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16. Abstract

This nighttime field study addressed the relative visibility of retroreflective pavement markings from trucks and cars. To do that, both low-beam headlamp mounting height and observer eye height were varied. The task involved detecting the presence of a strip of retroreflective pavement marking that was moved towards a stationary observer. The main finding is that headlamp mounting height had a statistically significant effect on detection distance. Increasing the mounting height from the lowest tested level (0.6 m) to the highest tested level (1.2 m) resulted in a 19% increase in detection distance. On the other hand, there was no effect of eye height over the range tested (1.2 m to 2.4 m). Because truck headlamps are generally mounted higher than car headlamps, the present findings imply that retroreflective pavement markings are more visible (and thus more effective) for truck drivers than car drivers. Furthermore, these findings are in support of higher headlamp mounting height for all types of vehicles. However, higher headlamp mounting heights lead to more glare for both oncoming drivers and preceding drivers via rearview mirrors. Consequently, determining an optimal headlamp mounting height would require a complex weighing of both visibility and glare considerations.

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CONTENTS

INTRODUCTION

Retroreflective materials are used to enhance the nighttime visibility of objects, such as traffic signs, pavement markings, pedestrians, and construction-area barriers. There are several different types of retroreflective materials, with the two main types being spherical beads and prisms. All retroreflective materials return most of the incident illumination back in the direction of the light source (e.g., a headlamp).

There are two important differences between the situations of truck drivers and car drivers that likely result in differential effectiveness of retroreflective markings for these two types of drivers. These differences involve higher seated eye position for truck drivers and higher headlamp mounting height for trucks. In the U.S., the average seated eye heights are 1.42 m for drivers in light trucks and vans and 1.11 m for drivers in cars, while the corresponding average headlamp mounting heights are 0.83 m and 0.62 m (Sivak et al., 1996). Analogous data for U.S. heavy trucks are not available; the U.K. data from Cobb (1989) indicate that the average seated eye height for heavy trucks is 2.33 m and the average headlamp mounting height is 0.85 m.

The differences in driver eye height and headlamp mounting height, in turn, influence four factors that affect the effectiveness of retroreflective markings. These factors include observation angle (the angle between the light source, the retroreflective material, and the driver's eyes), entrance angle (the angle between the normal to the material and the direction of illumination), reach of the headlamp, and projected area of the markings.

The first factor, observation angle, is relevant because the amount of reflected light decreases with an increase in observation angle. For car drivers the observation angles are relatively small. However, the observation angles are generally greater for truck drivers because of their increased seated eye height. (The mounting height of truck headlamps is also higher, but by less than the increase in eye height, and so the net effect is that the vertical separation of eyes and headlamps is greater for trucks.) Consequently, this factor would lead to less light being reflected back to the eyes of a truck driver than to the eyes of a car driver.

The second important factor involves entrance angle. As the headlamp mounting height increases, the entrance angle for a pavement marking (at a given distance) decreases, with a resulting increase in reflected illumination. Thus, because truck headlamps are generally mounted higher than those of cars, the entrance-angle consideration would lead to a prediction of more reflected light in the case of trucks than cars.

The third relevant factor involves the "reach" of low beam headlamps. Because the headlamps are normally aimed parallel to the ground regardless of their mounting height, the higher mounting height of trucks results in more light reaching distant pavement markings. The longer reach of truck low beam headlamps, in turn, would result in more light reaching the eyes of the observer from a retroreflective pavement marking at long distances.

The fourth factor, projected area of a pavement marking, is related to the higher seated eye position of truck drivers. Eye height influences the projected area subtended by a pavement marking. As the eye height increases, so does the projected area, thus possibly benefiting the truck driver.

In summary, three of the four factors considered (entrance angle, headlamp reach, and projected area) suggest that the visibility of pavement markings should be better for truck drivers. Only one factor (observation angle) is in favor of car drivers.

The present study was designed to investigate experimentally the relative visibility of retroreflective markings for truck drivers and car drivers.[1] This was a field study, in which a stationary observer indicated when a pavement marking that was moved towards the observer became visible. The primary independent variables were headlamp mounting height and observer eye height. Also varied independently was the width of the pavement marking. This allowed another manipulation of the projected area of the marking (in addition to the manipulation involved in changing the eye height). The main goal was to provide a general indication of the composite effect of the underlying factors (observation angle, entrance angle, headlamp reach, and projected area), and no attempt was made to experimentally isolate the effects of the individual underlying factors. However, the likely contributions of the underlying factors to the effects of headlamp mounting height and eye height will be discussed.

