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

www.nhtsa.gov

DOT HS 810 947 June 2008

Assessment of Headlamp Glare And Potential Countermeasures: The Effects of Headlamp Mounting Height

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Technical Report Documentation Page

1. Report No. DOT HS 810 947	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Assessment of Headlamp Glare and Potential Countermeasures: The Effects of Headlamp Mounting Height		5. Report Date June 2008 6. Performing Organization Code
7. Author(s) Yukio Akashi, John Van Derlofske, Ramesh Raghavan, John D. Bullough		8. Performing Organization Report No.
9. Performing Organization Name and Address Lighting Research Center, Rensselaer Polytechnic Institute 21 Union St., Troy, NY 12180		10. Work Unit No. (TRAIS) 11. Contract or Grant No. DTNH22-99-D-07005
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 14. Sponsoring Agency Code
15. Supplementary Notes Michael Perel was the NHTSA COTR for this project.		

16. Abstract

This project examined the effects of headlamp mounting height on the disability and the sensation of discomfort caused by glare. This was performed through a field study and a simulation study. In the field study, subjects evaluated the degree of glare from oncoming and following headlamps with different mounting heights and different intensity of headlamps. This field study provides data to suggest how headlamp mounting height affects discomfort glare. Additionally, to examine disability glare, two simulation analyses were also performed through calculations using existing models. One analyzed drivers' reaction times to peripheral targets. The other analyzed detection distances to small targets located along the roadway. Both analyses treated headlamp mounting height as one of several independent variables.

Overall, this project led to the conclusion that the mounting height of oncoming headlamps affects both disability glare and discomfort glare. A common tendency is that as the mounting height increases, glare is also increased. The increase in glare results in increased discomfort and reduction of visual performance (i.e., increased reaction times to detect objects and decreased detection distances).

17. Key Words headlamp, headlight, mounting height, visibility, glare, detection distance, de Boer rating, field study		18. Distribution Statement This report is free of charge from the NHTSA Web site at www.nhtsa.dot.gov	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

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Executive Summary:

Headlamps, while providing forward visibility, may also result in glare to other drivers. Primary determinants of glare severity are the intensity and angular location of a glare source relative to the viewer's line of sight. Studies have investigated how the intensity and location of a glare source contributes to glare (Stiles & Crawford, 1937; Fry, 1954); in general, as the intensity of a glare source increases and as the glare source becomes closer to the line of sight, the severity of glare increases. The results of these and other studies have led to the regulation of headlamp beam distribution to limit the amount of glare light. Additionally, studies have shown that a headlamp system with a higher mounting height may result in greater glare illuminance to other drivers and thus may cause more serious glare issues (Road Illumination Devices Standards Committee, 1996). For headlamp mounting height, however, detailed information and research data have not been readily available on which to make regulatory decisions, such as exact mounting heights at which the intensity of headlamps generate adverse safety consequences.

To identify the effects of headlamp mounting height on the sensation of discomfort and the visual disability caused by glare, the Lighting Research Center (LRC) at Rensselaer Polytechnic Institute in Troy, New York, conducted a field study and a simulation evaluation. In the field study, subjects evaluated the degree of glare from oncoming and following headlamps with different mounting heights and different intensities. This field study measured how headlamp mounting height affects discomfort glare. However, the field study did not explicitly examine the disability glare effects associated with the measures of driver comfort as a function of headlamp mounting height. Thus, two simulation analyses studies were also performed to examine disability glare from oncoming headlamps. One simulation analyzed drivers' reaction times to peripheral targets. The other analyzed detection distances to small targets located along the roadway. Both analyses treated headlamp mounting height as a variable; other independent variables include target locations and types of forward headlamps. Finally, the results from the field study and those from the simulation studies were used to develop conclusions.

The results of these studies suggest that the mounting height of oncoming headlamps affects both disability and discomfort glare. A common tendency is that as the mounting height increases, glare is also increased. The increase in glare results in reduction of visual performance, increased reaction

times, and decreased detection distances. The effects of mounting height on discomfort glare appear stronger than those on disability glare. However, this effect still needs further verification because the measured (field study) and simulated glare illuminances were not matched, possibly because the pavement surface of the test site might be uneven and slightly bent in the middle between the test car and the oncoming headlamps (see Appendix 1 for more details). The mounting height of following headlamps also affects discomfort glare, and these effects can, in the worst case (highest mounting height), be larger than those of oncoming headlamps.

A secondary goal of these studies was to understand how different headlamp types with different mounting heights affect target detection and visibility distance with and without oncoming glare. This analysis was done based on simulation calculations. Overall, there is no clear tendency that for different headlamp systems detection distance increases as the mounting height increases for the samples used in the calculations. However, one trend in this study was that high-intensity discharge (HID) headlamps provided longer detection distances (so one can detect something at a greater distance) than halogen headlamps.

To identify the validity of the 3-lux (lx) iso-illuminance contour line on the horizontal roadway surface, which is often used as a criterion of headlamp performance, the 3-lx iso-illuminance contour lines were compared with detection distances of a given target. The results of the comparison suggest that the 3-lx iso-illuminance contour lines are closer to drivers by up to 10 m than the detection distance calculations for an 18 cm and 18 cm target with a reflectance of 6 percent. However, the detection distances are subject to change depending on the size and reflectance of the targets; for instance, the use of a larger target with a higher reflectance will increase detection distances. To verify further this method, further research is needed with additional target conditions.

1. Objectives

Headlamps are a double-edged sword — while they provide forward visibility to drivers, headlamps may directly and indirectly impair oncoming drivers' visibility due to glare caused by the headlamps. Light coming from a glare source is scattered in the eye, directly reducing the luminance contrast of an object against the background. The reduction in luminance contrast leads to reduced visibility and visual performance. A glare source also causes discomfort to drivers, making drivers squint and blink their eyes more frequently and look away from the glare source. Such discomfort also results indirectly in reduced visual performance and safety if drivers are distracted from detecting potential hazards.

The primary determinants of glare are the intensity and location of a glare source. Studies have investigated how the intensity and location of a glare source contribute to glare (Stiles & Crawford, 1937; Fry, 1954). As the intensity of a glare source increases and as it becomes closer to the line of sight, the amount of glare is increased. The results of these studies have led to the regulation of headlamp beam distribution. Additionally, studies have shown that a headlamp system with a higher mounting height may result in greater glare illuminance to other drivers and thus may cause more serious glare issues (Road Illumination Devices Standards Committee, 1996). For headlamp mounting height, however, detailed information and research data have not been readily available on which to make regulatory decisions.

To identify the effects of headlamp mounting height on the sensation of discomfort and the visual disability caused by glare, the Lighting Research Center at Rensselaer Polytechnic Institute conducted a field study and a simulation study using existing models. In the field study, subjects evaluated the degree of glare from headlamps with different mounting heights and different headlamp intensities. The results of this field study led to a suggestion of how to deal with discomfort glare by manipulating headlamp mounting heights. However, from this field study it was not clear how headlamp mounting heights affect disability glare and therefore target visibility. To examine the effects of headlamp mounting height on target visibility while an oncoming car provides glare, two additional simulation studies were performed. One study analyzed simulated drivers' reaction times to peripheral targets based on an existing model. The other analyzed real drivers' detection distances to small targets located along the roadway. Both analyses treated headlamp mounting height as one of several independent variables. Finally, the results from the field study and those from the simulation studies were compared to develop conclusions regarding the effect of headlamp mounting height on glare. These findings and conclusions are described here.

2. Field study: Discomfort glare evaluations

2.1. Objective

The objective of this study was to explore the effects of headlamp mounting height in combination with headlamp intensity on discomfort glare.

2.2. Location and setup

This experiment took place on an unused runway at Schenectady County Airport in Scotia, New York. On the runway, a two-lane roadway approximately 100 m in length and 7 m in width was delineated along existing markings on the runway pavement. Along the roadway, three temporary roadway lighting poles were located, spaced at a distance of 30 m in a staggered arrangement. Two full-cutoff luminaire heads (G13-4XL-150HPS-277V-NP, Gardco Emco McPhilben) were mounted on the top of each pole. On each pole, one of the two heads was equipped with a 150 W high-pressure sodium lamp (LU150/55/MED67508-1, OSRAM SYLVANIA, Inc.) This head functioned as an illuminator and the other head was used to balance the weight. These three poles with mesh filters provided an average ambient illuminance of 2.2 lx over the two lanes with a minimum illuminance of 0.4 lx. This lighting condition matched that used in a previously published study (Akashi et al., 2003). Figure 1 shows the layout of the experimental setup and the view of the three poles.

At one end of the roadway, a compact passenger car was parked for subjects to be seated. Located in front of the car was a rack holding a model year (MY) 2000 projector headlamp system, conforming to the Society of Automotive Engineers (SAE) J1383 standard and containing 51W tungsten halogen lamps. This headlamp system was used in previously published research studies of visibility by the LRC (Van Derlofske et al., 2002). It provided forward lighting for the subjects in the driver's seat of the car. The mounting height of the forward headlamps was 0.65 m, a typical mounting height for a passenger car. The headlamp rack was not visible to subjects in the driver's seat of the car.

An MY 2000 reflector headlamp system was located 50 m away in front of the car to provide oncoming glare, or 15 m away behind the car for following glare. The headlamp system conformed to the SAE J1383 performance requirements for motor vehicle headlamps (SAE, 2002) and meeting the requirements of Federal Motor Vehicle Safety Standards and Regulations (FMVSS) No. 108. By covering the headlamp lenses with neutral-density filters, the luminous intensity of the headlamps was varied to 50 percent, 30 percent or 105 of its original intensity (100%).

As a fixation point, a numerical signboard composed of seven LED segments was placed facing subjects at a distance of 60 m from the car. The signboard displayed 30 cm × 20 cm numerical characters from 0 to 9 in a random order for one second each. The subjects fixated on the signboard and were assigned to read the number when the number was changed.

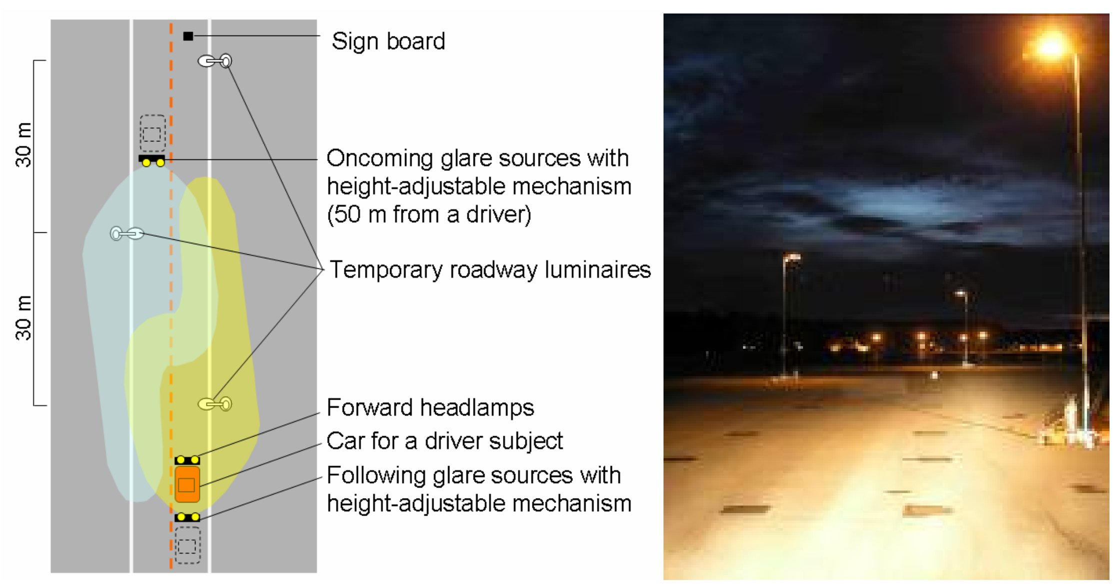


Figure 1. Layout of experimental setup including three fixed roadway lighting poles.

