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16. Abstract

The potential benefits offered by high-intensity discharge (HID) sources for vehicle headlamps have raised new issues in the design of headlamp beam patterns. The primary purpose of the present study is to address some of those issues by quantifying the effects of one major aspect of headlamp beam patterns—foreground light—on visual performance.

We measured the seeing distance to a dark-clad pedestrian at night on a two-lane road as a function of observer age, foreground luminance, and pavement condition (dry/wet). Observers sat in the driver's seat of a stationary vehicle positioned on the road while a pedestrian walked either toward or away from the vehicle. The observer indicated when the pedestrian just became visible or invisible, depending on the direction of movement.

Wet pavement resulted in longer seeing distances under all conditions. The effect of foreground luminance on seeing distance depended on both observer age and pavement wetness. High foreground luminance resulted in shorter seeing distances for older people and longer seeing distances for younger people. High foreground luminance also resulted in shorter seeing distances with dry pavement and longer seeing distances with wet pavement. However, all of the effects of foreground luminance were small, suggesting that although high foreground luminance does decrease seeing distances under some conditions, it is probably not a major problem for drivers.

Two major limitations apply to the interpretation of the effects observed in this study. First, the effects of glare from opposing headlamps were not measured. Second, only the effects of pavement wetness itself were measured, not the effects of active precipitation.

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Introduction

Drivers' perceptions of how well they can see at night may not always reflect their actual abilities as measured objectively. It therefore may be important in designing headlamp beam patterns to understand the effects of alternative designs on both objective seeing ability and drivers' perceptions of that ability. This may be especially important currently because of advances in the use of high-intensity discharge (HID) sources for vehicle headlamps. HID sources offer several potential benefits, including the ability to produce higher luminous flux from a lamp with moderate electrical power consumption and reasonable size. The primary purpose of the present study is to quantify the effects of one major aspect of headlamp beam patterns—foreground light—on visual performance.

Foreground light may increase driver confidence, but it is not clear that it should increase actual seeing ability for the kinds of things that a driver might need to see, such as a pedestrian in or near the lane of travel. In fact, either by increasing a driver's visual adaptation level, by causing more veiling glare due to scattered light in the eye, or by both of these mechanisms, it is possible that higher levels of foreground light actually decrease a driver's ability to see important stimuli.

Because pavement wetness greatly affects the reflective properties of most pavements, changing the pavements from relatively diffuse reflectors to more specular reflectors, it can be expected to interact with foreground light in terms of its effects on drivers' seeing ability. On dry pavement, higher foreground illumination should produce high foreground luminance, but on wet pavement much of the effect of an increase in foreground illumination may be negated because a relatively large fraction of the incident light is specularly reflected away from the eyes of the driver.

The effects of pavement wetness itself may represent another way in which actual visual performance and perceived performance differ. Although many drivers feel that they cannot see as well when the road surface is wet, it has been demonstrated that visual detection of objects on the road is improved by wet pavement (Helmers & Lundkvist, 1992). (Note that this discussion applies to wet pavement without significant active precipitation. When rain, snow, or fog are present, scattering of light in the air makes the situation more complicated and may lead to diminished ability to see.)

The effects of wet pavement can be readily explained by a simple analysis of the expected effects of relatively diffusely reflecting and relatively specularly reflecting pavements. Consider a vehicle traveling at night with no other vehicles present and no significant fixed sources of light. From the point of view of the driver, as the pavement becomes more specularly reflecting the pavement luminance diminishes. This produces the dark, blank appearance of a wet road that may make drivers believe they cannot see well. However, the surface that they cannot see well is the horizontal surface of the road, which, other than for lane definition, they probably do not need to see very well. The more critical surfaces probably tend to be vertical—including parts of pedestrians, animals, debris, and so forth—and the luminances of those surfaces should actually increase when the pavement is wet because the light reflected specularly from the road surface will add to the light striking vertical surfaces directly from the headlamps. This may be particularly important for overhead signs, which are located high enough that they often receive relatively weak direct illumination from low-beam headlamps.