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[1] For a general review of issues related to retroreflective markings, see Rumar and Marsh (1998). For an analytical approach to the influence of truck driver eye position on the effectiveness of retroreflective traffic signs, see Sivak, Flannagan, and Gellatly (1991).

METHOD

Task

The task was to indicate when a pavement marking that was moved toward the subject was detected.

Stimuli

The target material was white, heat-fused, durable, preformed pavement marking incorporating preapplied beads. The coefficient of retroreflected luminance of the material, at an observation angle of 1.5° and an entrance angle of 86.5°, was 300 mcd/m^2/lx.

Independent variables

- headlamp mounting height (0.6, 0.8, and 1.2 m)
- observer eye height (1.2, 1.4, and 2.4 m)
- size of the target (0.1 m wide by 3 m long, and 0.2 m wide by 3 m long)

Headlamp mounting height was manipulated by positioning the same headlamp in one of three fixed positions on a specially prepared, rigid stand. The aim of the headlamp was controlled by means of a laser permanently attached to the headlamp. The aim was verified at the beginning and end of each experimental session.

Observer eye height was varied by having the subject either sit on a chair positioned on the ground (1.2 m when sitting slouched, and 1.4 m when sitting straight), or stand on the back of a pick-up truck (2.4 m). The precise eye height was controlled by having the subject view the scene through narrow (3 cm by 15 cm) openings in a large black panel.

The size of the target was manipulated by using either a single strip of a material that was 0.1 m wide by 3 m long, or two such strips mounted side-by-side, yielding a width of 0.2 m.

All nine combinations of the three headlamp mounting heights and the three eye heights were tested. Three of these combinations were analogous to typical vehicles: a car (0.6 m/1.2 m), a light truck (0.8 m/1.4 m), and a heavy truck (0.8 m/2.4 m).

Dependent variable

The dependent variable was the distance at which the subject indicated that the marking was detected.

Test site

The study was conducted at the entrance drive to a local golf course. The segment of the roadway that was used is straight and relatively level, with no fixed lighting in the vicinity, and is about 175 m long. The roadway is relatively narrow (4.7 m wide) and tree lined. The surface is asphalt with no permanent pavement markings. There was no traffic on the roadway during the study.

Subjects

Four paid subjects participated. Because there was no reason to expect that the effect of headlamp mounting height and eye height would depend on subject sex and age, a relatively homogenous subject sample was selected. All subjects were males and were between 23 and 27 years of age (with a mean age of 25).

Procedure

A schematic diagram of the experimental setup is shown in Figure 1. The subjects were run individually. Subjects were instructed to look down at their laps between trials, and to look up only when the next trial started. On each trial, the target pavement marking was moved continuously towards the subject. At the start of each trial the subjects were instructed to look up, and indicate when the pavement marking was detected.

The pavement marking strip was attached to a cord that was 150 m long. The cord, in turn, was pulled by means of two small, battery-operated motors back and forth onto two reels. Both reels were out of the direct view of the subject: one reel was slightly behind the subject, and the other reel was 150 m ahead. On each trial, the cord was rolled onto the reel that was behind the subject; between the trials, the cord was rolled back onto the other reel. This arrangement allowed the pavement marking to be moved in a straight line at a constant speed of approximately 0.7 m/s, while keeping it flat on the ground.

To measure the detection distances, the cord that pulled the pavement marking included small marks every 5 m. (These marks were not visible from the subject's position.) To measure distances to the nearest centimeter (within the 5-m steps provided by the small marks on the cord), a tape measure was placed on the ground parallel to the cord near the reel that was behind the subject.