2.3. Experimental conditions

Table 1 summarizes the experimental conditions. As independent variables, the glare source position, mounting height, and intensity of the glare sources (headlamps) were changed. Two reference points were used to measure headlamp mounting heights, one at the center of the lamp and the other at the top edge of the lamp. Measurement at the top edge followed Economic Commission for Europe (ECE) regulation R48 rev. 2 on the Installation of Lamps.[1] The heights of 850 mm and 950 mm correlate to

[1] In section 2.9.2. "Illuminating surface of a light-signalling device other than a retro-reflector" (paragraphs 2.7.11. to 2.7.15., 2.7.17., 2.7.19. and 2.7.21. to 2.7.24.) means the orthogonal projection of the lamp in a plane perpendicular to its axis of reference and in contact with the exterior light-emitting surface of the lamp, this projection being bounded by the edges of screens situated in this plane, each allowing only 98 per cent of the total luminous intensity of the light to persist in the direction of the axis of reference. To determine the lower, upper, and lateral limits of the illuminating surface, only screens with horizontal or vertical edges shall be used.

mounting heights for sport utility vehicles (SUVs). The criterion of 950 mm to the upper edge is from the ECE standard and the other criterion, 850 mm at the center of the lamp, is a potential criterion for the SAE standard. The 950 mm and the 850 mm to mounting heights were chosen since these values were at the time of the study under discussion for international harmonization documents. Thus, it was important to understand whether discomfort from headlamps for both mounting height criteria were significantly different. In the case of the reflector headlamp system used in this experiment as a glare source, the criterion of 950 mm to the upper edge was approximately 20 mm higher than the other criterion of 850 mm at the center of the lamp. However, a smaller headlamps system, such as a projector system, could be approximately 75 mm higher. For consistency in describing experimental conditions, heights from the ground to the center of the lamps are used as headlamp mounting heights. Therefore, the four headlamp mounting heights employed in this experiment are described as 660 mm, 850 mm, 870 mm, and 1,120 mm in the remainder of the report. See Table 1 below.

Table 1. Experimental conditions (32 conditions in total).

Independent variables	**Range**	**Conditions**
Glare source position	50 m away in front of the car 15 m away behind the car	2
Mounting height (mm)	(1) **660 mm** to the center of lamp (475 mm lower from the average eye height) (2) **850 mm** to the center of lamp (285 mm lower from the average eye height) (3) 950 mm to the upper edge, equivalent to **870 mm** to the center (265 mm lower from the average eye height) (4) 1200 mm to the upper edge, equivalent to **1,120 mm** to the center (15 mm lower from the average eye height)	4
Headlamp intensity (%)	10, 30, 50, 100	4

2.4. Procedure

The experiment employed 11 young (22 to 34 years old) and 9 older (>56 years old) subjects, 20 in total. The experiments were conducted from approximately 9 p.m. to 12 a.m. for eight nights when the pavement was dry, between May 19, 2004, and July 28, 2004. On each night, two to five subjects participated in the glare evaluations for either the oncoming or following glare position. Each subject attended the experiments for two nights to complete both glare source positions. All glare presentations were divided into four mounting height sessions: 660 mm, 850 mm, 870 mm, and 1,120 mm. Between the sessions, the headlamp height was adjusted to each target mounting height. After each mounting height adjustment, the headlamps were re-aimed. The aiming technique is described in Appendix 2.

Prior to the experiment, an experimenter gave instructions about the procedure of the experiment to all subjects. Subjects read and signed informed consent forms. One subject at a time took part in the evaluation while other subjects stayed at a rest area. The first subject was escorted and seated in the driver's seat of the parked passenger car. An experimenter sat with the subject to help the subject with glare evaluations. First, the experimenter asked the subject to adjust the driver's seat, the rear-view mirror, and the side mirrors to the subject's normal positions and orientation. Second, the experimenter explained details of how a subject could evaluate glare. The experimenter in the car communicated with other experimenters, who presented and changed experimental conditions in the field by using a pair of walkie-talkies. While the experimenter explained the procedure to the first subject in the car, the field experimenters set the first mounting height condition.

Then, the glare headlamps, set to the first intensity condition, were presented to the subject for four seconds. It should be reemphasized here that both cars were stationary. After the four-second exposure to the glare source, the subject evaluated the degree of glare by choosing a number between 1 and 9 on the De Boer rating scale, shown below:

1. unbearable
2.
3. disturbing
4.
5. just permissible
6.
7. satisfactory
8.
9. just noticeable

The experimenter in the car recorded the subject response and let the field experimenter know of the completion of the first evaluation so that the field experimenters could change the headlamp luminous intensity. This procedure was repeated for four headlamp luminous intensities. After the four evaluations, the subject got out of the car and rested while other subjects participated in the glare evaluation. The next subject was escorted to the car and seated in the driver's seat. The subject evaluated the four headlamp luminous intensities in the same manner. The order of the headlamp intensity presentations was randomized and the order of the mounting height was counterbalanced across subjects. On the second day, all the subjects participated in the other half of the experiment for the other glare position. The order of the glare positions was also counterbalanced across subjects.

2.5. Measurements

To identify how much light reached a driver's eyes, illuminance was measured in the subject car at a height of 1.15 m from the pavement with 100 percent of the headlamp intensity (i.e., without any filters). The receptor of the illuminance meter faced forward during the measurements; this receptor direction was the same as the subjects' line of sight. The measurement height was regarded as a typical driver's eye height. Measurements of eye heights of 10 subjects (5 subjects from each age group), who participated in this study, found the mean eye height and standard deviation to be 1.13 m and 5.5 cm respectively. This measurement was repeated three times for each condition. Table 2 shows the means of the three illuminance measurements for the eight experimental conditions.

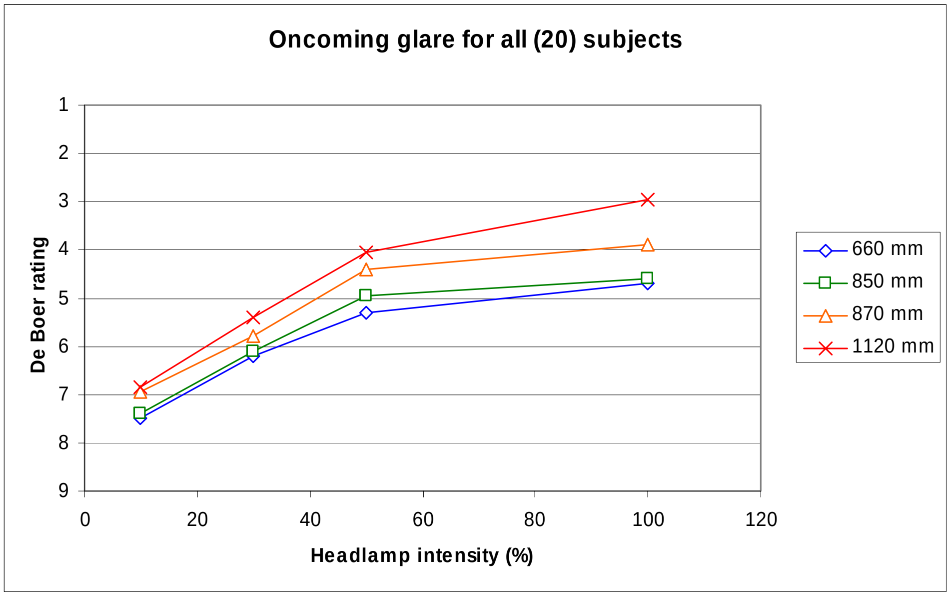
Table 2. Measurements of illuminance at a driver's eye (lx).

Glare position	**Mounting height (mm)**			
	660	**850**	**870**	**1120**
Oncoming	0.73	0.91	1.17	3.16
Following	0.07	0.36	0.41	1.41

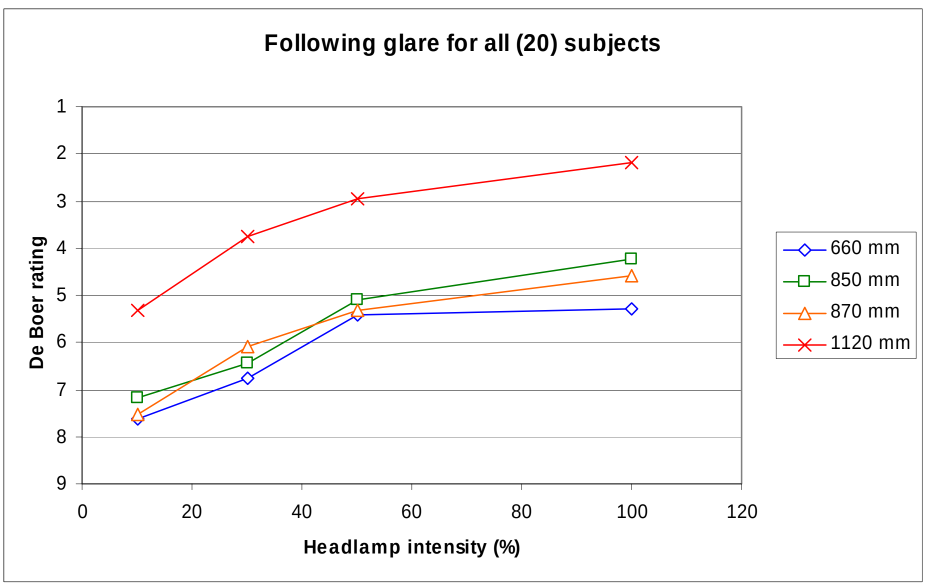
2.6. Results

The De Boer ratings of all 20 subjects were averaged for each condition. Figures 2 (a) and (b) show the glare evaluation results for the oncoming and following glare conditions. The glare evaluation data were also compared between the two age groups. Figure 3 shows the same data in three-dimensional diagrams. This analysis used, as a glare threshold, the fourth point "4" that is rated between "3:

disturbing" and "5: just acceptable" in the 9-point scale of the De Boer rating. Therefore, a headlamp system is not assumed to cause glare unless the glare rating of the system falls below "4".



(a) Oncoming glare



(b) Following glare

Figure 2. Results of oncoming and following glare for all 20 subjects.

(See Table 7 for details of mounting height and the distance from the lamp center to the average eye.)