In addition to quantifying the effects of foreground light, this study will address the effects of pavement wetness and the interaction between these two variables. Because older people are more susceptible to the disabling effects of glare, it can be expected that age will also interact with any variable that increases glare light. We therefore included two age groups in this study.

In order to have relatively precise control over lighting, we used a stationary vehicle and observer in this study. Observers sat in the driver's seat of a stationary vehicle on a closed road at night. A pedestrian walked toward or away from the vehicle and the observer's task was to signal when the pedestrian just became visible (when walking toward the vehicle) or invisible (when walking away). We measured seeing distance as a function of foreground illumination (manipulated by adding foreground lamps to the vehicles standard low-beam headlamps), pavement wetness (manipulated by watering the road halfway through each session of the study), and observer age group (younger or older).

Method

Subjects

Eighteen paid subjects participated in the experiment. There were nine subjects in each of two age groups, a younger group ranging from 20 to 25 with an average age of 22.3, and an older group ranging from 61 to 73 with and average age of 65.6. Each age group had five males and four females. All subjects were active, licensed drivers.

Test site and equipment

The experiment was conducted on an unlighted, closed, two-lane road at the University of Michigan Matthaei Botanical Gardens. Each lane was 12 feet (3.7 m) wide. A 1992 Toyota Corolla was placed in the middle of one lane of the road, facing so that it was in the normal position for right-hand driving. Subjects sat in the driver's seat of this car during testing. Along the right shoulder of the road (from the point of view of a driver of the vehicle), distances in front of the car were marked every two meters from 25 to 75 meters. The marks were on small pieces of tape flush with the surface of the road. They could be read easily by a pedestrian standing on the road near them, but they were not visible at night from the eye position of a driver of the car.

The standard low beams of the Corolla were used to provide part of the lighting in the experiment. They were supplemented at times by two low-beam headlamps mounted on a rack in front of the car. These supplemental beams, mounted 0.6 m above the pavement, were misaimed down 2.5 degrees. This resulted in the centers of the beam patterns (HV) being directed at points 13.7 m in front of the vehicle.

Hoses connected to the Botanical Gardens irrigation system along the side of the road allowed the pavement in front of the vehicle to be covered with water quickly.

The experimenter who served as the pedestrian wore dark clothing and shoes (all about 4% reflectivity).

Photometry

Two sets of photometric measures were taken: the luminance of a set of points on the pavement from the driver's eye position, and the illuminance of vertical surfaces at points along the right edge of the road (in the path of the pedestrian used for testing seeing distance).

Pavement luminance was measured from the subject's eye position, through the windshield of the car, using a Minolta LS-100 luminance meter with a 1-degree field of view. Measurements were taken at each of 15 points in a rectangular grid defined by three lateral positions and five distances from the car. The lateral positions were the left, middle, and right of the road. The left and right positions were slightly inside the shoulder of the road, just far enough that the field of view of the meter was entirely on the pavement. Measurements were made at distances of 5, 10, 15, 20, and 25 m from the car. Measurements were made for the four combinations of headlamp illumination (standard low beams only, or standard low beams combined with the supplemental foreground misaimed low beams) and pavement wetness (dry or wet). These luminance values are given in Table 1. The luminance values along the center of the road are also plotted in Figure 1.

The foreground lamps and pavement wetness both affect pavement luminance in ways that one might expect. Foreground lamps increase luminance values everywhere, but most strongly at the shorter distances (5 and 10 m). This makes sense because the HV points of the foreground lamps are aimed downward, toward a point on the pavement at a distance of 13.7 m, and the zones of maximum intensity of those lamps (the hot spots) are just inside that distance. Pavement wetness decreases luminance everywhere, and by substantial amounts (e.g., reduction by a factor of about 4.6 in the middle of the road, at the 10-m distance, with the foreground lamps off). This is presumably because the pavement reflects more specularly when wet than when dry.

