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Benefits of Intelligent Headlamp Technologies to Pedestrian Safety at Roundabouts

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Abstract

A two-part study of the influence of vehicle headlamps and roadway lighting on the ability of drivers to see pedestrians along crosswalks in roundabout intersections was conducted. In the first part of the study, the photometric performance of vehicle headlamp systems including conventional halogen and high intensity discharge (HID) low-beam headlamp systems and intelligent vehicle headlamp systems that might provide optimized illumination for navigating through roundabouts was compared. Relative visual performance analyses based on these comparisons were used to demonstrate when such vehicle headlamp technologies might offer benefits in terms of pedestrian safety and efficient navigation. In the second part of the study, an outdoor field experiment was conducted to assess observers' ability to detect and identify the walking direction of pedestrian targets in the field of view. Importantly, this experiment utilized many of the same conditions and geometric characteristics that were evaluated in the photometric simulation, and included calculations of visual performance. A secondary objective of the studies summarized in this report was to validate the use of visual performance modeling to predict driver visibility under conditions corresponding to illumination from vehicle headlamps and fixed roadway lighting.

Keywords: .... headlamps, roadway lighting, roundabouts, pedestrians, safety

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ABSTRACT

A two-part study of the influence of vehicle headlamps and roadway lighting on the ability of drivers to see pedestrians along crosswalks in roundabout intersections was conducted. In the first part of the study, the photometric performance of vehicle headlamp systems including conventional halogen and high intensity discharge (HID) low-beam headlamp systems and intelligent vehicle headlamp systems that might provide optimized illumination for navigating through roundabouts was compared. Relative visual performance analyses based on these comparisons were used to demonstrate when such vehicle headlamp technologies might offer benefits in terms of pedestrian safety and efficient navigation. In the second part of the study, an outdoor field experiment was conducted to assess observers' ability to detect and identify the walking direction of pedestrian targets in the field of view. Importantly, this experiment utilized many of the same conditions and geometric characteristics that were evaluated in the photometric simulation, and included calculations of visual performance. A secondary objective of the studies summarized in this report was to validate the use of visual performance modeling to predict driver visibility under conditions corresponding to illumination from vehicle headlamps and fixed roadway lighting.

INTRODUCTION

Roundabout intersections are becoming more common in North American highway design (Robinson et al., 2000) because they can help facilitate traffic flow and can reduce crash severity at roadway intersections compared to traditional intersection types. Often, roundabouts are lighted using fixed overhead pole-mounted systems (IES, 2008) that are relatively energy intensive. Further, overhead lighting systems do not always reinforce the visual information and guidance needed by drivers to safely and efficiently navigate through the roundabout (Bullough et al., 2009; Bullough, in press).

In particular, locations of pedestrian crosswalks along roundabouts are not always in locations that are intuitive to drivers, nor does overhead lighting always provide optimal visual contrast of a pedestrian against his or her background when vehicle forward lighting is present (Bullough et al., 2012). Thus, it is increasingly important to consider the visual performance of drivers as they negotiating the turns along roundabouts. Suboptimal roundabout lighting practices further underscore the need for adequate automotive forward lighting. The present report describes a study intended to determine how currently available headlamp technologies perform in the roundabout traffic environment under different fixed lighting conditions.

In the first part of the study, the photometric performance of vehicle headlamp systems including conventional halogen and high intensity discharge (HID) low-beam headlamp systems and intelligent vehicle headlamp systems that might provide optimized illumination for navigating through roundabouts was compared. Relative visual performance (RVP; Rea and Ouellette, 1991) analyses based on these comparisons were used to demonstrate when such vehicle headlamp technologies might offer benefits in terms of pedestrian safety and efficient navigation.

In the second part of the study, an outdoor field experiment was conducted to assess observers' ability to detect and identify the walking direction of pedestrian targets in the field of view. Importantly, this experiment utilized many of the same conditions and geometric characteristics that were evaluated in the photometric simulation, and included calculations of visual performance using the RVP model (Rea and Ouellette, 1991). A secondary objective of the studies summarized in this report was to validate the use of the RVP model to predict driver visibility under conditions corresponding to illumination from vehicle headlamps and fixed roadway lighting.