Figures 2 (a) and (b) suggest:

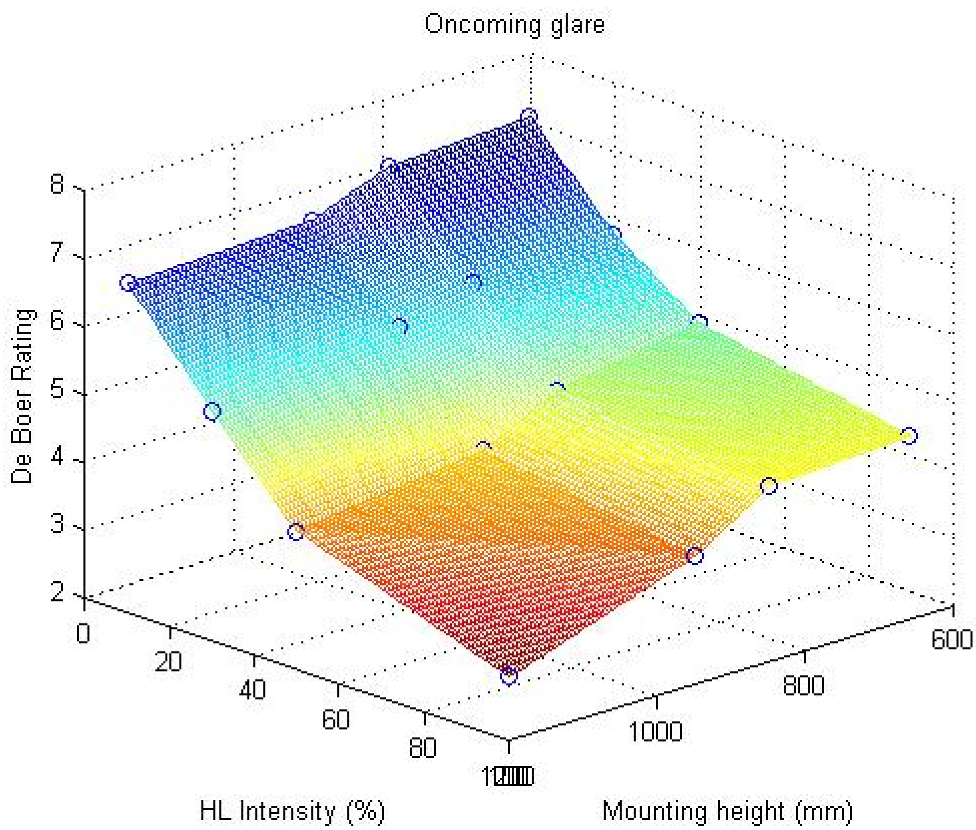
<u>For oncoming glare:</u>

- Glare was increased (i.e., the De Boer rating was a lower number) as the mounting height of headlamps increased.
- Between the lowest mounting height of 660 mm and the highest mounting height of 1,120 mm, there was a difference in glare of up to approximately 1.8 points in the De Boer rating (for 100% headlamp intensity condition), changing the rating from around “Just Permissible” to “Disturbing”.
- Glare for the mounting height of 850 mm was more acceptable than glare from headlamps at 870 mm. The difference in glare rating between the two mounting heights is approximately a half unit in the De Boer rating for all intensity conditions.
- For the mounting heights of 870 mm and 1,120 mm, if the luminous intensity was reduced to or below 50 percent of initial intensity. For the mounting heights of 660 mm and 850 mm, the glare was also acceptable at 50-percent intensity. No mounting height was acceptable at 100-percent intensity.

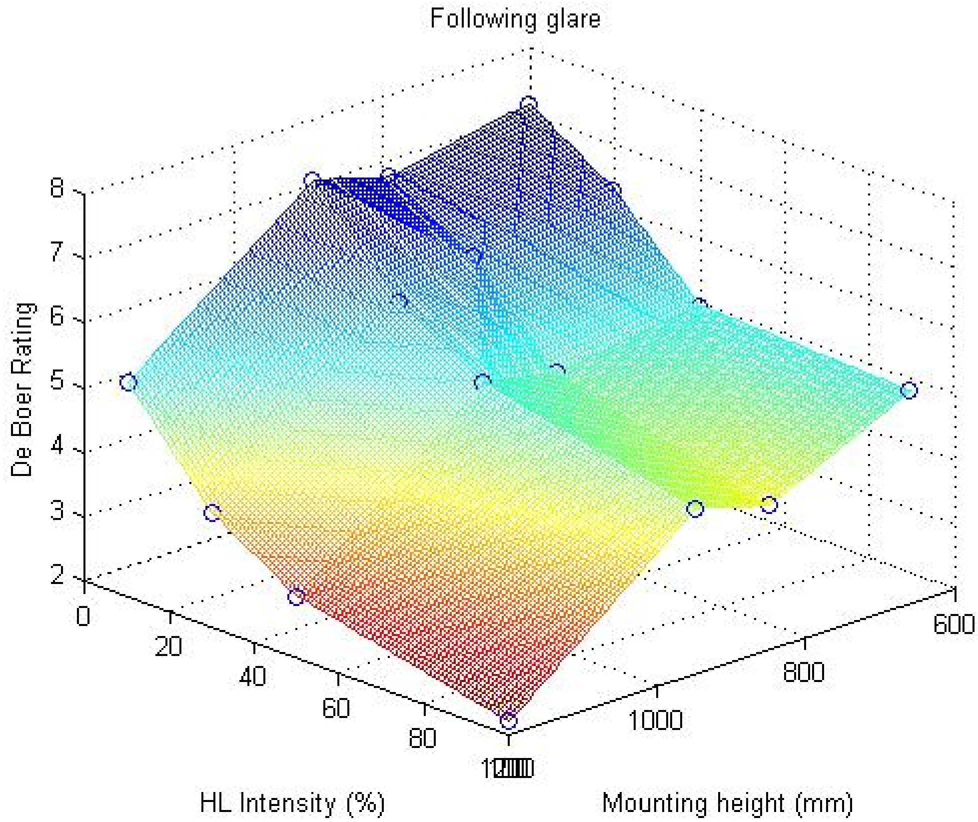
<u>For following glare:</u>

- Glare was increased (i.e., the De Boer rating was a lower number) as mounting height and luminous intensity of headlamps increased. At the mounting height of 1,120 mm, headlamps caused ratings of discomfort on the De Boer scale to be significantly lower (by 2 points) than the other three mounting heights, indicating greater discomfort.
- For the mounting heights of 660 mm, any headlamp luminous intensities were acceptable without a reduction. For the mounting heights of 850 and 870 mm, the glare was unacceptable at 100-percent intensity.
- For the mounting height of 1,120 mm, glare was acceptable only when the luminous intensity was 10 percent of its initial intensity.
- There was little difference in glare among the 660 mm, 850 mm, and 870 mm mounting heights.

The differences in glare among the four mounting heights was smaller for the oncoming headlamp position than the following headlamp position. For following glare in particular, headlamps at the mounting height of 1,120 mm appeared much more glaring than those with the other three mounting heights.



(a) Oncoming glare



(b) Following glare

Figure 3. Results of oncoming and following glare for all 20 subjects.
(All mounting heights were measured to the lamp center. See Table 7 for details.)

To confirm the above-described tendencies, a three-way analysis of variance (ANOVA) was conducted by using all 640 ratings (20 subjects × 2 positions × 4 mounting heights × 4 headlamp intensities). Appendix 3 summarizes the results of the ANOVA. The ANOVA results suggest that there are main effects of the mounting height ($p<0.001$) and headlamp intensity ($p<0.001$) on discomfort glare. There are significant interactions between the headlamp position and mounting height ($p<0.001$). This interaction implies that only at the highest mounting height (1,120 mm) do following headlamps cause much more serious glare than oncoming headlamps. The results of the ANOVA support all of the above-described findings.

2.7 Conclusions

For both oncoming and following glare, participants reported worse discomfort glare (i.e., gave a lower numerical rating on the De Boer scale) with increased mounting heights but the glare became more acceptable as the luminous intensity was decreased. For oncoming glare, glare ratings became acceptable if the headlamps were dimmed to less than 50 percent of the initial intensity for the two highest mounting heights (at 660 mm and 850 mm, glare ratings were acceptable at all intensities). For following glare, all luminous intensities were acceptable for a mounting height of 660 mm. However, for the mounting height of 1,120 mm, following glare was unacceptable only until the intensity was lower than 10 percent of its initial value. The effects of the mounting height of the following headlamps on discomfort glare can, in the worst case (highest mounting height), be larger than those of oncoming headlamps. However, this tendency could change depending on conditions including the distance between drivers and oncoming headlamps, and geometry and shape of vehicles.

In this study, a single reflector type headlamp system was used as the glare source, and the results would differ for different headlamps. This report focused on average levels of glare, and the trends associated with headlamp height and intensity level, rather than extreme cases.

3. Simulation study (1): Reaction times to peripheral targets

This simulation study did not involve an experiment using subjects but rather involved calculations using a published model developed by the LRC (Bullough & Van Derlofske, 2004). The objective of this simulation was to analyze how headlamp mounting heights affect drivers' peripheral target detection.

3.1. A model predicting drivers' reaction times

This analysis uses a model established by Bullough and Van Derlofske (2004). This model was developed to predict reaction times of drivers based on a series of off-axis detection studies (Van Derlofske et al., 2001, 2002; Bullough et al., 2003) with and without oncoming glare sources. Reaction time is defined as a period of time between when a target is presented and when a subject responds to the target. These previous studies used a small target, a 20 cm square target with a reflectance (ρ) of 0.2 or 0.4, located at a distance of 60 m from a driver at given eccentricity angles from the line of sight while the driver fixated on the central task. An oncoming glare source was located at an eccentricity of 5 degrees to the left from the central fixation point. Illuminance levels provided from the glare source were 0.2 lx, 1 lx, and 5 lx at the driver's eye position. Under the above described conditions, the model to identify reaction time (*RT*, in ms) without considering the oncoming glare source is expressed by the following formula:

$$RT = a \cdot E^{-0.33} + 400 \qquad (1)$$

$$a = b \cdot |\theta|^{c} + d \qquad (2)$$

where E=illuminance on target (in lx), θ = target eccentricity angle (in degrees), b=0.0065$\rho^{-2.64}$, c=3.52$\rho^{0.35}$, d=143$\rho^{-0.28}$. When an oncoming glare source is considered, an increment in reaction times (ΔRT, in ms) is expressed by Equation (3).

$$\Delta RT = 2 \cdot \left[\exp(m + n/(\theta + 20) + p \cdot \ln(\theta + 20))\right]^2 \cdot E_{gl}^{0.49} \qquad (3)$$

where m = -345(0.6-ρ), n = 2095(0.6-ρ), p = 82.3(0.6-ρ), ρ = the reflectance of targets, E_{gl} = glare illuminance at the eye (in lx). It was assumed that E_{gl} and θ in Equation (3) reflect the contributions of mounting heights to reaction times. Thus, mounting height is indirectly an independent variable of Equation (1).

This study reported here used Equations (1), (2), and (3) and analyzed whether drivers' reaction times for peripheral targets are affected by headlamp mounting heights.