Illuminance was measured at two points along the right edge of the road, at distances of 40 and 50 m from the car. Measurements were made with a Minolta T-1 illuminance meter fitted with a standard cosine receptor. The receptor was 0.75 m above the pavement and oriented perpendicular to a line from the illuminance meter to the car. These positions were both along the path that the pedestrian walked during the experiment, and they span most of the detection distances observed. Measurements were made for the same four combinations of headlighting and pavement wetness for which pavement luminance was measured. These illuminance values are given in Table 2, and plotted in Figure 2.

The effects of foreground lamps and pavement wetness on the illuminance values are also as might be expected. When the foreground lamps are on the illuminance values are higher. This is presumably due to a combination of direct light from the foreground lamps (even though the points at which illumination was measured were relatively high in the beam patterns of the foreground lamps, which were aimed strongly downward), and light from the foreground lamps that is reflected from the pavement. Pavement wetness also increases the illuminance values, presumably because it increases the amount of light reflected from the pavement to the points where illuminance was measured.

Table 1
Luminance values (cd/m^2) of the pavement measured from the subject's eye position (through the windshield) for the four combinations of headlamp illumination and pavement wetness. The values in this table for the middle of the road are also plotted in Figure 1.

Foreground lamps	Distance (m)	Pavement condition					
		Dry			Wet		
		Left	Middle	Right	Left	Middle	Right
Off	5	0.085	0.494	0.333	0.024	0.102	0.043
	10	0.322	2.426	1.261	0.107	0.528	0.386
	15	0.329	2.300	1.263	0.076	0.597	0.305
	20	0.189	1.228	0.688	0.078	0.380	0.231
	25	0.195	0.470	0.379	0.062	0.181	0.136
On	5	0.119	4.496	1.412	0.047	0.721	0.246
	10	0.449	6.120	2.188	0.130	2.363	0.486
	15	0.511	2.474	1.720	0.133	0.954	0.443
	20	0.335	2.069	0.952	0.113	0.359	0.263
	25	0.206	0.666	0.553	0.080	0.213	0.173

Table 2
Illuminance (lx) on a vertical surface, measured at two distances from the vehicle, along the right edge of the road, 0.75 m above the pavement, for the four combinations of headlamp illumination and pavement wetness. These data are plotted in Figure 2.

Foreground lamps	Distance (m)	Pavement condition	
		Dry	Wet
Off	40	0.296	0.360
	50	0.152	0.168
On	40	0.390	0.462
	50	0.188	0.220

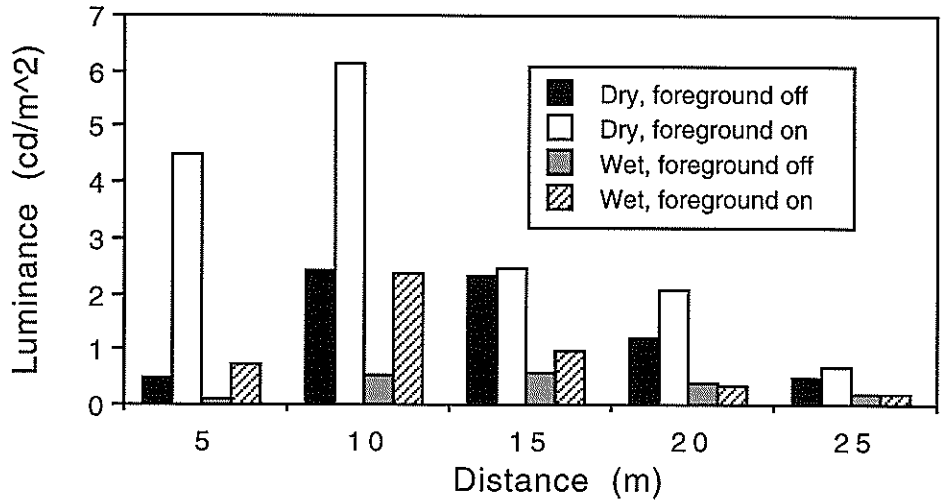

Figure 1. Luminance values measured from the subject's eyepoint for areas of pavement along the middle of the test road, at various distances, for all four combinations of pavement wetness and foreground lamp. These are the data from the columns of Table 1 labeled "middle."

