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Pedestrian Safety Margins Under Different Types of Headlamp Illumination

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Abstract

Several previous studies have been performed to evaluate the performance of vehicle headlamps with new technologies (e.g., high-intensity discharge, light-emitting diode, and adaptive forward lighting systems). Most of these studies have provided empirical evidence suggesting the promise of these newer technologies for improving roadway safety by improving visual performance of drivers. Recent efforts to develop predictive tools for characterizing headlamp performance have resulted in mathematical models to predict response times to potential hazardous objects varying in reflectance, size, angular position, and distance, as a function of the intensity and spectral characteristics of the light reaching such objects. These mathematical models can provide precise estimates of visual performance under quite controlled conditions not necessarily representative of those experienced by drivers in real-world conditions. The present report describes the results of a field study using different types of headlamp illumination (e.g., halogen and high-intensity discharge) for the detection and recognition of roadside pedestrian targets. The relative ability of drivers to stop in time when they detect pedestrians about to enter the roadway (as opposed to pedestrians about to exit the roadway) is presented. The correlation of these results to the mathematical response time models allows the results of calculations using such models to be transferable to more realistic, safety-relevant situations.

Keywords: .... headlamp, visibility, pedestrian,
safety, stopping distance, modeling

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ABSTRACT

Several previous studies have been performed to evaluate the performance of vehicle headlamps with new technologies (e.g., high-intensity discharge, light-emitting diode, and adaptive forward lighting systems). Most of these studies have provided empirical evidence suggesting the promise of these newer technologies for improving roadway safety by improving visual performance of drivers. Recent efforts to develop predictive tools for characterizing headlamp performance have resulted in mathematical models to predict response times to potential hazardous objects varying in reflectance, size, angular position, and distance, as a function of the intensity and spectral characteristics of the light reaching such objects. These mathematical models can provide precise estimates of visual performance under quite controlled conditions not necessarily representative of those experienced by drivers in real-world conditions. The present report describes the results of a field study using different types of headlamp illumination (e.g., halogen and high-intensity discharge) for the detection and recognition of roadside pedestrian targets. The relative ability of drivers to stop in time when they detect pedestrians about to enter the roadway (as opposed to pedestrians about to exit the roadway) is presented. The correlation of these results to the mathematical response time models allows the results of calculations using such models to be transferable to more realistic, safety-relevant situations.

INTRODUCTION

The main purpose of vehicle headlighting systems is to provide forward visibility for the driver; this is especially important considering that most roadways are unlighted, so that headlamps are often the only source of illumination present. Despite the inherent limitations of low beam headlamp patterns (Andre and Owens, 2001) caused by the necessity for glare control, high beam headlamp patterns are used infrequently (Sullivan et al., 2004). Recently, headlamp technologies have evolved quite rapidly to include high-intensity discharge (HID) and light-emitting diode (LED) sources. HID headlamps, for example, produce about twice the light output of halogen headlamps presently most common on vehicles (Jost, 1995); this has implications for the light distribution from HID headlamps compared to halogen ones. Generally, luminous intensities in the central portion of the low beam pattern do not differ greatly between halogen and HID types (although HID intensity values are somewhat higher [Akashi et al., 2008]). However, in the peripheral portion of the beam pattern, HID headlamps tend to have significantly higher light output with the result that they produce longer detection distances (Hamm and Steinhart, 1999) and shorter response times (RTs) (Van Derlofske et al., 2001, 2002) especially to peripheral targets.

Synthesizing the results of a series of field studies using different headlamp systems but similar methodologies (Van Derlofske et al., 2001, 2002), Bullough (2002) and Bullough and Van Derlofske (2004) developed a predictive model of RT to targets varying in angular location, reflectance and as a function of the headlamp illumination on them. Subsequently these authors have investigated the spectral distribution of headlamp illumination (Van Derlofske and Bullough, 2003), the distance to the target, and target size (Bullough et al., 2006; Bullough, 2009). The current model for prediction of visual RT values is:

$$RT = 8.89\theta - 115\log E - 332\log S + 409\log D - 49.3\log\rho - 23.4R + 291$$

where RT is the predicted RT (in ms), θ is the angular location of the target (in deg), E is the vertical illuminance on the target (in lx), S is the target size (in cm), D is the distance to the target (in m), ρ is the target reflectance and R is the scotopic/photopic (S/P) ratio (IESNA, 2006) of the headlamp illumination.

