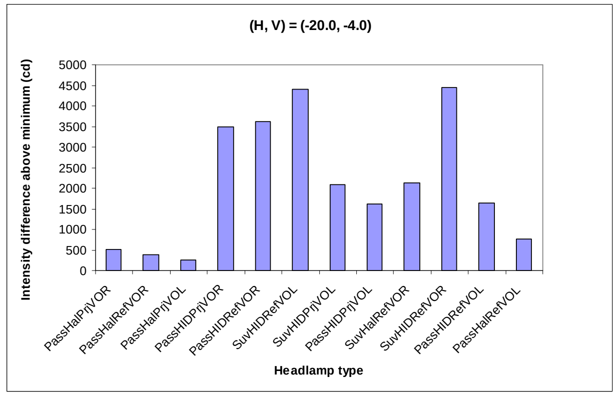

(H, V) = (2.0, -1.5)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type

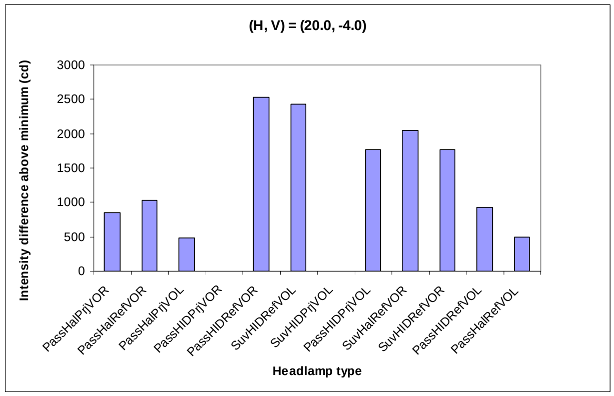

(H, V) = (-15.0, -2.0)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type


(H, V) = (-9.0, -2.0)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type


(H, V) = (9.0, -2.0)
Intensity difference above minimum (cd)
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type


(H, V) = (15.0, -2.0)
Intensity difference above minimum (cd)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type


(H, V) = (-20.0, -4.0)
Intensity difference above minimum (cd)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type


(H, V) = (20.0, -4.0)
Intensity difference above minimum (cd)
0
500
1000
1500
2000
2500
3000
PassHalPrjVOR
PassHalRefVOR
PassHalPrjVOL
PassHIDPrjVOR
PassHIDRefVOR
SuvHIDRefVOL
SuvHIDPrjVOL
PassHIDPrjVOL
SuvHalRefVOR
SuvHIDRefVOR
PassHIDRefVOL
PassHalRefVOL
Headlamp type

Appendix 4: Results of ANOVA under normal aiming conditions

Table A-4 (a): Results of ANOVA for veiling luminance under normal aiming conditions

Source	SS	Df	MS	F	Sig.
MH	0.0554	1	0.0554	38.1615	**p<0.0001**
Lamp	0.0003	1	0.0003	0.2067	p>0.05
Optics	0.0111	1	0.0111	7.6461	**p<0.05**
Align	0.0155	1	0.0155	10.6770	**p<0.01**
Distance	0.1122	4	0.0281	19.3219	**p<0.0001**
MH * Lamp	0.0066	1	0.0066	4.5463	**p<0.05**
MH * Optics	0.0051	1	0.0051	3.5131	p>0.05
MH * Align	0.0008	1	0.0008	0.5511	p>0.05
MH * Distance	0.0032	4	0.0008	0.5511	p>0.05
Lamp * Optics	0.0055	1	0.0055	3.7886	p>0.05
Lamp * Align	0.0010	1	0.0010	0.6888	p>0.05
Lamp * Distance	0.0016	4	0.0004	0.2755	p>0.05
Optics * Align	0.0019	1	0.0019	1.3088	p>0.05
Optics * Distance	0.0067	4	0.0017	1.1538	p>0.05
Align * Distance	0.0013	4	0.0003	0.2239	p>0.05
Error	0.0421	29	0.0015		

Table A-4 (b): Results of ANOVA for de Boer rating under normal aiming conditions

Source	SS	Df	MS	F	Sig.
MH	2.1038	1	2.1038	22.7472	**p<0.001**
Lamp	1.0621	1	1.0621	11.4839	**p<0.01**
Optics	0.5582	1	0.5582	6.0355	**p<0.05**
Align	2.3881	1	2.3881	25.8211	**p<0.0001**
Distance	13.0021	4	3.2505	35.1461	**p<0.0001**
MH * Lamp	0.1022	1	0.1022	1.1050	p>0.05
MH * Optics	0.4662	1	0.4662	5.0408	**p<0.05**
MH * Align	0.0410	1	0.0410	0.4433	p>0.05
MH * Distance	0.3282	4	0.0821	0.8872	p>0.05
Lamp * Optics	0.4118	1	0.4118	4.4526	**p<0.05**
Lamp * Align	0.1921	1	0.1921	2.0771	p>0.05
Lamp * Distance	0.0599	4	0.0150	0.1619	p>0.05
Optics * Align	1.9021	1	1.9021	20.5663	**p<0.001**
Optics * Distance	0.0121	4	0.0030	0.0327	p>0.05
Align * Distance	0.0679	4	0.0170	0.1835	p>0.05
Error	2.6821	29	0.0925		