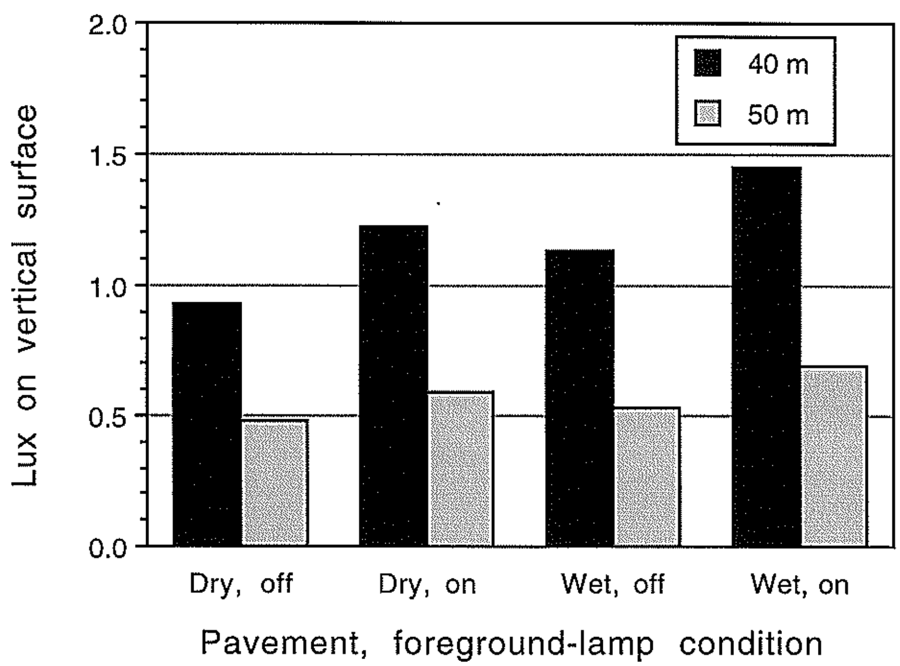

Figure 2. Illuminance at points along the right edge of the road at two distances from the test vehicle, for all four combinations of pavement wetness and foreground-lamp. Wetting the pavement and turning on the foreground lamps both increase illuminance values. These data are from Table 2.

Procedure

The experiment was conducted on moonless nights during which there was no natural precipitation. The surface of the test road was always dry at the beginning of a session.

Although each subject participated in actual data collection individually, subjects reported to the test site in groups of six, one group per night on three different nights, and took turns participating in actual data collection. This was done because we wanted to vary pavement wetness within subjects, and because once the pavement was wetted the dry condition could not be realized again within the same session. Each session lasted about two hours, but the data collection for each individual subject occupied only about 15 minutes.

Each session was divided into four parts of equal duration. Each subject participated four times, once in each quarter of the session. While they were not actively participating, subjects waited in an area where they could not see the test road. Subjects thus could not see each other's performance, and they were reminded not to discuss the experiment until after the session was completed.

During two of the sessions (involving 12 subjects) the pavement was wetted halfway through the session, between the second and third quarters. During the other session (involving 6 subjects) the pavement was not wetted, and thus remained dry throughout the session. The all-dry session served as a control for the effects of time, which was otherwise confounded with pavement wetness. This confounding was necessary because the pavement could be changed from dry to wet, but not vice versa, during a session, and because we wanted to be able to compare each subject's performance with wet and dry pavement within a single session.