3.2. Conditions

In this study, headlamp mounting heights and target locations were changed as independent variables and calculated reaction times were used as a dependent variable. This study used the same headlamp mounting height conditions and the same reflector type headlamp system (as the glare source) as those in the field study to compare results from both studies (see Sections 2.2. and 2.3.). Forward lighting, target, and headlamp beam and locations of the oncoming glare were maintained constant. Target reflectance was maintained constant as 6 percent—this is equivalent to that of typical winter clothes (Dewar & Olson, 2001). Figure 4 shows the layout of the car, oncoming glare headlamps, and targets used in this simulation. Conditions used in this study are listed below:

Independent variables:

- Mounting height of oncoming headlamps: 660, 850, 870, and 1,120 mm from the pavement to the center of lens
- Target location: 1, 5, and 10 degrees off-axis

Dependent variable:

- Reaction time

Fixed variables:

- Forward lighting: Reflector type with a mounting height of 660 mm
- Target
    - Size: 18 cm square
    - Reflectance: 6 %

- Oncoming glare
  - Headlamp: Reflector type
  - Location: 5 degrees off-axis on the left side

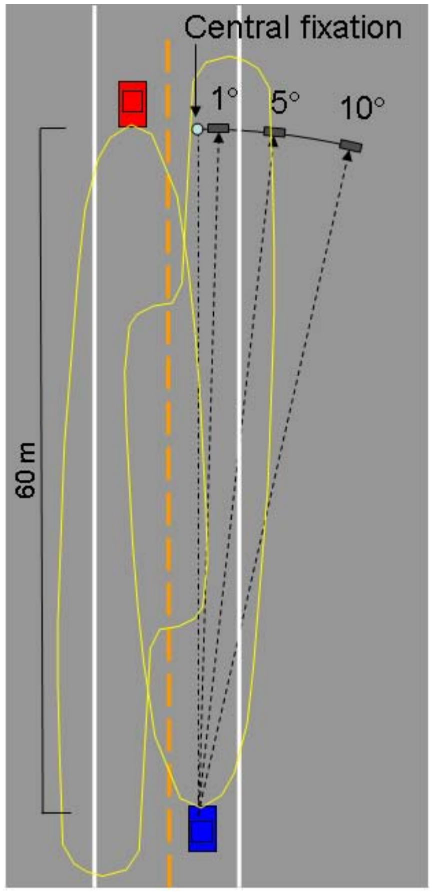


Figure 4. Layout of simulation scenario.

3.3. Procedure

Input variables to Equations (1), (2), and (3) are the eccentricity of the target, the target illuminance, the target reflectance, and the glare illuminance. Among them, target reflectance and target eccentricity were determined as described above (see Section 3.2.) The other input variable, glare illuminance, was calculated for the different headlamp mounting heights. This calculation used TarVIP, which is a Windows-based computer model developed in Matlab. It was developed by the Operator Performance Laboratory (OPL) of the University of Iowa (2004). TarVIP allows for evaluating visibility of targets (pedestrians, small targets, and pavement markings) by calculating approximate detection distances and legibility distances of traffic signs based on existing published models. Finally, reaction times were calculated by using Equations (1), (2), and (3) as a function of headlamp mounting height.

3.4. Results

Figure 5 shows the results of glare illuminance calculations. As the mounting height increases, the glare illuminance becomes higher. The difference in glare illuminance between 660 mm and 1,120 mm is approximately 0.14 lx, while the difference in glare illuminance between 850 mm and 870 mm is negligible.

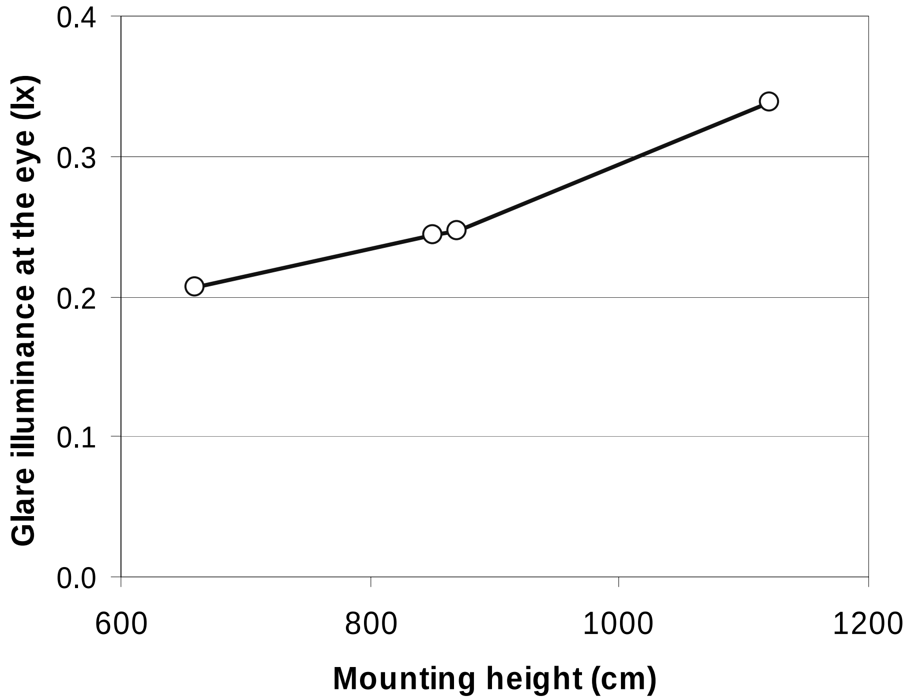


Figure 5. Glare illuminances at a driver's eye for different mounting heights Of oncoming headlamps for the simulation study.

By using these glare illuminances, reaction times in terms of noticing a given target were calculated. Figure 6 illustrates the results of the calculations, showing reaction times for different headlamp mounting heights for various target angular positions.

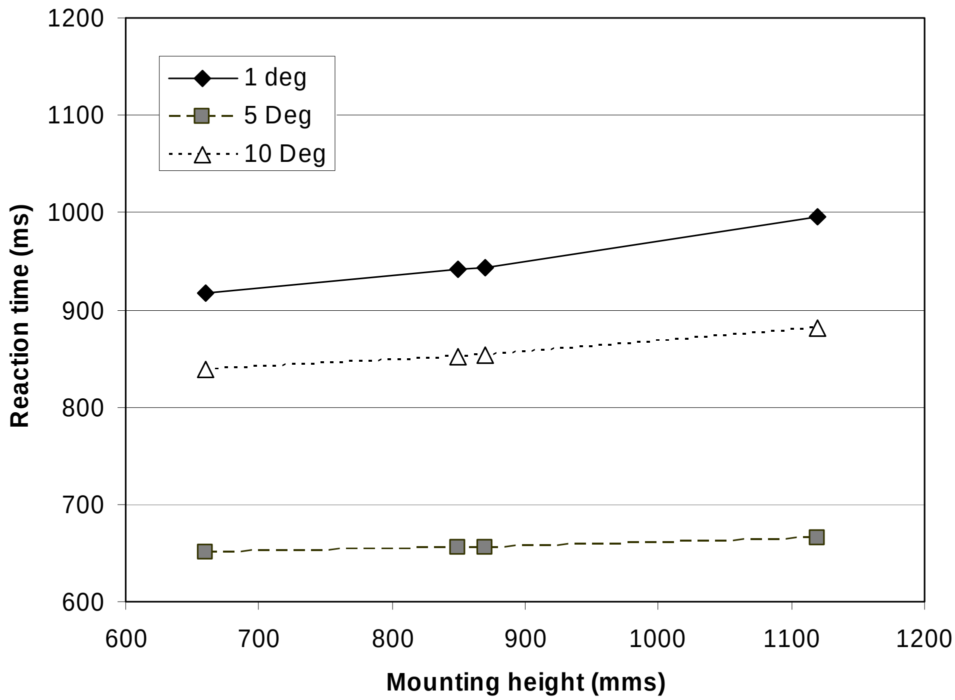


Figure 6. Reaction time as a function of headlamp mounting height for three target locations.

Figure 6 suggests:

- As headlamp mounting height increases, reaction times are increased. For example, the difference in reaction time between the mounting height of 1,120 mm and 660 mm is approximately 50 milliseconds for the target eccentricity of 10 degrees. However, the difference in reaction times between 850 mm and 870 mm is very small. As seen in Equation (1), such a tendency corresponds to a small difference in glare illuminance between these two heights. The same tendency is seen for the other target eccentricities.
- An intransitivity in reaction times as the target eccentricity increases from 1 to 5 to 10 degrees is observed in Figure 6. This is because it has been shown in previous research (Bullough et al., 2003) that reaction times in the presence of glare are most affected for targets closest to a glare source and for targets furthest from the line of sight, but for different reasons. The target located 1 degree off-axis had the largest veiling luminance superimposed over it in the retinal image (Fry, 1954). Targets furthest from the line of sight, on the other hand, are generally closer to visual threshold (Van Derlofske et al., 2001, 2002) and thus more susceptible to the contrast reduction produced by a glare source. The target at an eccentricity of 5 degrees is in a more optimal location, being less

off-axis than the 10-degree target and having a lower veiling luminance than the 1-degree target. If there were no glare present, the transitivity of reaction times would be present (Bullough et al., 2003).

4. Simulation study (2): Detection distance

By using an existing model of visibility (Adrian, 1989; based on Blackwell, 1946), this simulation calculated detection distances for given targets as a function of mounting height of oncoming headlamps. This simulation did not involve any experiment using subjects. These calculations also used the above described computer program, TarVIP.

4.1. Conditions

As independent variables, this simulation changed the mounting height of oncoming headlamps, types of forward headlamps, and target locations. This study used the same headlamp mounting height conditions and the same glare headlamp system as those in the field study to compare results from both studies (see Sections 2.2. and 2.3.) As a dependent variable, the detection distances of targets were calculated. Detailed conditions in this simulation are listed below. However, the variables in the list were examples. As forward headlamp systems, both high-intensity discharge and halogen headlamps systems were selected for different mounting heights from the TarVIP database of headlamp luminous intensity distributions. A single oncoming reflector headlamp was used to determine glare illuminance. This oncoming beam pattern was the same as the one in the field study.