Table A-4(c): Results of ANOVA for veiling luminance under normal and mis-aiming conditions

Source	SS	df	MS	F	Sig.
MH	0.1762	1	0.1762	0.1437	p>0.05
Lamp	6.0283	1	5.9365	4.8406	**p<0.05**
Optics	0.6688	1	0.6669	0.5438	p>0.05
Align	26.9840	1	24.7366	20.1701	**p<0.0001**
Misaim	352.8472	3	110.6211	90.1999	**p<0.0001**
Distance	132.8973	4	33.7535	27.5224	**p<0.0001**
MH * Lamp	0.1023	1	0.1266	0.1032	p>0.05
MH * Optics	2.9821	1	3.0421	2.4805	p>0.05
MH * Align	1.8109	1	1.7741	1.4466	p>0.05
MH * Misaim	3.5109	3	1.1929	0.9727	p>0.05
MH * Distance	4.5587	4	1.1330	0.9238	p>0.05
Lamp * Optics	7.0132	1	6.9438	5.6619	**p<0.05**
Lamp * Align	2.4002	1	2.3370	1.9056	p>0.05
Lamp * Misaim	4.1265	3	1.3709	1.1178	p>0.05
Lamp * Distance	0.9998	4	0.2540	0.2071	p>0.05
Optics * Align	1.4927	1	1.3670	1.1146	p>0.05
Optics * Misaim	1.5273	3	0.5350	0.4362	p>0.05
Optics * Distance	0.4101	4	0.0970	0.0791	p>0.05
Align * Misaim	71.0023	3	22.2010	18.1026	**p<0.0001**
Align * Distance	37.7256	4	8.5459	6.9683	**p<0.0001**
Misaim * Distance	147.2923	12	12.0603	9.8339	**p<0.0001**
Error	224.8912	182	1.2264		

Table A-4(d): Results of ANOVA for de Boer rating under normal and mis-aiming conditions

Source	SS	df	MS	F	Sig.
MH	14.8263	1	14.8263	83.4814	**p<0.0001**
Lamp	1.1927	1	1.1610	6.5372	**p<0.05**
Optics	0.0670	1	0.0651	0.3666	p>0.05
Align	0.0277	1	0.0240	0.1351	p>0.05
Misaim	134.9372	3	52.3422	294.7196	**p<0.0001**
Distance	4.2432	4	1.0306	5.8029	**p<0.001**
MH * Lamp	2.0192	1	1.9908	11.2095	**p<0.01**
MH * Optics	0.6210	1	0.6538	3.6813	p>0.05
MH * Align	0.7546	1	0.8154	4.5912	**p<0.05**
MH * Misaim	0.7223	3	0.3206	1.8052	p>0.05
MH * Distance	5.0172	4	1.2494	7.0349	**p<0.0001**
Lamp * Optics	0.5298	1	0.5760	3.2432	p>0.05
Lamp * Align	0.1283	1	0.1334	0.7511	p>0.05
Lamp * Misaim	0.3559	3	0.1241	0.6988	p>0.05
Lamp * Distance	0.6102	4	0.1428	0.8041	p>0.05
Optics * Align	2.3556	1	2.3474	13.2173	**p<0.001**
Optics * Misaim	2.1022	3	0.6943	3.9093	**p<0.01**
Optics * Distance	2.1400	4	0.5322	2.9966	**p<0.05**
Align * Misaim	9.3281	3	3.1480	17.7252	**p<0.0001**
Align * Distance	8.8762	4	2.1290	11.9876	**p<0.0001**
Misaim * Distance	31.8270	12	2.6418	14.8750	**p<0.0001**
Error	33.4221	182	0.1776		

Appendix 5: Results of a five-way ANOVA for glare dose

Table A-5: Results of a five-way ANOVA for glare dose

Source	SS	df	MS	F	Sig.
MH	11.9837	1	11.9837	10.8352	**p<0.01**
Lamp	14.9782	1	14.8867	13.4599	**p<0.01**
Optics	0.2973	1	0.3117	0.2818	p>0.05
Align	0.6193	1	0.6499	0.5876	p>0.05
Misaim	255.8347	3	78.0066	70.5304	**p<0.0001**
MH * Lamp	4.2189	1	4.2985	3.8865	p>0.05
MH * Optics	0.9521	1	0.9522	0.8609	p>0.05
MH * Align	7.7005	1	7.6978	6.9600	**p<0.05**
MH * Misaim	28.2942	3	9.1135	8.2401	**p<0.001**
Lamp * Optics	4.1948	1	4.2225	3.8178	p>0.05
Lamp * Align	0.5193	1	0.5096	0.4608	p>0.05
Lamp * Misaim	6.0938	3	2.0983	1.8972	p>0.05
Optics * Align	0.1198	1	0.1366	0.1235	p>0.05
Optics * Misaim	0.3872	3	0.1457	0.1317	p>0.05
Align * Misaim	9.5219	3	3.1983	2.8918	p>0.05
Error	23.3322	22	1.1060		