PHOTOMETRIC SIMULATION STUDY

Method

A calculation based method was employed to determine whether and to what extent pedestrian-representative targets would be visible to motorists approaching pedestrian crosswalks in roundabouts. Specifically, the method used was the relative visual performance (RVP) model (Rea and Ouellette, 1991). The RVP model takes many factors into account, including observer age, overall light level, target size, and target-background contrast. It was developed from data spanning the mesopic and photopic adaptation regions.

RVP surfaces are graphically depicted in Figure 1; take note of the "plateau" and "escarpment" features which are present in all of the surface graphs. These are significant because once a particular level of visual performance on the plateau is obtained, only small improvements can be made, even if very large light level increases are provided.

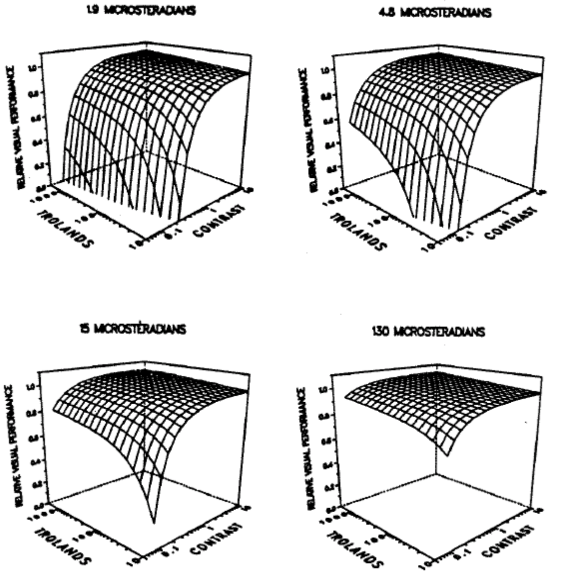

Figure 1: Graphical depiction of the RVP model for various size targets (Rea and Ouellette, 1991).

The RVP model has been found to be highly correlated with measures of performance for driving-related tasks such as sign visibility (Goodspeed and Rea, 1999; Schnell et al., 2009) and pedestrian detection (Zhang, 2009; Bullough and Skinner, 2009; Bullough et al., 2012). Zhang (2009) measured the time needed by drivers in a field study of crosswalk illumination to identify adult- and child-sized pedestrians and found strong correlations between the identification times and corresponding RVP values (Figure 2). Comparisons of recent pedestrian safety margin data (Bullough and Skinner, 2009) with predictions from the RVP model suggested that pedestrian identification, while driving, for different headlamps and pedestrian locations occurred when there was sufficient illumination, contrast and/or size to achieve an RVP value of nearly 0.8 (Table 1).

Condition	Angle (deg)	Target Illum (lx)	Size (cm)	Reflectance	Distance (m)	RVP	RT (ms)
Halogen left	7	2.2	30	5%	33.3	0.79	491
HID left	3	1.68	30	5%	40.0	0.77	510
Halogen right	8	2.58	30	5%	35.5	0.78	496
HID right	9	2.88	30	5%	41.8	0.76	513

Table 1: Predicted RVP values and response times (RT) for pedestrian identification distances measured by Bullough and Skinner (2009).

A roundabout recently constructed in the Albany area of New York State in the U.S. was used as the basis for the calculations; it is depicted in Figure 3. Two pedestrian target locations were defined and are denoted as "Ped. A" and "Ped. B" in the figure. In addition to the pedestrian targets, observer positions were defined in the inner and outer lanes ("Car A" and "Car B" respectively). In addition, Cars A and B were placed at two positions: one within the roundabout ("Position 1") and another where the driver would wait to merge into the roundabout ("Position 2").