Water was applied to the road across its entire width, and from immediately in front of the vehicle to a distance of 50 m. When it was first applied, between the second and third quarters of the session, approximately 400 liters of water was applied evenly over that area. Between the third and fourth quarters another 200 liters was applied in the same way. During the periods of actual data collection, which took about 15 to 20 minutes for each quarter of the session, the water supply was turned off, and some drainage occurred.

Four times during the session, once in each quarter, each subject was asked to sit in the driver's seat of the vehicle and make judgments about the distance at which a dark clad pedestrian could be seen. The experimenter serving as the pedestrian started at a point 75 m from the vehicle (which was always beyond any subjects' seeing distance) and began walking toward it along the right edge of the road. The subject indicated when he or she could first see the pedestrian by tapping the car's horn. The pedestrian experimenter noted his position when he heard the horn, but continued walking until he reached a point 25 m from car. He then turned around and began walking away along the same path. The subject tapped the horn again when the pedestrian just disappeared. The pedestrian again noted his position and continued walking until he reached the point he had started from (i.e., 75 m from the vehicle). This sequence was immediately repeated, after which the subject had completed his or her contribution to that quarter of the experiment and was replaced in the test vehicle by another subject. Thus, each subject made four judgments per quarter (two for the pedestrian approaching and two for the pedestrian walking away). The sequence always started with the pedestrian approaching.

The headlighting condition (foreground lamps off or on) remained the same for individual subjects during those four judgments within each quarter of the experiment, but was changed between quarters. The order of headlighting conditions was balanced both within subjects (between halves of the session) and between subjects. The sequence across quarters was either (on, off, off, on) or (off, on, on, off). Those two orders were used for equal numbers of subjects. The standard low beams of the Corolla remained on throughout the experiment.

Results and Discussion

Dry-pavement data (first half of each session)

Through the first half of all subjects' sessions the pavement was dry and all subjects (including the all-dry-pavement controls) received the same treatments. We performed an analysis of variance for the seeing distances from the first half of the sessions for all 18 subjects. The independent variables of most interest were subject age group (younger or older) and foreground lamps (on or off). Age group had a significant effect on seeing distance, $F(1,16) = 7.16$, $p = .017$. As shown in Figure 3, the younger group had a longer average seeing distance (47.7 m) than the older group (41.9 m).

Foreground lamps did not have a significant main effect, $F(1,16) = 2.25$, $p = .50$. However, there was a strong interaction of foreground lamps with subject age group, $F(1,16) = 5.89$, $p = .027$. That interaction is shown in Figure 4. The nature of the interaction is that foreground lamps being on tends to improve the performance of younger subjects but hurt that of older subjects. This could be due to older subjects being more susceptible to the disabling effects of glare in general, including glare from the bright foreground in this situation. For the older subjects, the disabling glare from the bright foreground may have outweighed any positive effect of extra light on the pedestrian from the foreground lamps, thus resulting in a net decrease in seeing distance when the foreground lamps were on. Because younger subjects are less affected by disabling glare, the bright foreground may have had a smaller negative effect, possibly outweighed by the increase in illumination of the pedestrian when the foreground lamps were on.

Effects of pavement wetness

In order to assess the effects of pavement wetness, we performed an analysis of variance on the seeing distance data from the complete sessions of the 12 subjects who experienced both dry and wet pavement conditions. Note that in these data there is a confounding of pavement wetness and temporal order. However, temporal order seems to have had at most minor effects (see the discussion of data from the all-dry-pavement control subjects below).

Pavement wetness had a strong and significant effect on seeing distance, $F(1,10) = 70.0$, $p < .001$. As shown in Figure 5, seeing distances were substantially longer (48.6 m) when the pavement was wet than when it was dry (44.2 m). The main effect of foreground lamps did not quite reach the conventional .05 significance criterion, $F(1,10) = 4.41$, $p =$

.062. However, there was a strong and significant interaction of foreground lamps with pavement wetness, $F(1,10) = 11.7$, $p = .0065$. This interaction is shown in Figure 6. Adding foreground lamps to the standard low beams led to shorter seeing distances when the pavement was dry, and longer seeing distances when the pavement was wet.