A single low-beam headlamp was used to illuminate the scene. The lamp was manufactured for a popular, late-model pick-up truck. An isocandela diagram of the light

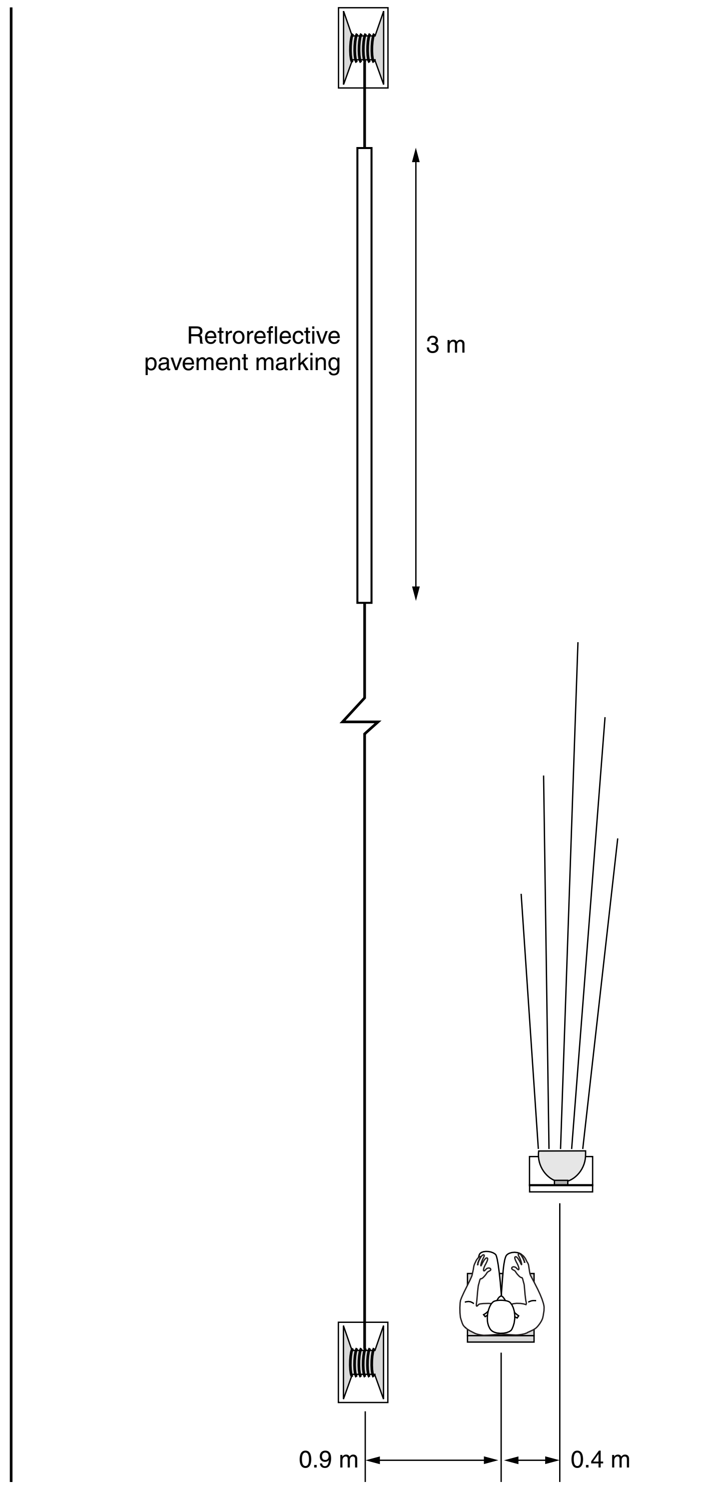

Figure 1. A schematic diagram of the experimental setup.

output of this lamp is shown in Figure 2. The lamp was positioned 0.4 m to the right and 1 m in front of the subject. (Because we used only one lamp to illuminate the marking and no glare illumination, the absolute detection distances are not meaningful.)

The subject was positioned 0.9 m to the right of the path along which the pavement marking was moved. Thus, from the point of view of the subject, the pavement marking approximated a section of a road centerline.

Design

Each session consisted of 20 experimental trials (2 replications of each of the 9 combinations of headlamp mounting height and eye height for the narrower pavement marking, and 2 replications for the wider pavement marking at the 0.8 m headlamp mounting height and the 1.4 m eye height). The 18 trials for the narrower pavement marking were partially blocked by headlamp mounting height. This involved changing headlamp mounting height after every three trials—one for each of the three eye heights. The orders of headlamp mounting heights and eye heights were varied systematically. The two trials for the wider pavement marking were given in the middle of each experimental session (i.e., after the first nine trials with the narrower pavement marking).