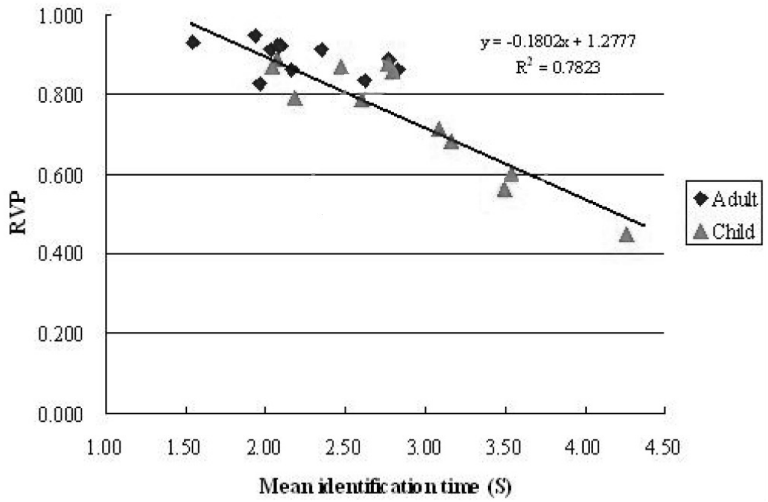

Figure 2: Correlation between RVP values and pedestrian identification times (Zhang, 2009).

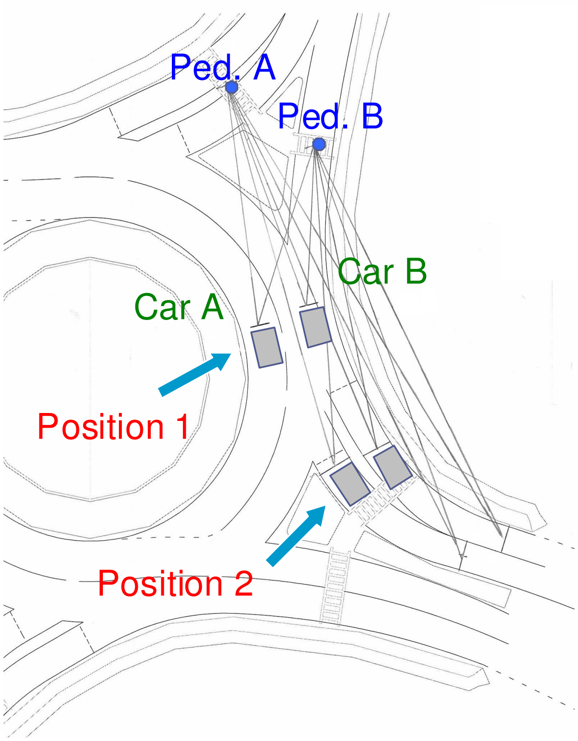

Figure 3: Roundabout used for geometrical reference in calculations.

Once the observer positions were defined as depicted in Figure 3, the distances and angles to the target locations were measured. These measurements are summarized in Table 2.

		Ped. A			Ped. B		
		Distance	Angle (vrt)	Angle (hrz)	Distance	Angle (vrt)	Angle (hrz)
Car A	1	30.21	-0.655	5	23.61	-0.838	30
	2	49.48	-0.400	13	40.09	-0.494	26
Car B	1	29.21	-0.678	-7	19.96	-0.992	17
	2	49.21	-0.402	3	38.56	-0.513	14

Table 2: Geometry of observer positions to targets (distances in m, angles in deg).

In addition to fixed headlamp distribution geometries, the possibility that the headlight distribution could be swiveled [such as in an adaptive forward-lighting system (AFS)] was considered also. Swiveling of the headlamp distributions was preformed such that the horizontal angle of the beam to the target was as close to 0° as possible (with a maximum swivel angle of 15°). The swiveled distribution angles are summarized in Table 3.

		Ped. A			Ped. B		
		Distance	Angle (vrt)	Angle (hrz)	Distance	Angle (vrt)	Angle (hrz)
Car A	1	30.21	-0.655	0	23.61	-0.83818	15
	2	49.48	-0.400	0	40.09	-0.49368	11
Car B	1	29.21	-0.678	0	19.96	-0.99175	2
	2	49.21	-0.402	0	38.56	-0.51333	0

Table 3: Swiveled distribution geometry to targets (distances in m, angles in deg).

Two headlamp distributions were considered in this study. The first was the 2004 market-weighted halogen low-beam distribution compiled and published by the University of Michigan (Schoettle et al., 2004). The second headlamp distribution was measured at the Lighting Research Center from an AFS equipped HID headlamp unit used in a production car sold in the United States market.