Models such as this one can be used to predict RTs to targets of varying characteristics under arbitrary headlamp illumination characteristics. Typically, these RT values are on the order of 400 to 700 ms; they represent responses of subjects who are sitting in a stationary vehicle. This is not the case in real world driving, when drivers might be occupied with the driving task, which would be expected to increase RTs to potential hazards such as pedestrians that might appear in the visual periphery along the roadside.

In order to determine whether the simple RT model above could be useful in predicting the usefulness of headlamps to support peripheral vision for pedestrian detection, a field study to measure drivers' ability to see and identify the salient details of a pedestrian, and to stop their vehicle when necessary, was conducted.

METHOD

The study was conducted along an unlighted, two lane suburban roadway at the Rensselaer Technology Park in Troy, NY, USA. Eleven subjects aged 24 to 62 years (mean age, 40 years) were instructed to drive a test vehicle (1999 Ford Contour) down the road at a speed not to exceed 30 mph, and as soon as they detected a black-painted plywood pedestrian cutout target (reflectance = 0.05) that was facing the road, to bring the vehicle to a complete stop. At two of six marked locations on either side of the road (three on each side, 10 m apart), two pedestrian cutout figures (Figure 1) were placed (both on the same side of the road); the orientations were chosen randomly, but at least one was facing the road, while the other may have been facing away from the road. Subjects were instructed to keep driving if they detected a target facing away from the road.

Figure 1. *a. Test car; b. Pedestrian target.*

The test car was instrumented with a GPS data logger (Race Technologies DL-1) that recorded the speed and distance traveled, and activation of the brake pedal, at 100 Hz. A frame was mounted to the front of the vehicle (Figure 1) on which one of two headlamp sets could be mounted, either halogen reflector VOL headlamps or HID projector VOL headlamps. Headlamps were properly aimed for each trial. Each subject performed four trials, one with each headlamp set and with the pedestrian targets on each side of the road. All of the target locations were on a portion of the road that had a constant slight curvature to the right. Separately from the subjects' trials, the vertical illuminances on the targets from a range of distances were measured (Figure 2).