All-dry-pavement control subjects

In order to assess whether the observed effects of pavement wetness were influenced by the confounding of temporal order with pavement wetness, we performed an analysis of variance on all of the data from all 18 subjects. Independent variables for first versus second half of the session, and for subject group (dry/wet or dry/dry) were included. The interaction of those two variables was highly significant, $F(1,16) = 31.3$, $p < .001$, indicating that the difference in seeing distance between the first and second halves of the session was different for these two groups of subjects. As shown in Figure 7, it appears that the subjects who saw only dry pavement in both halves of the experiment performed the same in both halves. This suggests that time itself did not affect seeing distance and that the difference between first- and second-half seeing distance for the subjects who experienced dry followed by wet pavement should be attributed to wetness rather than to time.

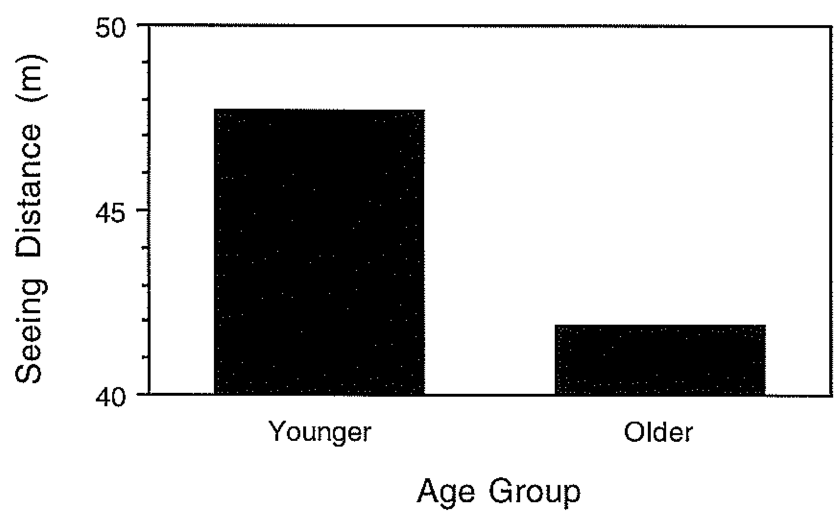

Figure 3. Average seeing distance for the younger and older age groups. These data are for dry pavement only (data from the first half of each session). All 18 subjects are included.