In addition to the 20 experimental trials, there was one catch trial with no pavement marking present. (The subjects were told that there would be at least one trial with no pavement marking present.) One or two practice trials (as needed) were given prior to running the actual experiment. The study was performed on nights with no precipitation. Each session started at least one hour after sunset, and lasted about 1.5 hours.

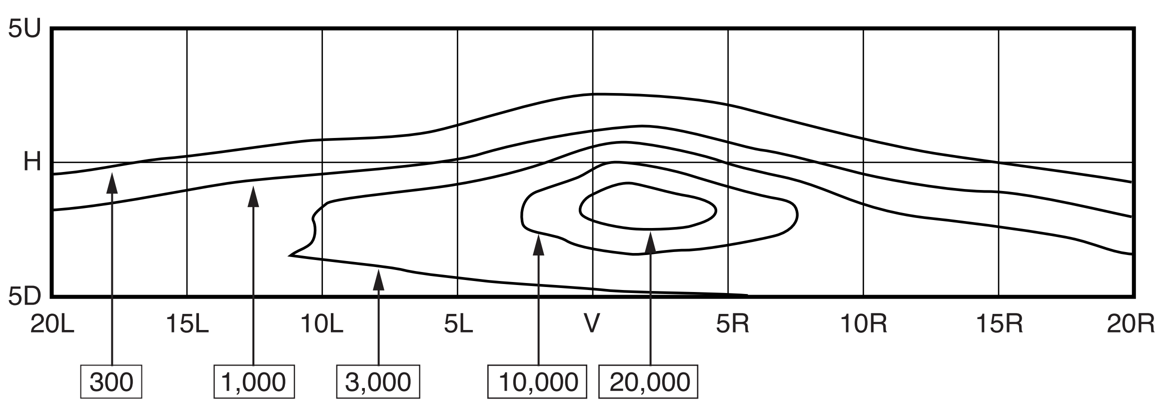

Figure 2. Isocandela diagram of the light output of the lamp used in the study.

RESULTS

An analysis of variance was performed on the detection distances for the narrower (0.1 m by 3 m) pavement marking. The independent variables were headlamp mounting height (0.6, 0.8, and 1.2 m), driver eye height (1.2, 1.4, and 2.4 m), and replication (first and second).

The main result of this analysis is that the effect of headlamp mounting height was statistically significant, $F(2,6) = 11.3$, $p = .04$. (For this and all other tests involving within-subject independent variables with more than two levels, the Greenhouse-Geiser adjustment was used.) As the mounting height increased, so did the detection distance (see Table 1 and Figure 3). For example, doubling the mounting height from 0.6 m to 1.2 m increased the detection distance from 88.6 m to 105.4 m, an increase of 19%. None of the other effects were statistically significant, including the effect of eye height, $F(2, 6) = 2.6$, $p = .20$, and mounting height by eye height interaction, $F(4, 12) < 1$.

The wider (0.2 m by 3 m) pavement marking was tested only with the headlamp mounting height of 0.8 m and the eye height of 1.4 m. The mean detection distance was 104.7 m, compared to 93.8 m for the narrower (0.1 m by 3 m) pavement marking under the same conditions, for an increase of 12%. A paired t-test showed that this difference was statistically significant, $t(3) = 3.97$, $p < .05$.

Table 1
The effects of headlamp mounting height and eye height on detection distance for the narrower (0.1 m by 3 m) pavement marking. All entries are in meters.

Eye height	Headlamp mounting height			Mean
	0.6	0.8	1.2	
1.2	87.5	92.8	103.8	94.7
1.4	89.5	93.8	106.6	96.6
2.4	88.7	93.4	105.9	96.1
Mean	88.6	93.4	105.4	95.8