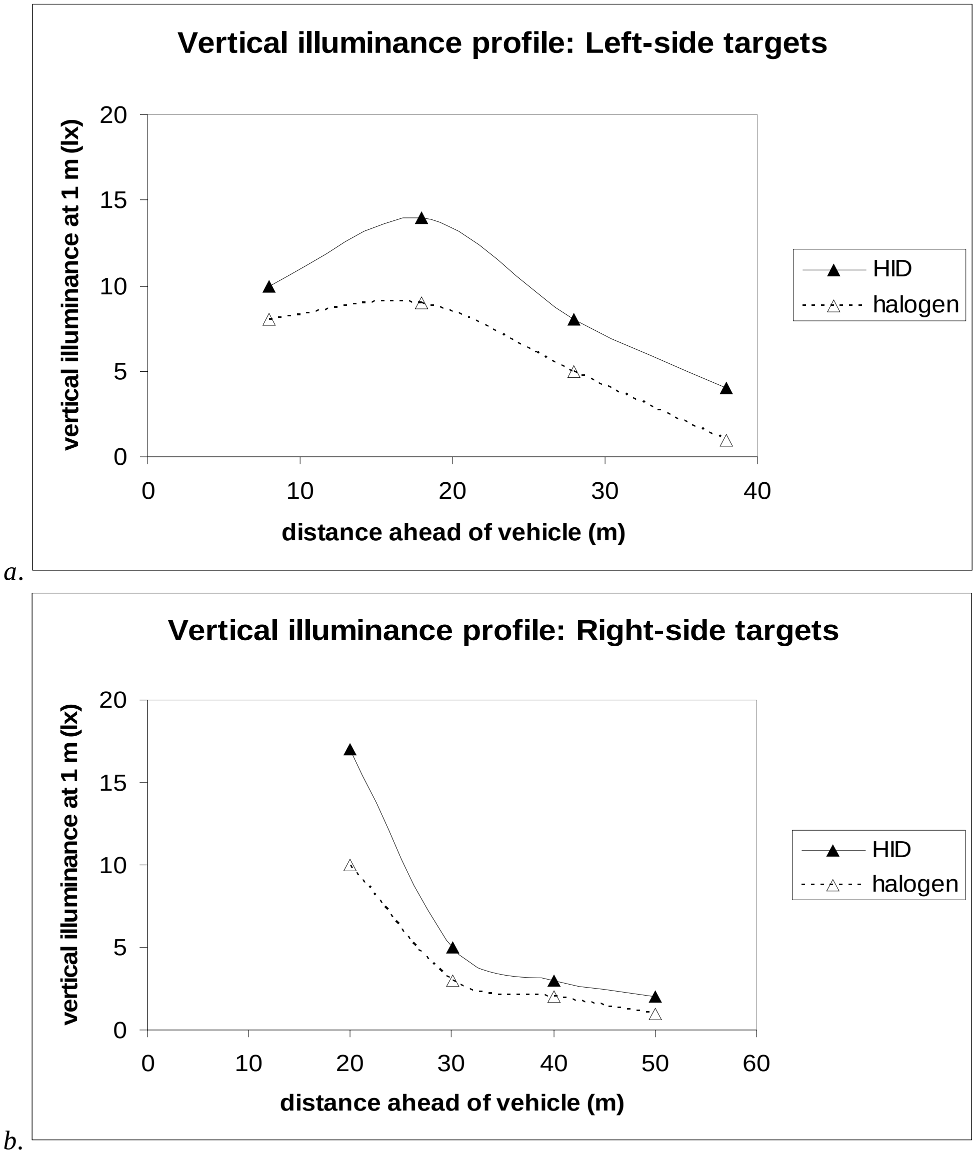

Figure 2. *Illuminances on (a) left-side and (b) right-side targets as a function of vehicle distance.*

After each trial, the distance between the vehicle and the appropriate pedestrian target (denoted the safety margin) was measured and recorded. Each session occurred after the end of civil twilight during dry weather.

RESULTS

In the present report, the pedestrian safety margin is defined as the distance ahead of the appropriate target when it came to a stop (i.e., a safety margin of 0 m means the vehicle came to a stop exactly at the target location). Figure 3 shows the mean safety margins for targets on each side of the road for each headlamp set. The HID headlamps afforded a mean safety margin that was almost 10 m longer than for the halogen headlamps.

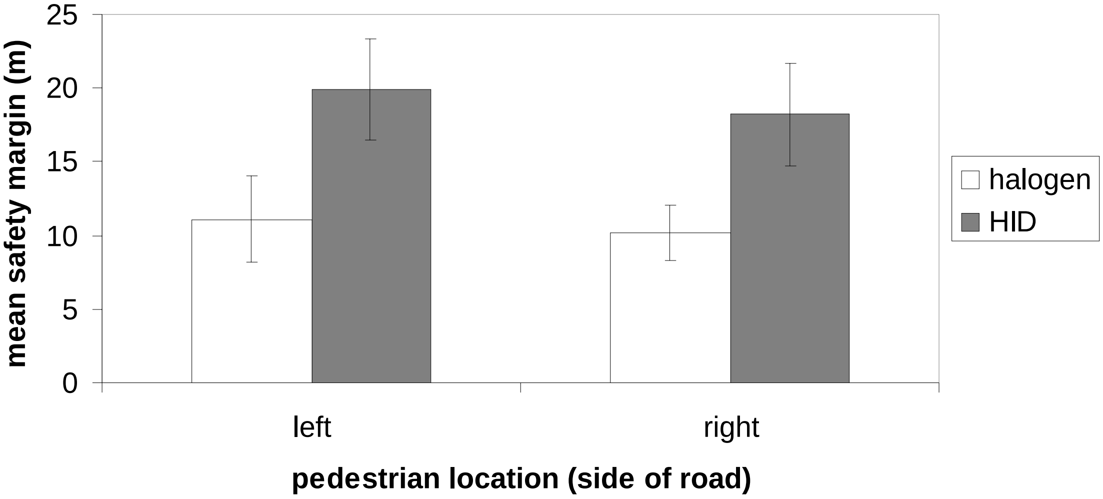

Figure 3. *Mean (+/- s.e.m.) safety margins for left- and right-side targets under each headlamp set.*

To compare the results of the study to the model, it was necessary to determine an estimate of the identification distance, since the visual/lighting conditions at this point, and not at the point where the vehicle came to a stop, determined when the target was not simply detected but seen to be facing toward the road. Through the GPS information from the data logger, it is possible to determine the location at which the brake was applied, and the distance ($D_{stopping}$) from that location where the vehicle came to a stop. This distance is added to the safety margin (D_{margin}) to obtain the identification distance ($D_{identification}$): the distance from the relevant target at which the brake was applied. Figure 4 shows the mean identification distances for the targets under each headlamp set; they indicate a similar improvement (nearly 10 m) for the HID headlamps over the halogen headlamps. This is consistent with the notion that the vehicle stopping distances under all conditions were about equivalent, as would be expected for vehicles along the same road being driven at about the same speed.