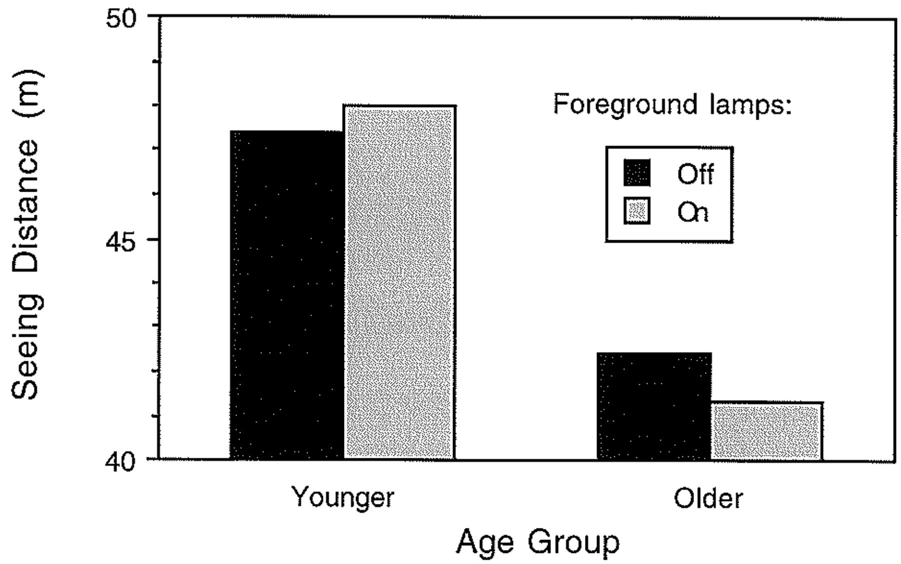

Figure 4. The interaction of age group and foreground lamps. Foreground lamps led to longer seeing distance for the younger group, but shorter seeing distance for the older group. These data are from the same conditions as those in Figure 3 (dry pavement only, all 18 subjects).

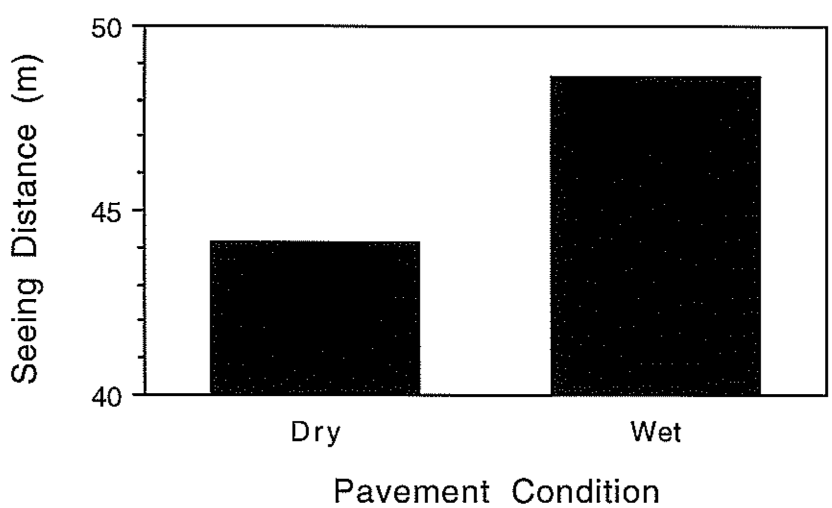

Figure 5. The effect of pavement wetness on seeing distance. Seeing distances were longer when the pavement was wet. These data are from the complete sessions of the 12 subjects who served in both dry- and wet-pavement conditions.

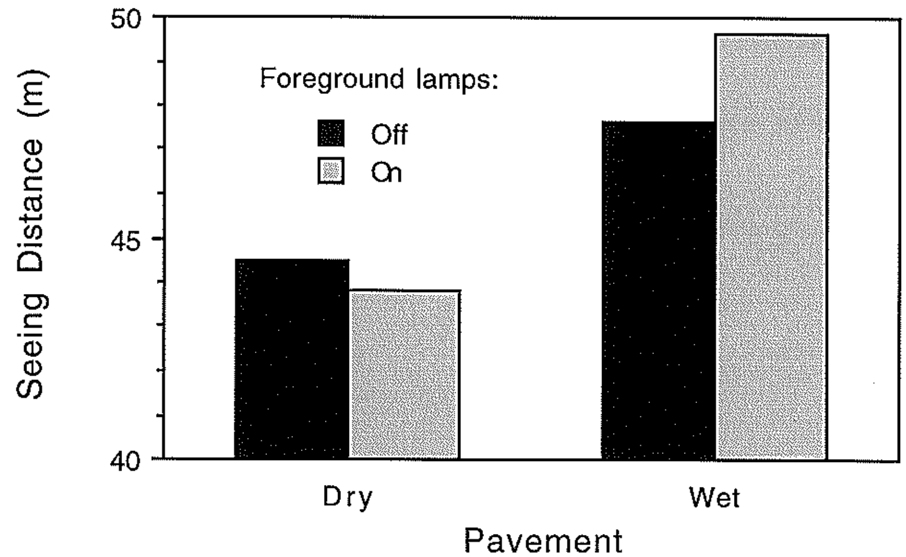

Figure 6. The interaction of foreground lamps and pavement wetness. Adding foreground lamps to the standard low beams led to shorter seeing distances when the pavement was dry, and longer seeing distances when the pavement was wet. These data are from the same conditions as those in Figure 5 (complete sessions of the 12 subjects who experienced both dry and wet pavement).