The intensities of the headlamp distributions at the geometries shown in Tables 1 and 2 were computed using bi-parabolic interpolation. The interpolated intensities were used with the geometries described in the tables to determine the vertical illuminances on the targets (Figures 4 and 5) and the horizontal illuminances on the ground under each of them. The luminances of the targets and ground were calculated using these values. The target (30.5 cm width by 61 cm height, standing on the ground) was assumed to have a lambertian reflectance of 5% and the ground was assumed to have a lambertian reflectance of 15%.

For the visual performance calculations, additional ambient illuminances of 0.2 and 2 lx were included as well as no additional ambient illuminance to represent the potential impact of roadway lighting and illumination from nearby commercial properties that could influence visual performance. These values are representative of those measured in suburban and urban locations (Li et al., 2006).

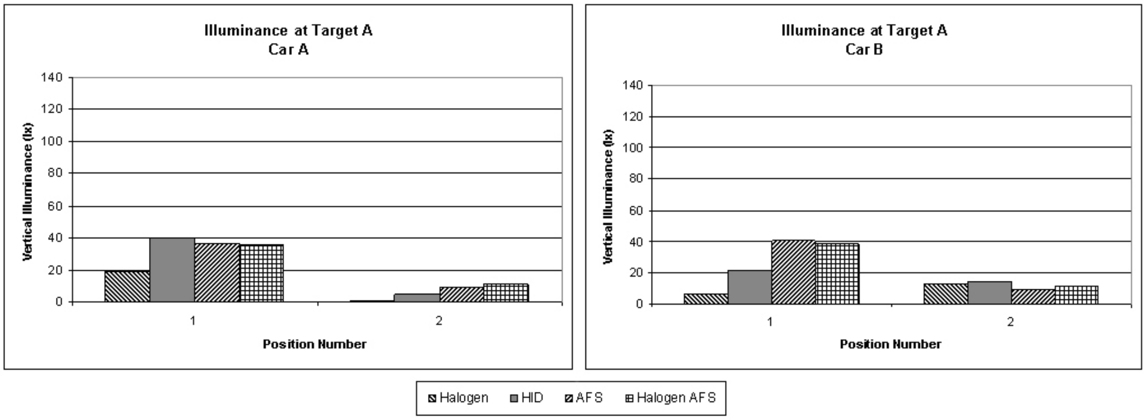

Figure 4: Vertical illuminances on Ped. Target A for each geometry.

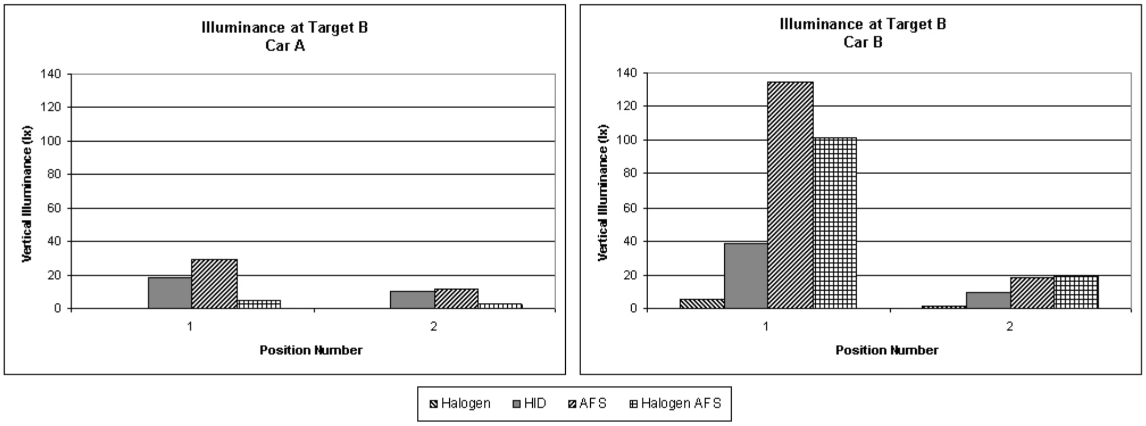

Figure 5: Vertical illuminances on Ped. Target B for each geometry.

Results

The results of the RVP calculations are summarized in Tables 4, 5 and 6, and in Figures 6 and 7. These tables contain the RVP values for all of the configurations, for 20, 40, and 60 year-old observers respectively. Positive numbers represent targets that are above the threshold for detection and identification. The greater the value, the more quickly an observer can identify the visual target. Negative numbers indicate that the target is above the detection threshold but below the identification threshold. Table entries of "NRV" indicate that the target is not reliably visible to the observer (below detection threshold).