Appendix 6: Results of ANOVAs for detection distance

Table A-6(a): Results of six-way ANOVA for detection distance without oncoming glare

Source	SS	df	MS	F	Sig.
MH	3.1937	1	3.1937	0.0711	p>0.05
Lamp	959.8373	1	960.0214	21.3827	**p<0.0001**
Optics	9.9278	1	11.0200	0.2455	p>0.05
Align	2.3389	1	2.3450	0.0522	p>0.05
DMisaim	2811.9487	1	2622.8129	58.4183	**p<0.0001**
Target	3659.8948	2	1825.8817	40.6681	**p<0.0001**
MH * Lamp	515.0238	1	514.0824	11.4502	**p<0.01**
MH * Optics	0.1392	1	0.1547	0.0034	p>0.05
MH * Align	1040.0838	1	1035.2043	23.0573	**p<0.0001**
MH * DMisaim	4.4425	1	4.5567	0.1015	p>0.05
MH * Target	37.0012	2	19.8372	0.4418	p>0.05
Lamp * Optics	214.8373	1	215.2651	4.7946	**p<0.05**
Lamp * Align	790.0784	1	780.9340	17.3939	**p<0.001**
Lamp * DMisaim	24.9347	1	29.1326	0.6489	p>0.05
Lamp * Target	118.9372	2	63.1737	1.4071	p>0.05
Optics * Align	4.2422	1	6.2424	0.1390	p>0.05
Optics * Dmisaim	147.8272	1	146.2875	3.2583	p>0.05
Optics * Target	17.7352	2	8.9064	0.1984	p>0.05
Align * DMisaim	73.0928	1	73.5765	1.6388	p>0.05
Align * Target	155.3873	2	79.8578	1.7787	p>0.05
DMisaim * Target	122.0272	2	60.8251	1.3548	p>0.05
Error	1972.3842	44	44.8971		

Table A-6(b): Results of seven-way ANOVA for detection distance with oncoming glare

Source	SS	Df	MS	F	Sig.
MH	2998.6245	1	2998.6245	271.3231	**p<0.0001**
Lamp	56.0177	1	56.0177	5.0686	**p<0.05**
Optics	144.0784	1	144.0784	13.0366	**p<0.001**
Align	6.1456	1	6.1456	0.5561	p>0.05
DMisaim	755.8953	1	755.8953	68.3953	**p<0.0001**
Target	29086.8360	2	14543.4180	1315.9253	**p<0.0001**
Omisaim	6683.8762	3	2227.9587	201.5913	**p<0.0001**
MH * Lamp	20.7530	1	20.7530	1.8778	p>0.05
MH * Optics	323.4419	1	323.4419	29.2658	**p<0.0001**
MH * Align	102.9736	1	102.9736	9.3173	**p<0.01**
MH * Dmisaim	20.5383	1	20.5383	1.8584	p>0.05
MH * Target	731.6230	2	365.8115	33.0995	**p<0.0001**
MH * Omisaim	39.0836	3	13.0279	1.1788	p>0.05
Lamp * Optics	711.6384	1	711.6384	64.3908	**p<0.0001**
Lamp * Align	130.9731	1	130.9731	11.8508	**p<0.001**
Lamp * DMisaim	120.9376	1	120.9376	10.9427	**p<0.01**
Lamp * Target	620.9381	2	310.4691	28.0920	**p<0.0001**
Lamp * Omisaim	91.1028	3	30.3676	2.7477	**p<0.05**
Optics * Align	510.8948	1	510.8948	46.2271	**p<0.0001**
Optics * Dmisaim	33.9378	1	33.9378	3.0708	p>0.05
Optics * Target	2.9348	2	1.4674	0.1328	p>0.05
Optics * Omisaim	2.3836	3	0.7945	0.0719	p>0.05
Align * Dmisaim	23.8937	1	23.8937	2.1620	p>0.05
Align * Target	265.0384	2	132.5192	11.9907	**p<0.0001**
Align * Omisaim	120.3526	3	40.1175	3.6299	**p<0.05**
Dmisaim * Target	203.8372	2	101.9186	9.2219	**p<0.001**
Dmisaim * Omisaim	82.0273	3	27.3424	2.4740	p>0.05
Target * Omisaim	109.2730	6	18.2122	1.6479	p>0.05
Error	2608.2383	236	11.0519		

DOT HS 811 055
December 2008

U.S. Department
of Transportation
National Highway
Traffic Safety
Administration

www.nhtsa.gov