Independent variables:

- Mounting height of oncoming headlamps: no glare, 660, 850, 870, and 1,120 mm
- Target location: left shoulder, center, right shoulder of the roadway
- Forward headlamp characteristics:

Label	Year	Type	Lamp	Mounting height (mm)
A	2002	Passenger	HID	660
B	2001	Passenger	HID	700
C	2001	SUV	HID	803
D	2002	SUV	HID	885
E	2000	Passenger	TH	660
F	2000	Passenger	TH	681
G	2001	SUV	TH	850
H	1999	Minivan	TH	870

Dependent variable:

- Detection distance based on Blackwell's (1946) visibility data

Fixed variables:

- Target:
  - Size: 18 cm square
  - Reflectance: 6 percent
- Oncoming glare
  - Headlamp: Reflector type, halogen
  - Location: 50 m away on the opponent lane (approximately 5 degree off-axis)
- Subject age: 65 years old

4.2. Procedure

The scenario of the calculations assumed that a car with a given headlamp type moves along a straight roadway. Figure 7 shows the layout of the simulation scenario. On the roadway, targets were located on the central line, left shoulder, and right shoulder. To identify a detection distance for a given condition, targets were placed every 1 m along a straight line. For each target, a required luminance at which a driver can detect the target was calculated. The input variables for this calculation included the size and reflectance of the target and ambient luminance surrounding the target. This calculation used Blackwell's data (1946) that defines the threshold luminance contrast at which 50 percent of drivers can detect a target with a given size and a given reflectance. The luminance contrast of each target in the array was examined. If the luminance contrast of the target is higher than the threshold contrast, the target is considered to be visible (detectable) to drivers (in a probability of 50%). The calculation started with a target at a distance of 70 m away from a driver on one of the three lines (left, center, and right), followed by the second farthest target at a distance of 69 m. The calculation was repeated until the first detectable target was found. The distance to the first detectable target from the driver was regarded as the detection distance along the line (left, center, or right).

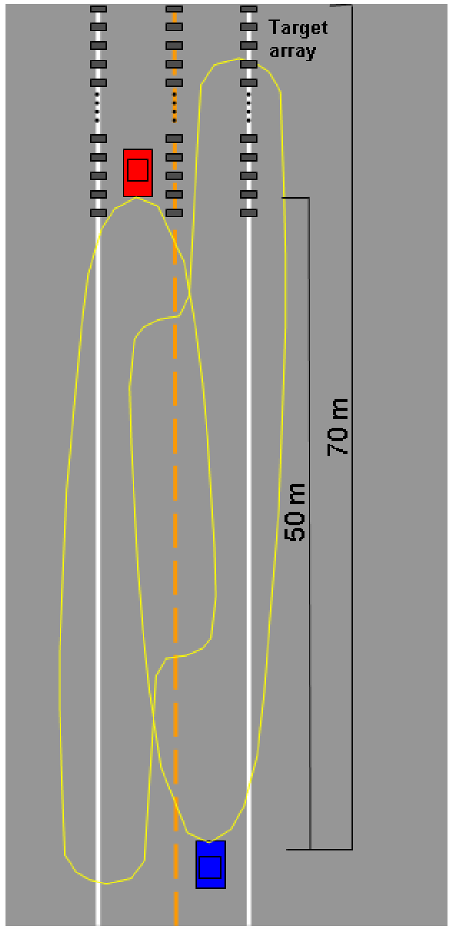
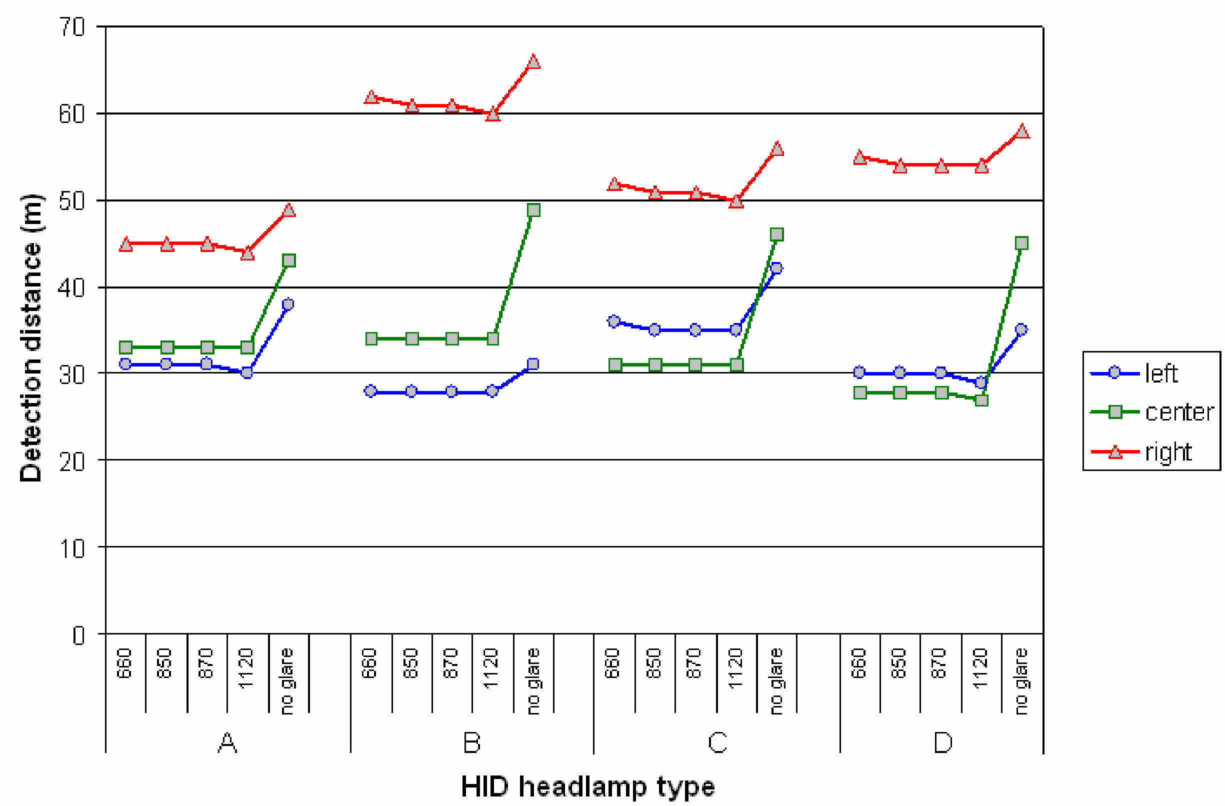


Figure 7. Layout of simulation scenario.

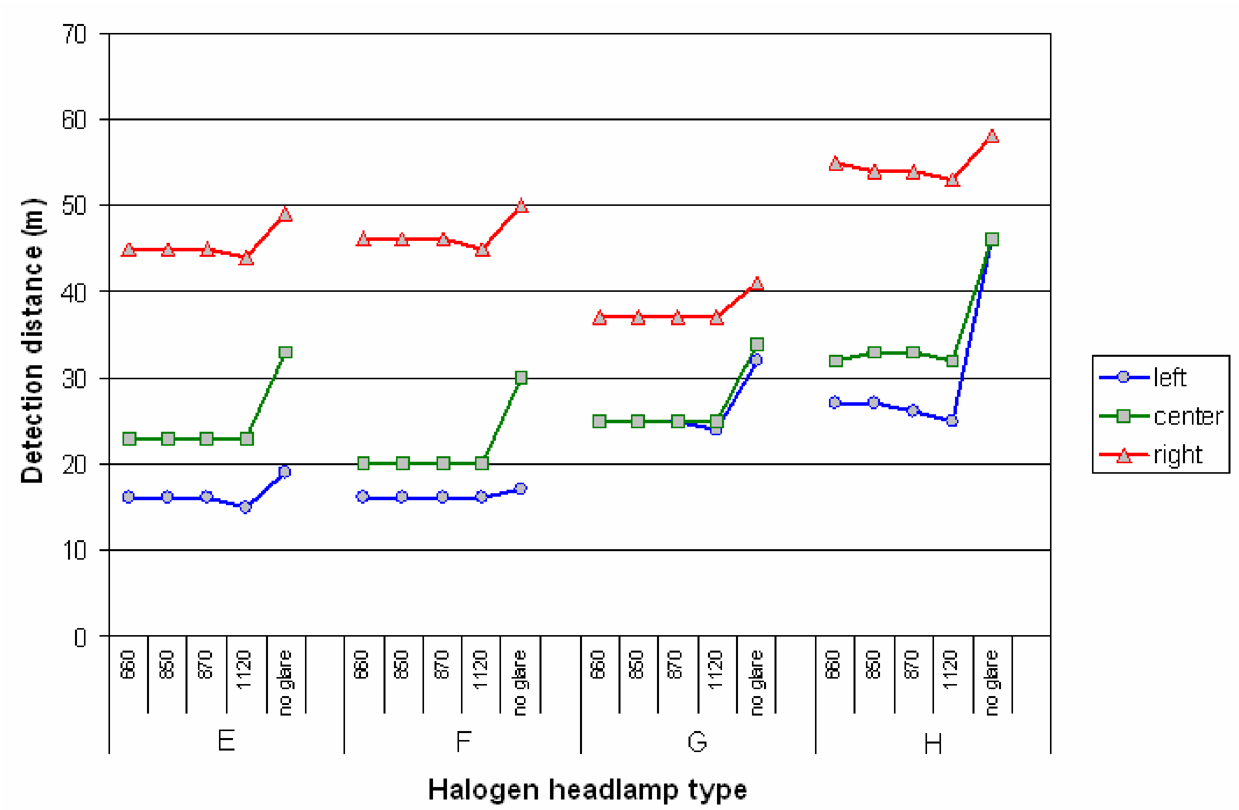
Targets were placed every 1 m along the central, left, and right line on the roadway.

4.3. Results

Figure 8 shows the detection distances for different mounting heights of glare headlamps, different vehicle types, and three target locations.



(a) HID headlamps



(b) Halogen headlamps

Figure 8. Detection distances as a function of oncoming Headlamp mounting height for different beam types.

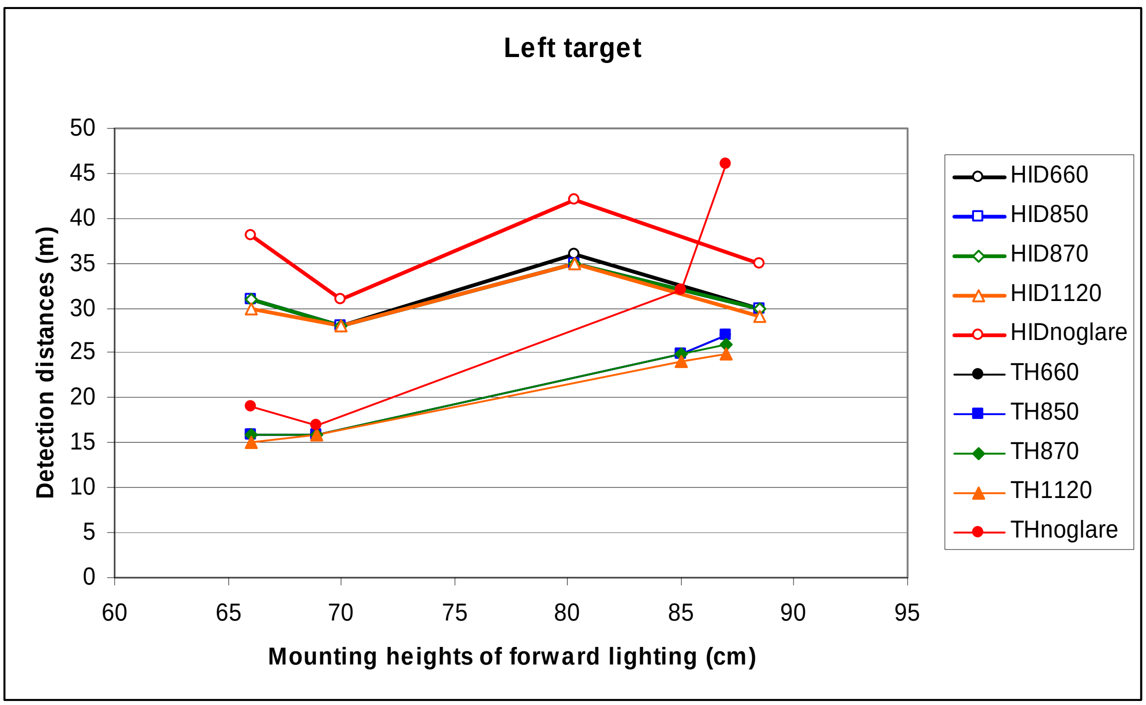
Figure 8 reveals the following general tendencies:

- Oncoming glare reduces detection distances (or impairs drivers' visibility).
- Targets on the right shoulder have the longest detection distances, followed by the central targets.
- Detection distances are reduced as the mounting height of the oncoming headlamps increase. However, the reduction in detection distances is small—the difference is a few meters in most cases. The results could be changed with more powerful headlamps. If a driver had more powerful forward headlamps, a higher mounting height could increase detection distances. In this case, the effects of the mounting height of the driver's forward headlamps on detection distance become more pronounced. However, if the oncoming headlamps were more powerful, the impact of the

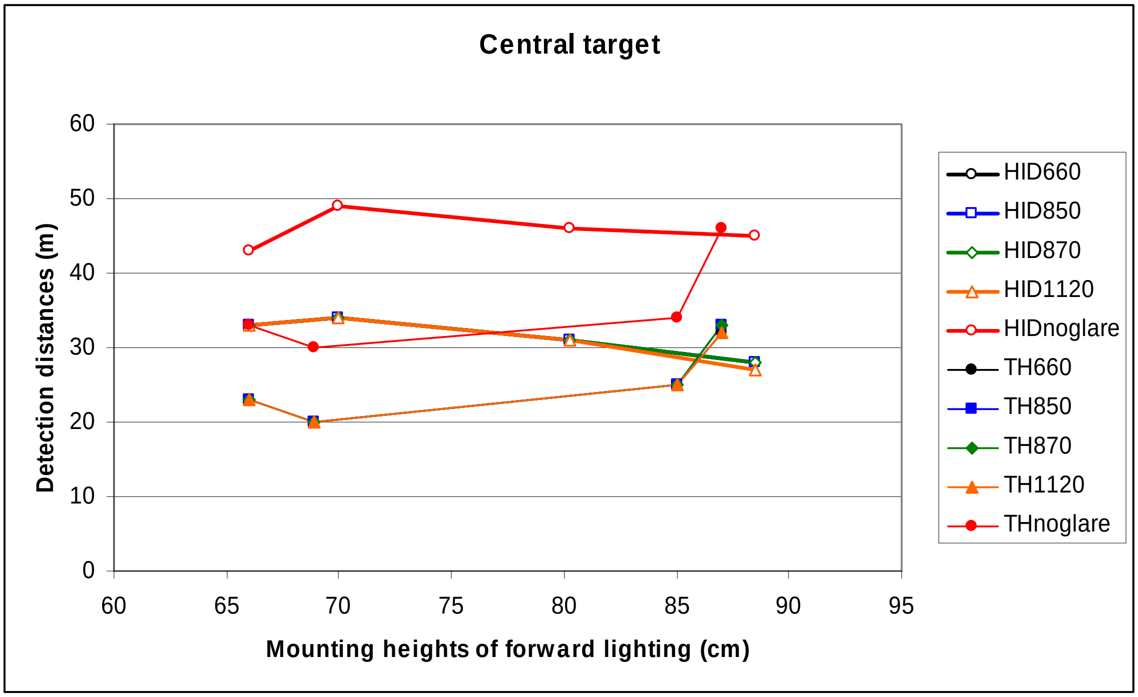
mounting height of the driver’s forward headlamps on detection distances could become less pronounced.

- In some cases, detection distances were improved as the mounting heights of forward headlamps increase. However, exceptions exist; those exceptions are discussed below.
- For the small sample of headlamps used in this study, detection distances with HID forward lighting tend to be longer than those with halogen forward lighting for similar headlamp mounting heights, e.g., comparisons between headlamps B (HID) and F (halogen) or between C (HID) and F (halogen).

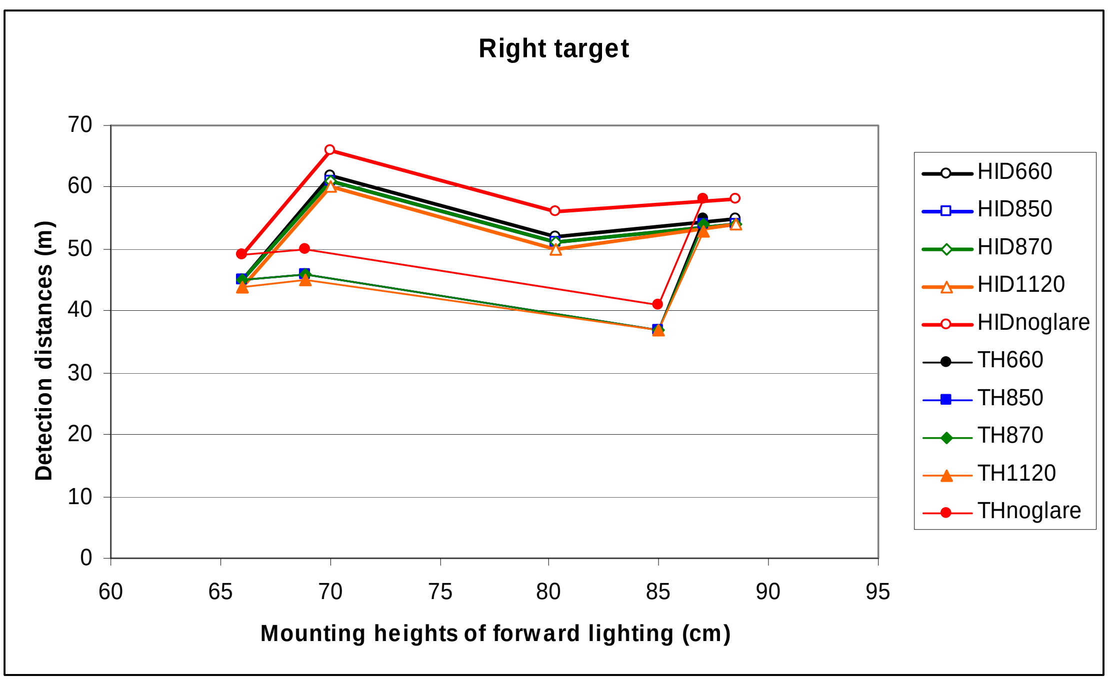
Figure 9 (a), (b), and (c), show the same results as Figure 8 in a different way by showing detection distances as a function of the mounting height of forward lighting. These graphs compare detection distances of three targets (located in the center and on the left and right road shoulders) from drivers in eight different types of cars (four with HID headlamps and four with halogen headlamps) for five mounting heights of oncoming headlamps, including a non-glare condition.



(a) Left targets



(b) Central targets



(c) Right targets

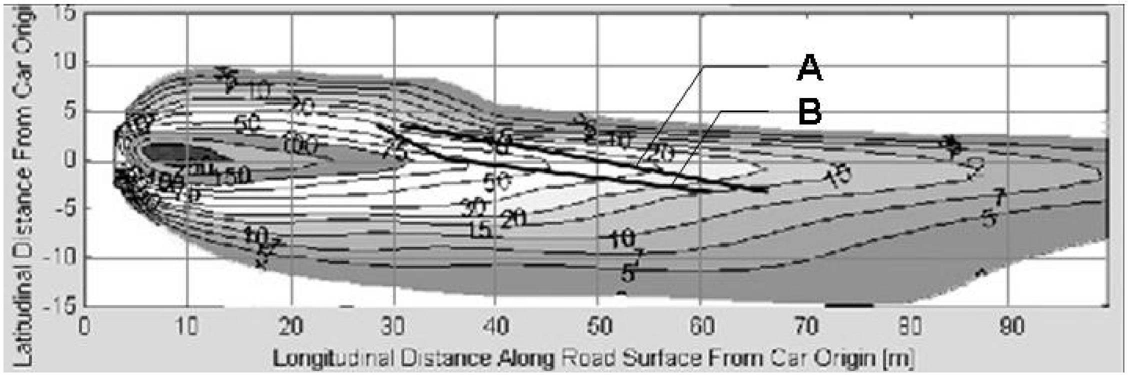
Figure 9. Detection distances of targets as a function of mounting height.

Although it was expected that forward lighting with a higher mounting height would provide better visibility (longer detection distances), Figure 9 suggests that this expectation is not always true. First, the HID headlamps used in this study generally have longer detection distances than the halogen headlamps, regardless of mounting heights. Even within a lamp type (halogen or HID), there are counterexamples to this trend, as seen in Figure 8. For example, HID headlamp system B has the longest detection distance for the right target, although the headlamps are mounted at a relatively low (700 mm) height. Halogen headlamp system G, which has a relatively high mounting height (850 mm), has the shortest detection distances for the right target. Clearly, individual differences among headlamps can influence forward visibility, even if they meet the same nominal performance specifications.

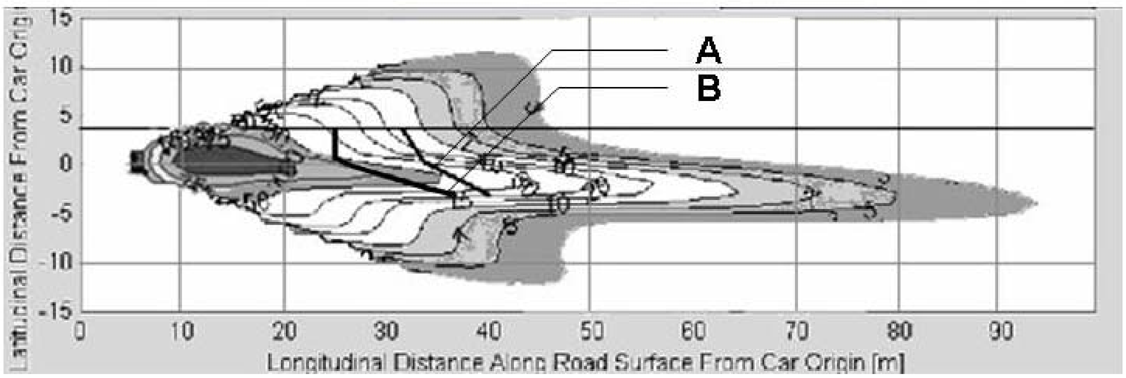
4.4. Comparison of detection distances and 3 lx iso-illuminance contour

An often used criterion to evaluate the performance of headlamps is the 3 lx iso-illuminance contour line, which can be drawn by connecting points on the roadway pavement which are illuminated at an illuminance of 3 lx by a given headlamp system. If a target is located farther than the 3 lx contour line, the target is considered to be invisible to the driver. However, whether a target is visible to a driver is determined not only by the illuminance on (or luminance of) a target, but also by the apparent size and contrast of the target. To verify the validity of this method, the 3 lx iso-illuminance contour line was compared with detection distances for each headlamp.