Car B is in the only lane from which a vehicle may exit the roundabout. If a pedestrian collision is to be avoided, it is critical that the driver of Car B can see the pedestrian targets. Figures 6 and 7 show the performance of a 20-year-old driver in Car B under various ambient lighting conditions. This driver age was chosen so that the effect of adding additional ambient light could be more readily identified.

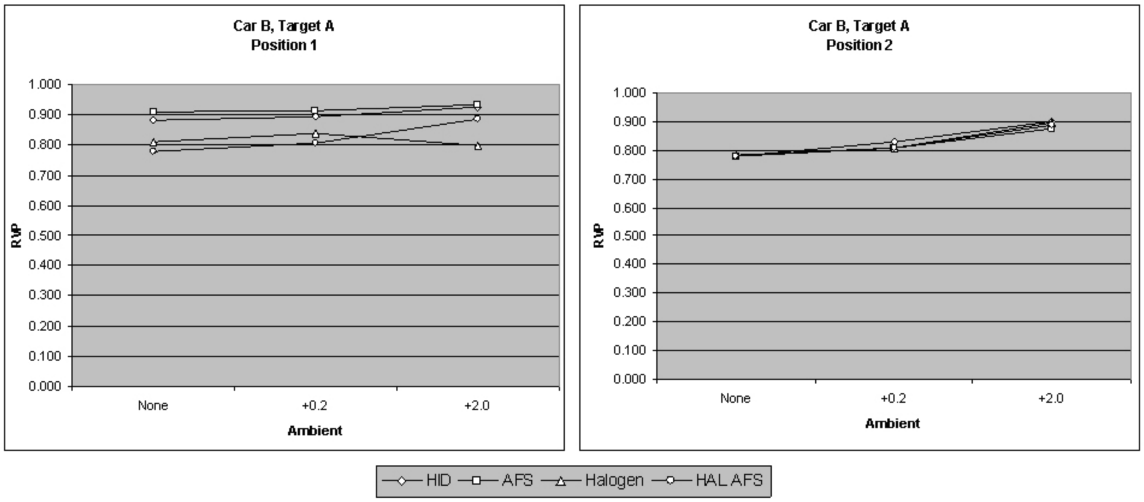

Figure 6: RVP values for Ped. Target A from Car B in Positions 1 and 2, given a 20-year-old observer and various ambient conditions (in lx).

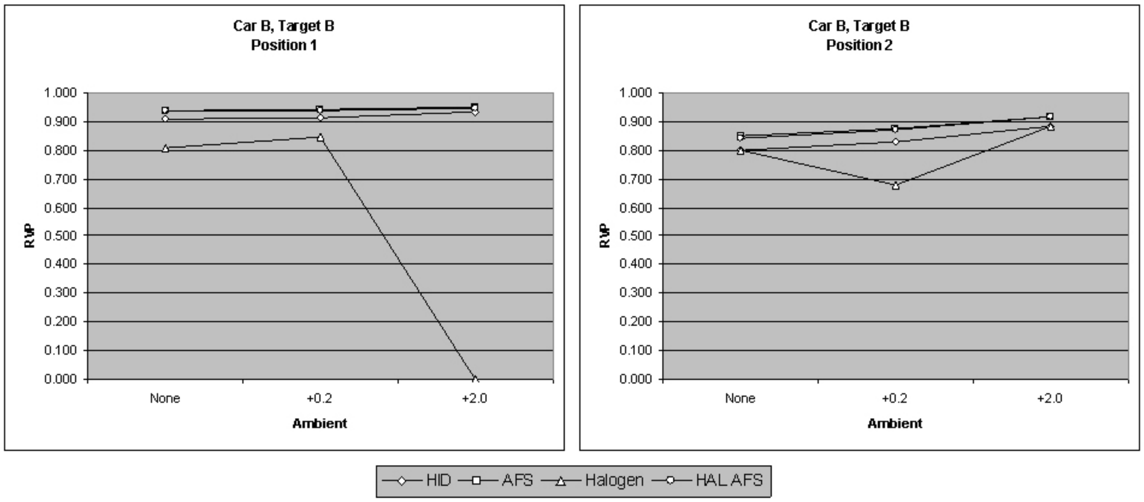

Figure 7: RVP values for Ped. Target A from Car B in Positions 1 and 2, given a 20-year-old observer and various ambient conditions (in lx).