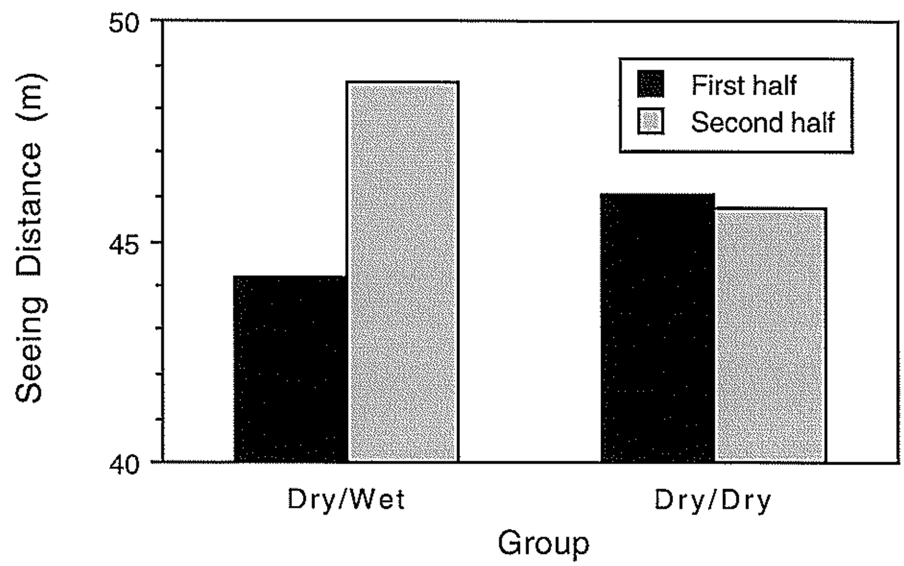

Figure 7. Seeing distances in the first and second half of the experiment for the group that experienced dry pavement followed by wet pavement (12 subjects) and the group that experienced dry pavement in both halves of the experiment (6 subjects). There appears to be no effect of time itself (no effect for the dry/dry subjects), implying that the effect of pavement wetness is not distorted by the confounding with time.

Summary and Conclusions

All of the effects on seeing distance observed in this study are predictable, in general form, from the photometric measurements and from a theoretical model of the observers in which older observers are more affected by disabling glare than younger ones. The magnitudes of the effects observed in this study indicate that foreground illumination, although it does decrease seeing distances under some conditions, does not have large effects. The manipulation of foreground luminance used here, produced by adding an entire second low-beam pattern aimed 2.5 degrees down to an existing pattern, was very strong relative to changes in foreground light that might be realistically contemplated in beam design, or that might result from typical levels of vertical misaim. Even with this rather strong manipulation, the effects on seeing distance were small. Thus, while high foreground illumination does not improve seeing ability (except perhaps for minor effects with younger drivers or wet pavement), at least it does not have strong negative effects.

The present results are relevant to wet pavement, but not necessarily to conditions with active precipitation. Scattering of light from substantial amounts of rain or snow in the air would be expected to reduce seeing distances generally, and might alter the effects of foreground light on seeing distances. Also, the present study did not evaluate how the existence of opposing glare might interact with high foreground illumination.

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Helmers, G., & Lundkvist, S.-O. (1992). *Low beam visibility distances to targets on dry and wet road surfaces related to reflection properties of these surfaces* (Report No. VTI-379). Linköping, Sweden: Swedish Road and Traffic Research Institute (VTI).