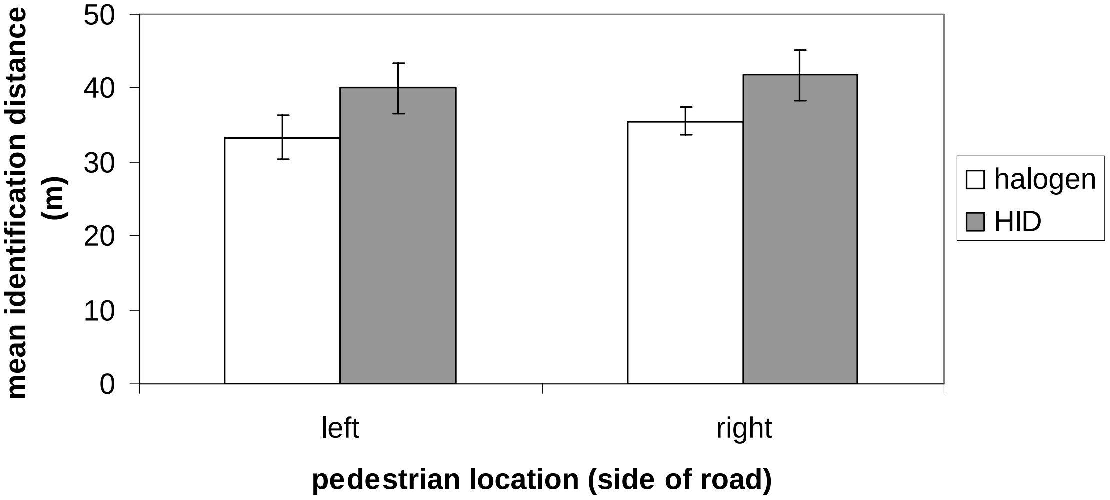

Figure 4. *Mean (+/- s.e.m.) identification distances for left- and right-side targets under each headlamp set.*

Interpolating the illuminance values in Figure 2 for each headlamp and side of the road, at the mean identification distances, the target reflectance, the S/P ratio (IESNA, 2006) of the headlamps, using a relevant detail size of 30 cm, and calculating the angle of the target location for each identification distance from a line of sight directed straight ahead, the predicted RT values are shown in Table 1 to be very close to one another, with a value of approximately 500 ms.

Table 1. *Target and Headlamp Illumination Characteristics at the Mean Measured Identification Distances, and Predicted RT Values*

Condition	Angle (deg)	Illum (lx)	Size (cm)	Reflectance	Distance (m)	S/P Ratio	RT (ms)
Halogen left	7	2.2	30	0.05	33.3	1.57	484
HID left	3	1.68	30	0.05	40.0	1.62	483
Halogen right	8	2.58	30	0.05	35.5	1.57	495
HID right	9	2.88	30	0.05	41.8	1.62	508

The results in Table 1 suggest that regardless of the side of the road the target was on, or under what type of illumination was used, responses to all of the pedestrian targets (determined by when the brake pedal was activated) occurred when the relevant target details were predicted to elicit an equivalent RT value (of ~500 ms), or when they were equally visible in subjects' peripheral vision.

DISCUSSION

The results described above, and the subsequent analysis using the RT model based upon previous experimental data (Van Derlofske et al., 2001, 2002; Van Derlofske and Bullough, 2003; Bullough et al., 2006; Bullough, 2009) suggest that this model can be applied in a constructive and practical manner to real-world situations such as stopping a vehicle when a pedestrian facing toward the road is seen. The empirical data suggesting that the HID headlamp set used offers a longer safety margin than the halogen set are consistent with the greater peripheral output of most HID headlamps (Hamm and Steinhart, 1999; Van Derlofske et al., 2001, 2002), which is the case with the presently used lamps, as illustrated in Figure 2.

In this experiment, the visual task performed by subjects was more complex that that used by subjects in many other studies. The subjects were driving an actual vehicle and were required to safety navigate along a roadway, and they were not simply requested to reply to the onset or mere appearance of a target, but instead they had to discern, after detecting a target, whether it was facing toward or away from the road, and then had to make a cognitive decision about whether to stop. Logically, these additional steps would require longer RTs than simply releasing a button in response to a target onset under a static situation. Nonetheless, the results appear to demonstrate that the visual component of pedestrian detection while driving can be correlated to visual RTs predicted by a model such as that described above.