Analysis

In most of the cases shown in Figures 6 and 7, the addition of ambient light did not negatively affect the observer's visual performance. Generally speaking, increasing the ambient level marginally increased the RVP value, consistent with expectations from increasing the overall adaptation level. The primary exception to this trend was for the static halogen distribution. Reversals in the RVP/ambient illuminance trend were caused by a reversal of contrast from positive (bright object in dark background) to negative contrast (dark object in bright background) as the background level was increased.

Although preliminary, there are several potential implications of these results. A majority of vehicles in the U.S. have static, halogen headlamps, so visual performance for motorists navigating roundabouts may less than desirable, especially considering the conventional overhead lighting practices employed at many of these installations. New headlamp technologies appear to offer some promise to avoiding the luminance contrast reversals that seem to be present in pedestrian crosswalks along roundabouts as described here, and in other pedestrian crosswalk configurations as well (Bullough et al., 2010). As new roadway configurations are utilized, it is important for vehicle lighting to be considered in addition to fixed roadway lighting as a significant part of the solution for ensuring adequate visual performance.

		RVP							
		HID		AFS		Halogen		Halogen AFS	
Target	→	A	B	A	B	A	B	A	B
Car A	1	0.903	0.889	0.902	0.897	0.859	0.819	0.895	0.810
	2	0.778	0.800	0.777	0.797	0.780	0.799	0.779	0.799
Car B	1	0.880	0.907	0.907	0.939	0.809	0.808	0.900	0.936
	2	0.778	0.800	0.777	0.849	0.781	0.799	0.780	0.841
		RVP (+ 0.2 lx Ambient)							
		HID		AFS		Halogen		Halogen AFS	
Target	→	A	B	A	B	A	B	A	B
Car A	1	0.909	0.898	0.909	0.905	0.880	0.502	0.904	0.824
	2	0.752	0.814	0.806	0.838	0.495	0.620	0.805	0.744
Car B	1	0.892	0.913	0.912	0.940	0.837	0.845	0.907	0.937
	2	0.830	0.829	0.808	0.873	0.807	0.680	0.807	0.869
		RVP (+ 2.0 lx Ambient)							
		HID		AFS		Halogen		Halogen AFS	
Target	→	A	B	A	B	A	B	A	B
Car A	1	0.932	0.922	0.931	0.930	0.919	0.914	0.930	NRV
	2	0.573	0.890	0.872	0.895	0.883	0.907	0.886	0.835
Car B	1	0.923	0.934	0.933	0.949	0.797	-0.714	0.932	0.946
	2	0.898	0.882	0.874	0.915	0.894	0.883	0.888	0.916

Table 4: RVP values for a 20-year-old observer.

		RVP							
		HID		AFS		Halogen		Halogen AFS	
Target →		A	B	A	B	A	B	A	B
Car A	1	0.881	0.860	0.879	0.871	0.806	NRV	0.869	NRV
	2	NRV	NRV	NRV	NRV	NRV	NRV	NRV	NRV
Car B	1	0.845	0.886	0.886	0.927	NRV	NRV	0.876	0.923
	2	NRV	NRV	NRV	0.789	NRV	NRV	NRV	0.757

		RVP (+ 0.2 lx Ambient)							
		HID		AFS		Halogen		Halogen AFS	
Target →		A	B	A	B	A	B	A	B
Car A	1	0.889	0.873	0.888	0.883	0.847	NRV	0.881	0.656
	2	NRV	NRV	0.626	0.764	NRV	NRV	0.539	NRV
Car B	1	0.865	0.894	0.893	0.929	0.747	0.778	0.886	0.925
	2	0.753	0.719	0.645	0.835	0.532	NRV	0.580	0.829

		RVP (+ 2.0 lx Ambient)							
		HID		AFS		Halogen		Halogen AFS	
Target →		A	B	A	B	A	B	A	B
Car A	1	0.918	0.905	0.917	0.915	0.902	0.895	0.916	NRV
	2	0.361	0.862	0.837	0.869	0.853	0.885	0.857	0.784
Car B	1	0.906	0.921	0.920	0.939	0.728	-56.231	0.918	0.936
	2	0.873	0.851	0.840	0.896	0.868	0.852	0.859	0.897

Table 5: RVP values for a 40-year-old observer.