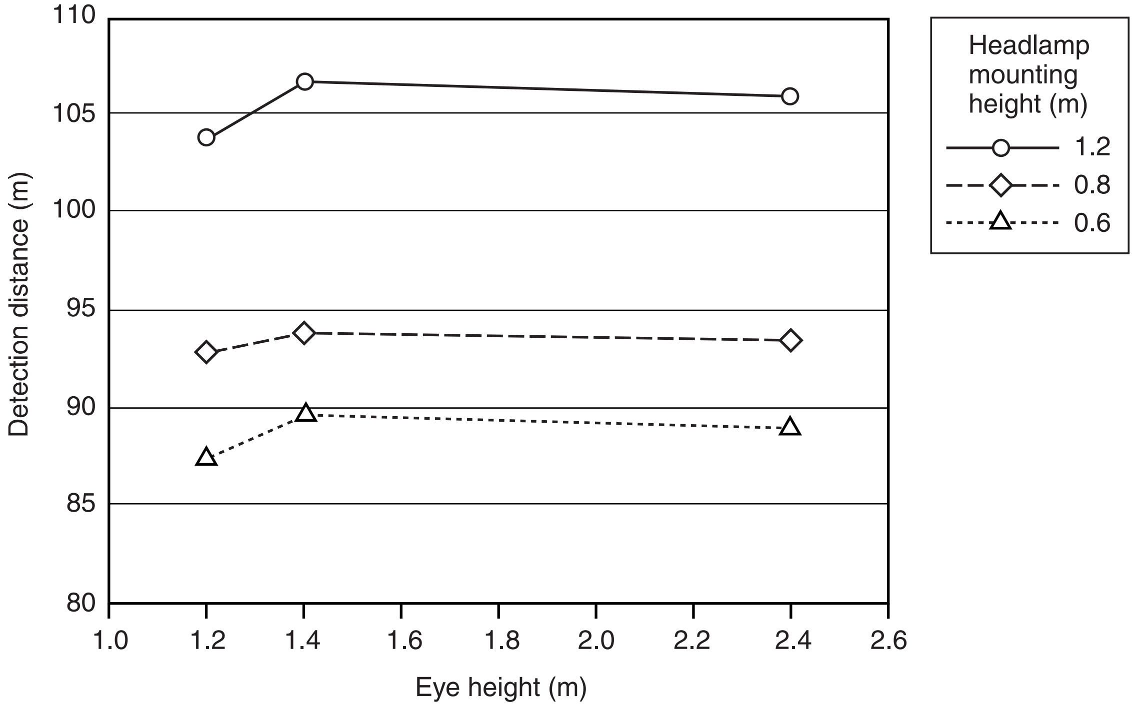

Figure 3. The effects of headlamp mounting height and eye height on detection distance for the narrower (0.1 m by 3 m) pavement marking.

DISCUSSION

Trucks versus cars: headlamp mounting height and driver eye height

The main goal of this study was to provide evidence concerning the relative visibility of retroreflective pavement markings for truck drivers and car drivers, through manipulations of headlamp mounting height and observer eye height. The results indicate that the effect of headlamp mounting height was statistically significant, with higher mounting positions leading to longer visibility distances. On the other hand, the effect of observer eye height was not significant. Because truck headlamps are generally mounted higher than car headlamps, the main implication of this study is that retroreflective pavement markings are more visible to truck drivers than they are to car drivers.

Because the effect of headlamp mounting height proved to be monotonic (see Table 1), the present results support higher mounting heights of headlamps in general. However, optimum headlamp mounting cannot be determined solely by considering the quality of the vehicle guidance provided by pavement markings. Other important considerations involve visibility of other roadside objects and susceptibility of the headlamp to dirt (both favoring higher mounting heights), and glare to oncoming drivers and glare to preceding drivers via rearview mirrors (both favoring lower mounting heights). Consequently, arriving at an optimum headlamp mounting height would require complex weighing of visibility and glare considerations.

Effects of the underlying variables

Headlamp mounting height and observer eye height were manipulated because they influence observation angle, entrance angle, reach of the headlamp, and projected area of the pavement marking. These four underlying variables, in turn, are known to affect the amount of light reaching the observer from a retroreflective pavement marking, with consequent effects on its visibility. Although the present study was not designed to experimentally isolate the effects of each of these underlying variables, based on theoretical considerations we can make predictions about the directions of the effects on visibility of the two manipulated variables via the four underlying variables. These predictions are summarized in Table 2.

Table 2
Predicted effects on visibility of retroreflective markings caused by *increasing* headlamp mounting height and eye height, via the effects of observation angle, entrance angle, headlamp reach, and projected area of the marking.

Underlying variable	Manipulated variable	
	Headlamp mounting height (at a fixed eye height)	Eye height (at a fixed headlamp mounting height)
Observation angle*	positive	negative
Entrance angle	positive	none
Headlamp reach	positive	none
Projected area of the marking	none	positive
Net effect	positive	?