The analysis illustrated in Table 1 can be applied to any arbitrary headlamp distribution. For example, Olson and Sivak (1981) published luminous intensity data for a sealed-beam, low-beam headlamp commonly used in North America in the early 1980s and earlier, before the widespread introduction of halogen headlamps with replaceable lamps. Using these data it is possible to calculate the vertical illuminances on, and the angular locations of, the pedestrian targets used in the present study that would be achieved at various distances while driving along the same road. As expected, the illuminances are lower than from halogen headlamps. Using the model equation presented above, it is possible to determine the distance from the target at which the predicted RT value would be 500 ms. For the left- and right-side targets, the sealed-beam headlamps would be expected to produce identification distances of 25 m and 33 m, respectively, shorter than were determined under the halogen and HID headlamps (Figure 4). Assuming a fixed vehicle stopping distance as found in the present experiment, and combining the results for the left- and right-side targets, Figure 5 shows a comparison of the pedestrian stopping safety margins for sealed-beam, halogen and HID low-beam headlamps.

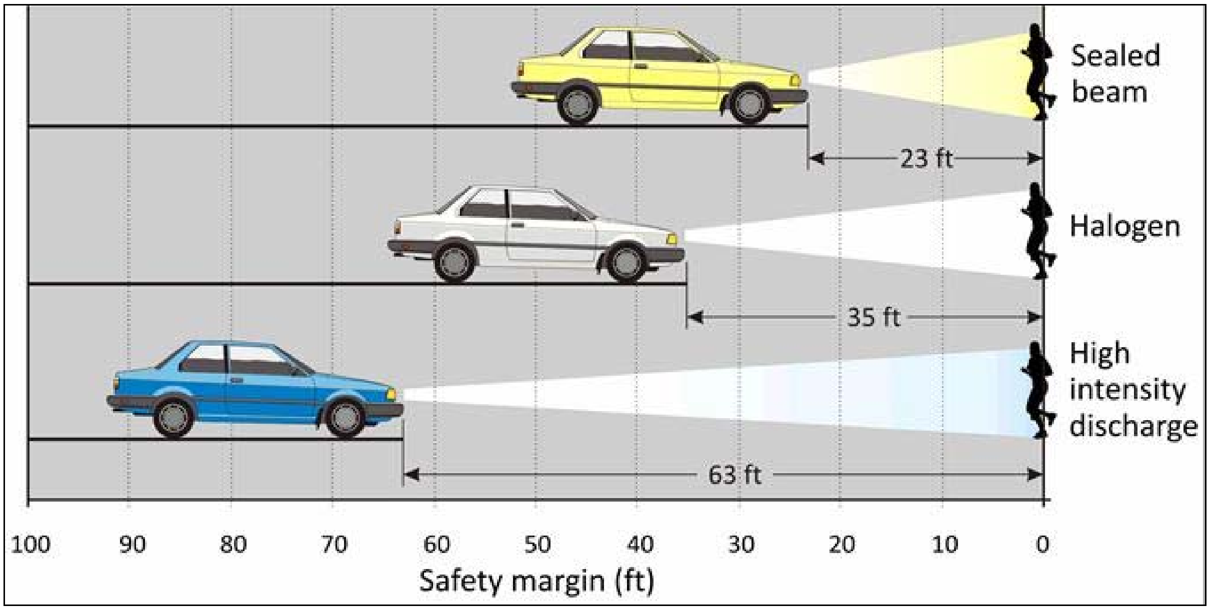

Figure 5. *Pedestrian stopping safety margins for three headlamp types investigated in the present study; data for the sealed-beam headlamp are predictions based on the RT model analysis.*

Analyzing the impact of the light/dark transition associated with daylight savings time on crashes, Sullivan and Flannagan (2002) concluded that pedestrian crashes were strongly associated with lighting conditions. The present data are consistent with that conclusion, and provide a basis to conclude that the transition in vehicle forward lighting technology from sealed-beam headlamps, to halogen lamps, and to HID headlamps is likely a beneficial one, in terms of pedestrian safety, when one is driving along an unlighted roadway without opposing traffic. Quite simply, drivers can stop sooner, and with a greater margin of safety under the halogen headlamp than under the sealed-beam headlamp and sooner yet under the HID headlamp. Obviously the data in Figure 5 are for specific lamps, but these lamps are representative of sealed-beam, halogen and HID types in general (Olson and Sivak, 1981; Hamm and Steinhart, 1999; Van Derlofske et al., 2001, 2002; Akashi et al., 2008).

The present data also suggest that the model of peripheral RTs described above can be applied to real-world data such as those in the present paper, to analyze the potential of any arbitrary light distribution on forward visibility. This finding, if it can be further validated under a broader set of lighting and geometric conditions, can lead to a powerful analytical tool in headlamp design as new technologies such as LED headlamps and adaptive forward-lighting systems (AFS) become more common.

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