Figure 10 shows two examples of such comparisons. Results of other headlamps are listed in Appendix 4. Figure 10 and Appendix 4 show that in all cases, just-visible targets are located closer to the driver than the 3 lx iso-illuminance contour lines (when the illuminance on the target exceeds 3 lx). Therefore, the 3 lx iso-illuminance contour method is more optimistic than the detection distance calculations. However, the detection distances are subject to change depending on the size and reflectance of the targets. The use of a larger target with a higher reflectance will increase detection distances. For the verification of this method, further research is needed with various target conditions.



(a) HID headlamp system B



(b) Halogen headlamp system G

Figure 10. Comparisons between 3 lx contour lines and target detection distances. The outline of the distribution of each graph represents the 3 lx contour line. Lines A represent detection distances of targets (ρ=6%) without oncoming glare and Lines B represent detection distances of the same targets with oncoming glare.

5. Comparisons of results between the field and simulation studies

The field study evaluated discomfort glare from oncoming headlamps with different headlamp mounting heights, while the simulation study investigated the effects of mounting heights of oncoming headlamps on target detection through calculations. In both studies, the influences of oncoming headlamp glare (i.e., both discomfort and disability glare) become larger as the mounting height increases. However, when the mounting height reaches 1,120 mm, the increments in discomfort glare are much larger than those in disability glare.

To identify the reason why there were differences between the field study (discomfort glare) and the simulation study (disability glare), glare illuminances (i.e., illuminances at drivers' eyes) were compared between Table 2 (for the field study) and Figure 5 (for the simulation study). This comparison was conducted because glare illuminances primarily affect reaction times, as seen in Equation (1). The results of the comparison suggest that although the glare illuminances were increased as the mounting height increased in both data, the absolute values of glare illuminances measured in the field study were not matched with those in the simulation study.

To identify how the field study's glare illuminances influence the effects of mounting heights on reaction times, they were applied to Equation (1). Figure 11 shows the results of the calculations. Figure 11 suggests that there are larger effects of mounting height on reaction times with the field study glare illuminances than seen in Figure 6, e.g., approximately 0.6 second difference between the 660 mm and 1,120 mm mounting heights. This suggests that there could be differences in the actual light distribution produced by the reflector headlamp set used in the field study and the luminous intensity distribution used in the modeling calculations, possibly because of lens wear or other factors, which could include unevenness in the roadway surface where the field study was performed.

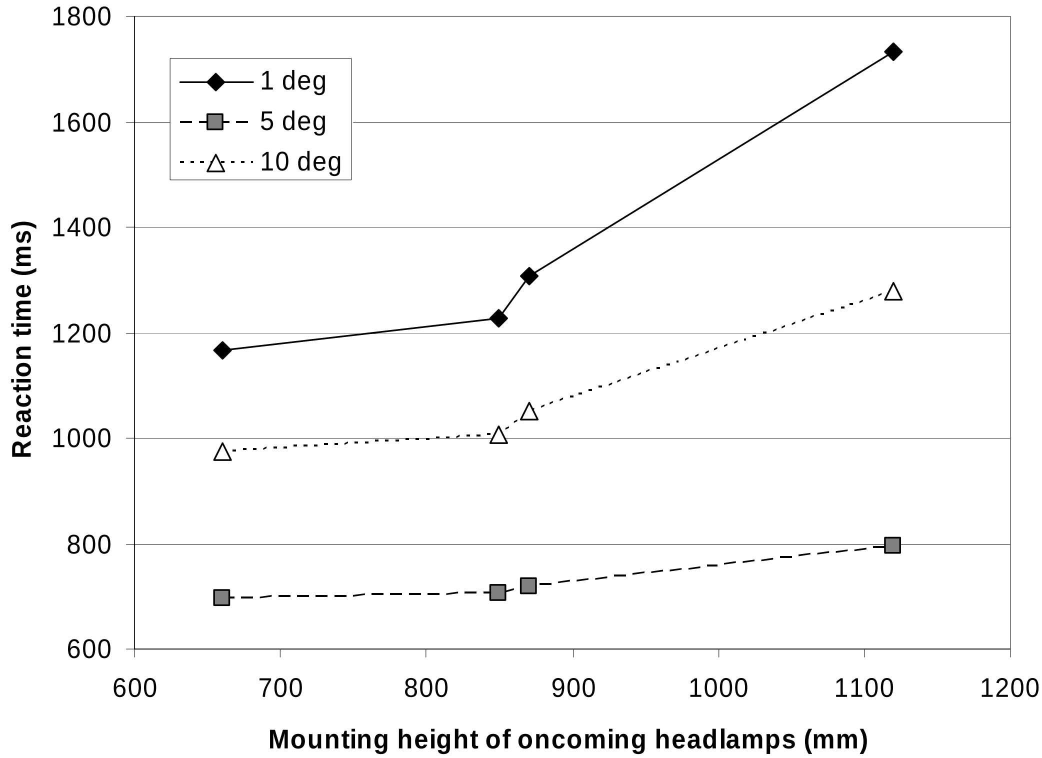


Figure 11. Glare illuminances at a driver's eye for different mounting heights Of oncoming headlamps for the simulation study (detection distance)

6. General conclusions on influence of mounting height

The first goal of this study examined the effects of headlamp mounting height on disability and discomfort glare. The mounting height of oncoming headlamps affects both disability glare and discomfort glare. The results indicated that a common tendency is that as the mounting height increases, glare is also increased. The increase in glare results in reduction of visual performance, increased reaction times, and decreased detection distances. The effects of mounting height on discomfort glare appear stronger than those on disability glare. However, further verification is required because as described above, the glare illuminances measured in the field study were not predicted well using the luminous intensity distribution provided for the headlamp set used in the simulation study. The mounting height of following headlamps also affects discomfort glare, and these effects can, in the worst case (highest mounting height), be larger than those of oncoming headlamps.

The second goal of this study was to understand how different forward (driving) headlamp types with different mounting heights affect target detection and visibility distance at different levels of oncoming glare headlamps. Although it was expected that forward lighting with a higher mounting height may in general result in better visibility (longer detection distances), this study suggested that expectation is not always true. For instance, the lowest forward mounting height is not always shortest in detection distance among HID headlamps. HID headlamps with a low mounting height sometimes provided a longer detection distance than others with higher mounting heights. This implies that if headlamp distribution is optimized, it is possible to improve detection distances, regardless of mounting height. Detection distance is dependent on a number of factors including mounting and beam distribution. While for the same headlamp higher mounting heights may result in longer detection distances, for different headlamps with different beam distributions this study did not find that in general higher mounting heights led to longer detection distances. However, one clear general tendency among the headlamps used in this study is that the HID headlamps studied allow for longer detection distances than halogen headlamps studied.

The results of comparisons between the 3 lx iso-illuminance contour method and detection distances suggest that the 3 lx iso-illuminance contour method is more optimistic than the detection distance calculations regarding the distance at which targets can be seen. However, the detection distances are subject to change depending on the size and reflectance of the targets; for instance, the use of a larger target with a higher reflectance will increase detection distances. For the verification of this method, further research is needed with various target conditions.

This study attempted to use three metrics to evaluate the effect of headlamp mounting height on glare impacts. These were subjective discomfort glare evaluation, disability glare on peripheral target detection, and disability glare on central target detection. The results suggest that all metrics were sensitive to the mounting height variable. Among them, the subjective discomfort glare evaluation was the most sensitive metric to evaluate the effect of mounting heights within the conditions used in this study.

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Appendix 1: Comparison of glare illuminances between the measurements and the results of calculations for different misaiming angles

This study followed the standard aiming method and aimed the headlamps before conducting glare evaluations for each subject group. However, the measured illuminances at the drivers' eye caused by the test headlamps were higher than those caused by the same headlamps with a normal aiming angle are supposed to be. To identify at what angle the headlamps were misaimed in the experiment, glare illuminances at a driver's eyes caused by oncoming headlamps were calculated for different misaiming angles. These calculations used a luminous intensity distribution dataset of the same type of headlamps as the test headlamps was the following calculations were ed headlamps the calculations suggested. Figure A-1 shows the results of the glare illuminance calculations compared to the measured glare illuminances. Figure A-1 suggests that the misaiming angles of the test headlamps are equivalent to 0.8 degrees for the mounting heights of 660 mm and 850 mm, 1 degree for the mounting height of 870 mm, and 1.3 degrees for the mounting height of 1,120 mm. In other words, the misaiming angle appeared to increase as the mounting height increased. However, the test headlamps were appropriately aimed for each condition. This suggests that the pavement surface of the test site was not flat and was bent in the center between the driver's car and the oncoming headlamps.

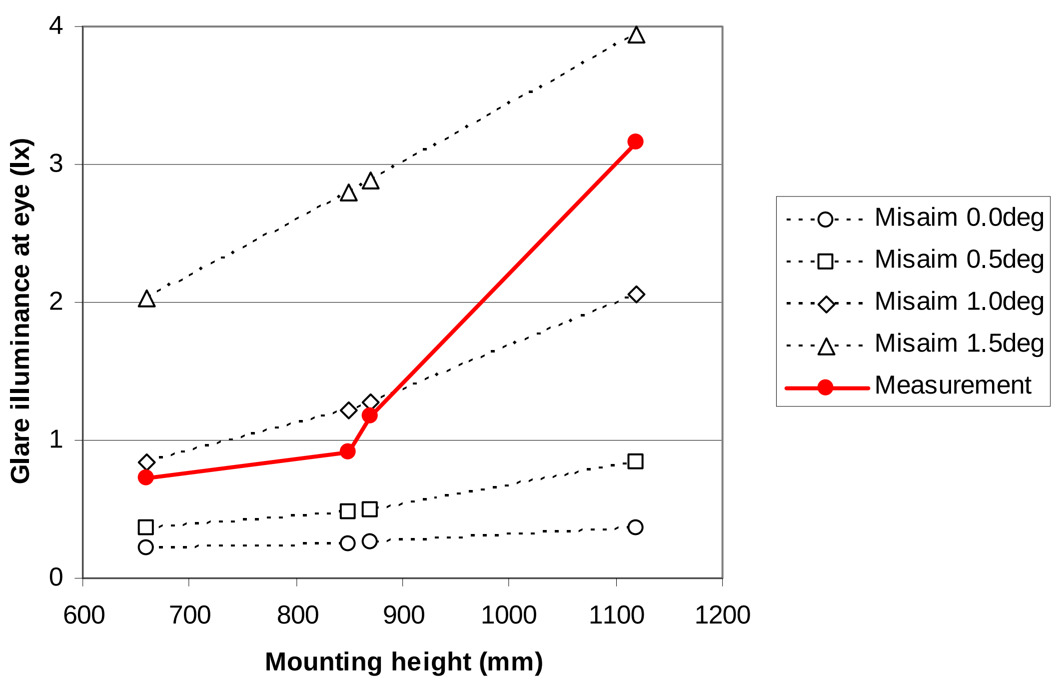


Figure A-1: Comparisons of glare illuminances between the measurements and the calculation results for different misaiming angles.