		RVP							
		HID		AFS		Halogen		Halogen AFS	
Target →		A	B	A	B	A	B	A	B
Car A	1	0.800	NRV	0.796	0.686	NRV	NRV	0.709	NRV
	2	NRV	NRV	NRV	NRV	NRV	NRV	NRV	NRV
Car B	1	NRV	0.814	0.817	0.899	NRV	NRV	0.776	0.892
	2	NRV	NRV	NRV	NRV	NRV	NRV	NRV	NRV

		RVP (+ 0.2 lx Ambient)							
		HID		AFS		Halogen		Halogen AFS	
Target →		A	B	A	B	A	B	A	B
Car A	1	0.827	0.767	0.824	0.805	NRV	NRV	0.803	NRV
	2	NRV	NRV	NRV	NRV	NRV	NRV	NRV	NRV
Car B	1	0.626	0.836	0.836	0.901	NRV	NRV	0.817	0.895
	2	NRV	NRV	NRV	NRV	NRV	NRV	NRV	NRV

		RVP (+ 2.0 lx Ambient)							
		HID		AFS		Halogen		Halogen AFS	
Target →		A	B	A	B	A	B	A	B
Car A	1	0.884	0.861	0.882	0.879	0.855	0.841	0.880	NRV
	2	-1.547	0.779	0.729	0.793	0.760	0.823	0.770	0.602
Car B	1	0.863	0.888	0.886	0.916	0.442	NRV	0.883	0.912
	2	0.802	0.756	0.734	0.844	0.790	0.757	0.773	0.847

Table 6: RVP values for a 60-year-old observer.

FIELD EXPERIMENT

Method

In an outdoor location demarcated as a modern roundabout intersection (with asphalt pavement of 10%-15% reflectance), study participants were instructed to identify the walking direction (left or right) of a pedestrian target consisting of a black-painted (reflectance, 5%) silhouette (1 m height) of a walking child (Figure 8), as quickly as possible. Subjects ranged in age from 28 to 65 years (mean 50, s.d. 15).

Two headlamp systems were used: a halogen low-beam set, and a high-intensity discharge (HID) set equipped with swiveling functionality. The headlamp and target geometries were set to match, as closely as possible, vehicle-headlamp-pedestrian geometries evaluated by Skinner and Bullough (2011) in their simulation analyses. During some of the experimental trials, targets were located directly in front of the test vehicle to represent the effect of swiveled headlamps in the direction of the pedestrians. The distances and angular positions of the pedestrian target (a child-sized silhouette) and measured target/pavement luminances are summarized in Table 7.

		Halogen		**HID**	
Distance (m)	**Angle (deg.)**	**Target Lum. (cd/m^2)**	**Pavement Lum. (cd/m^2)**	**Target Lum. (cd/m^2)**	**Pavement Lum. (cd/m^2)**
20	2º	1.26	0.12	1.23	0.12
23	15º	0.11	0.01	0.51	0.04
30	0º	1.17	0.12	1.47	0.15
39	11º	0.06	0.003	0.26	0.01
40	0º	1.00	0.09	1.20	0.10
50	0º	0.38	0.02	0.41	0.02

Table 7: Geometric and photometric characteristics of the targets in the field experiment.

For some of the test locations, the illuminance from a nearby fixed exterior lighting system was approximately 2 lx, corresponding to the maximum ambient illumination level evaluated in the photometric simulation study. In other locations, the illuminance from the fixed system was negligible.

Subjects viewed each of the six target locations under each lighting configuration in a randomized order, in two groups of five. Each subject was seated behind the headlamp system and held a laptop computer that provided instructions and recorded their response times. After the lighting and target condition was set (while subjects looked toward their laptop screens), the software indicated when subjects should look up for a pedestrian target and press the left or right arrow, corresponding to the walking direction of the pedestrian target.

Figure 8: Target used in the field experiment.