*The predicted effects via observation angle apply to increases in headlamp mounting for which the resultant headlamp mounting height does not exceed the eye height, and to increases in eye height for which the initial eye height is not lower than the headlamp mounting height.

As shown in Table 2, the expected effects of all underlying variables that are sensitive to headlamp mounting height are in the same direction. Specifically, as headlamp mounting height is increased, considerations involving observation angle, entrance angle, and headlamp reach all lead to predicting an increase in detection distance of retroreflective pavement markings. (The direction of the effect via observation angle applies only if the resultant headlamp mounting height does not exceed the eye height.) Consequently, it is not surprising that the present experimental data show a positive overall effect of increased headlamp mounting height.

Predicting the overall effect of observer eye height is more complex (see Table 2). On one hand, observation angle considerations suggest that increases in eye height should result in *decreases* in visibility distance (as long as the initial eye height is not lower than the headlamp mounting height). On the other hand, considerations involving the projected area of the marking suggest that increases in eye height should result in *increases* in visibility distance. The present study was not designed to untangle the effects of the underlying variables, and thus the study did not contain a pure manipulation of observation angle (i.e., there were no two conditions that differed by observation angle only). On the other hand, this study did contain a pure manipulation of the projected area, by varying the width of the pavement marking (for one combination of headlamp mounting height and eye height). Increasing the width of the marking by 100% (from 0.1 m to 0.2 m) resulted in a 12% increase in visibility distance. It is interesting to compare this effect to the difference in visibility distance between the lowest and highest eye heights used in this study (1.2 m vs. 2.4 m). The difference in eye heights also involves a 100% increase in the projected area of the pavement marking. (Because the angle between the subject's line of sight and the plane of the pavement marking is very small, increases in eye height result in virtually proportional increases in projected area.) If these two ways of increasing projected area (doubling the actual width of the marking or doubling eye height) are assumed to have the same perceptual effect, then we can infer that the change in eye height from 1.2 m to 2.4 m increased visibility by 12% (i.e., the same amount attributable to doubling the width of the marking). However, because there was no net effect of eye height on detection distance, it is possible that the effect of observation angle fully compensated for the opposite effect of projected area (see Table 2). Following this line of argument, we could infer that observation-angle changes due to the eye-height change from 1.2 m to 2.4 m resulted in a just-compensating *decrease* in visibility distance of about 12%. (The actual changes in observation angle depend on the various headlamp mounting heights. Furthermore, precise calculations of observation angle would need to take into account the fact that the headlamp was always offset laterally by 0.4 m from the driver's eye point.)

There were two conditions that had the same observation angle, with headlamp mounting heights and eye heights of 0.6 m/1.2 m, and 0.8 m/1.4 m. The latter condition would be predicted to lead to longer visibility distances, because it leads to smaller entrance angle and longer reach of the headlamp (because of the higher headlamp mounting height), and to greater projected area of the pavement marking (because of the higher eye height). Indeed, the results confirmed this prediction: Changing headlamp mounting height and eye height from 0.6 m/1.2 m to 0.8 m/1.4 m increased the detection distance by 7% (from 87.5 m to 93.8 m—see Table 1).

SUMMARY

This nighttime field study addressed the relative visibility of retroreflective pavement markings from trucks and cars. To do that, both low-beam headlamp mounting height and observer eye height were varied. The task involved detecting the presence of a strip of retroreflective pavement marking that was moved towards a stationary observer. The main finding is that headlamp mounting height had a statistically significant effect on detection distance. Increasing the mounting height from the lowest tested level (0.6 m) to the highest tested level (1.2 m) resulted in a 19% increase in detection distance. On the other hand, there was no effect of eye height over the range tested (1.2 m to 2.4 m). Because truck headlamps are generally mounted higher than car headlamps, the present findings imply that retroreflective pavement markings are more visible (and thus more effective) for truck drivers than car drivers. Furthermore, these findings are in support of higher headlamp mounting height for all types of vehicles. However, higher headlamp mounting heights lead to more glare for both oncoming drivers and preceding drivers via rearview mirrors. Consequently, determining an optimal headlamp mounting height would require a complex weighing of both visibility and glare considerations.

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