Appendix 2: Aiming technique

To aim the test headlamps appropriately, we used a three foot (914 mm) × five foot (1524 mm) wood board as an aiming screen and held the aiming screen so the height of the bottom of the screen could be two feet from the ground. Prior to the experiment, we first turned on the headlamps and held the screen close to the headlamps. On the aiming screen, headlamp beam patterns provided by both left and right headlamps were projected. Second, we covered one headlamp (e.g., the left one) with a piece of black fabric and identified the glare cutoff line of the other headlamp on the aiming screen. Third, we marked a V-shape line on the projected glare cutoff line. We repeated this procedure for the four mounting height and the other side of the headlamp. We had eight marks on the aiming screen for four mounting heights and for both left and right headlamps. Those marks on the aiming screen were used for headlamp aiming throughout the experiment.

To aim the test headlamps consistently during the experiment, we repeated the following aiming procedure whenever we changed the headlamp conditions. The aiming procedure was to first set the aiming board at a distance of 25 feet (7.5 m) from the headlamps (we marked the position of the screen on the pavement beforehand). Second, we covered one headlamp with a piece of black fabric and aligned the other headlamp until the projected cutoff line matched with the marked V-shape line. Then, we repeated this procedure for the other headlamp.

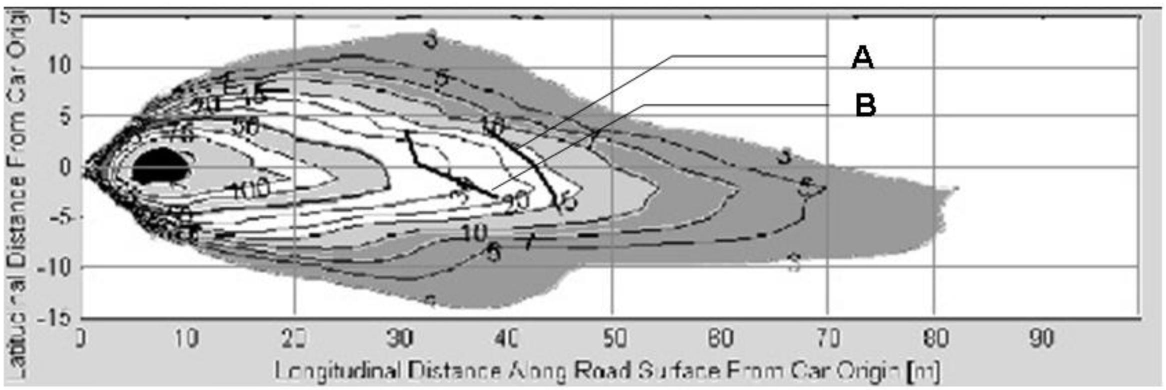
Appendix 3: Results of ANOVA in the field study

Source	SS	df	MS	F	p-value
Intercept	18,644.918	1	18,644.918	2,520.865	0.000
position	0.756	1	0.756	0.536	0.464
MH	346.673	3	115.558	81.931	0.000
HL	852.339	3	284.113	201.438	0.000
subject	150.768	20	7.538	5.345	0.000
position * MH	84.027	3	28.009	19.859	0.000
position * HL	2.351	3	0.784	0.556	0.644
MH * HL	10.546	9	1.172	0.831	0.588
position * MH * HL	9.924	9	1.103	0.782	0.633

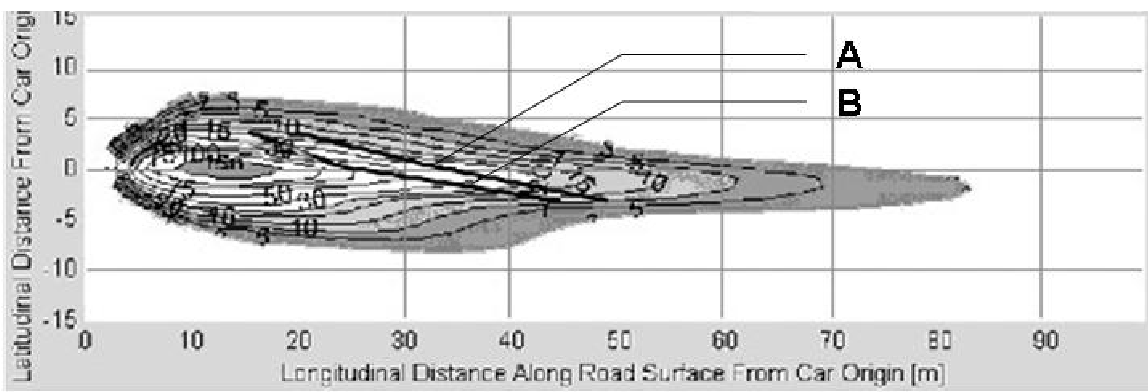
MH: mounting height, HL: headlamp intensity

Appendix 4: Comparisons between 3 lx contour lines and target detection distances for the rest of headlamps

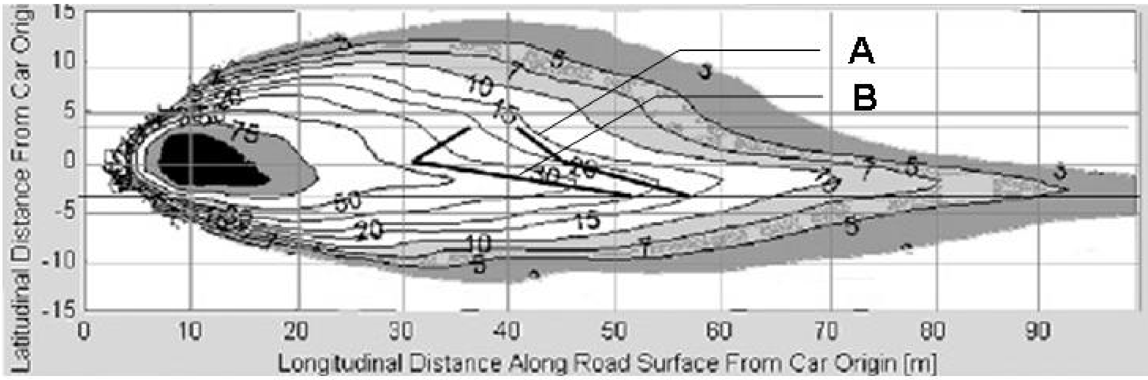
Comparisons between 3 lx iso-illuminance contours with detection distances. The outline of the distribution of each graph represents the 3 lx contour line. Lines A represent detection distances of targets (ρ=6%) without oncoming glare and Lines B represent detection distances of the same targets with oncoming glare.



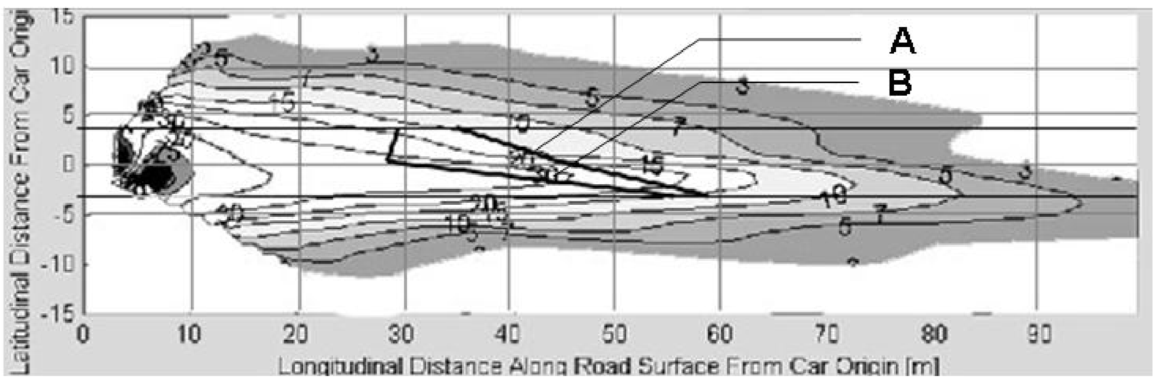
(a) HID headlamp system A



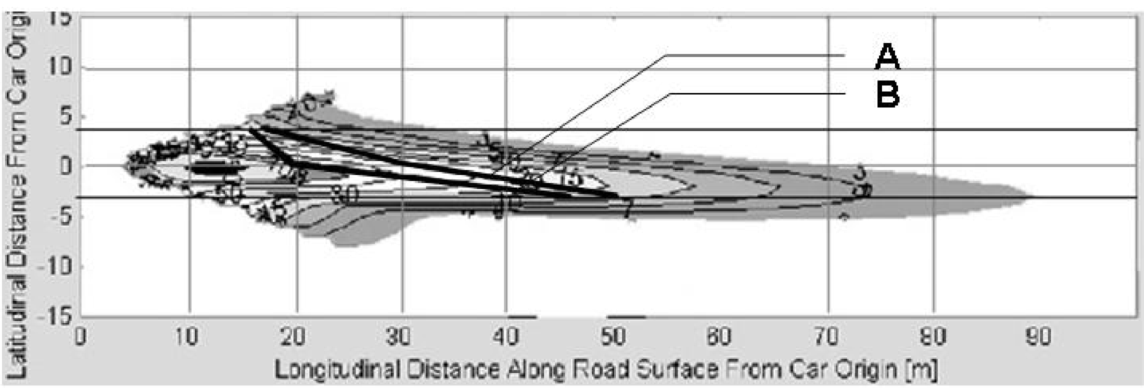
(b) Halogen headlamp system E



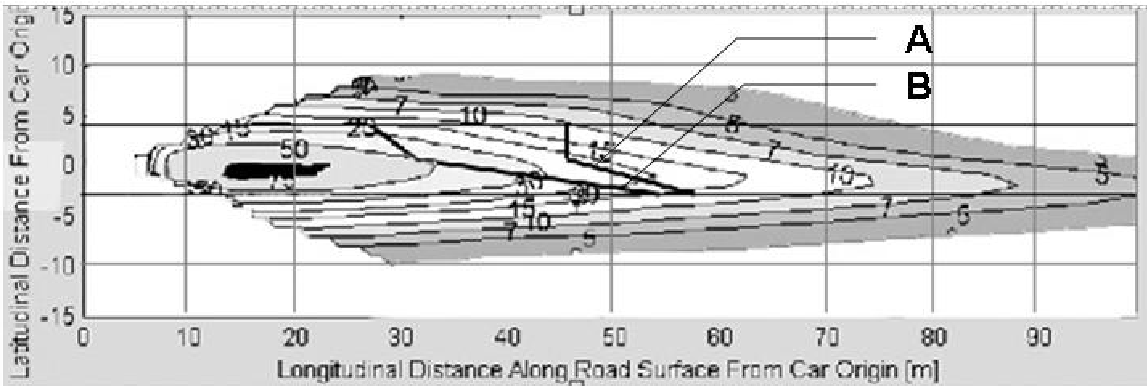
(c) HID headlamp system C



(d) HID headlamp system D



(e) Halogen headlamp system F



(f) Halogen headlamp system H

DOT HS 810 947
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