Results

Table 8 lists the mean identification times (and standard deviations) for each target location and lighting configuration. In general, for the targets located furthest away or in the peripheral field of view, identification times were longer. A repeated-measured analysis of variance on the identification times revealed statistically significant ($p<0.05$) effects of lamp type and of the use of swiveling in the direction of the targets. Identification times were shorter under HID illumination and when headlamps were swiveled toward the targets.

		Halogen	**HID**
Distance, m	**Angle, deg.**	**Mean Identification Time, s (s.d.)**	**Mean Identification Time, s (s.d.)**
20	2º	1.37 (0.43)	1.43 (0.33)
23	15º	1.87 (0.66)	1.04 (0.30)
30	0º	1.98 (0.35)	1.10 (0.16)
39	11º	5.94 (2.09)	5.22 (1.63)
40	0º	2.20 (0.43)	1.48 (0.21)
50	0	3.79 (1.19)	1.70 (0.55)

Table 8: Mean identification times for each experimental condition.

DISCUSSION

The results from the photometric simulation study and the field experiment suggest that vehicle headlamps have a significant role to play in pedestrian detection along roundabout intersections. Systems such as HID headlamps, which produce greater amounts of peripheral illumination (Van Derlofske et al., 2001, 2002), can result in shorter identification times for pedestrians, including when the location of the pedestrian is not known in advance. Swiveling of headlamps also can improve visual performance by increasing illumination on potential hazards. The use of swiveling headlamps presents a challenge to roundabouts, however, because of the reversals in steering that are needed with navigating through these types of roadway intersections. Perhaps as infrastructure-to-vehicle communications, part of intelligent transportation systems (ITS), evolve, sensor-based communication with vehicle lighting could permit a headlamp system to anticipate and respond to complex roadway geometries.

Regarding modeling of the results from the present experiment, Figure 9 shows that there is a reasonably robust ($r^2=0.81$) negative correlation between the mean measured identification times and the visual performance predictions made from the measured photometric values. This correspondence suggests that the RVP model, used in the photometric simulation described in the previous section of this report, and used by Bullough and Rea (2010) in their study of the interactions between vehicle lighting and fixed roadway lighting, provides predictions that can be used with some degree of confidence in assessing visibility under nighttime driving conditions.

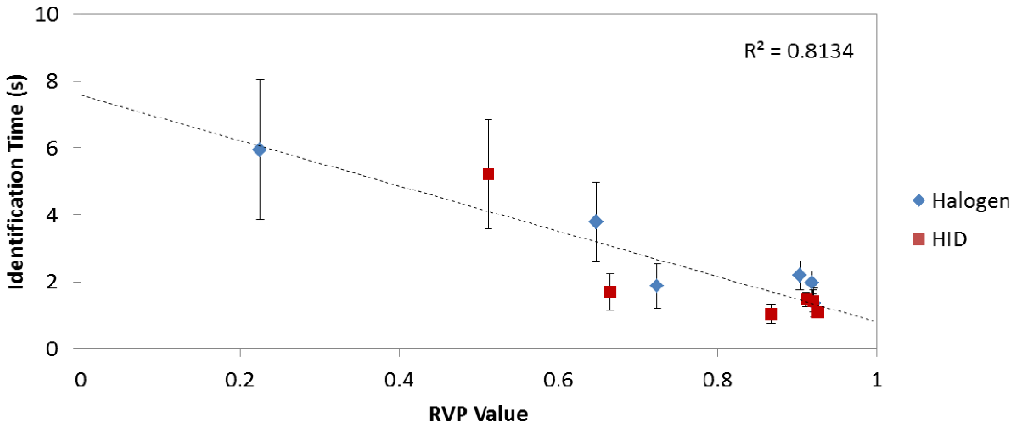

Figure 9: Mean identification times from Table 2 (+/- standard deviation), plotted as a function of the calculated RVP values for each experimental condition.

This point is of particular importance given the recent findings from Bullough and Rea (2011) that reductions in nighttime crashes associated with lighting at different types of roadway intersections in Minnesota were strongly correlated with the increments in visual performance afforded by lighting at those locations. Although that study focused on fixed roadway lighting and no on different forms of vehicle lighting, similar relationships between visual detection/identification times and RVP values to the one in Figure 9, which is for different forward vehicle lighting configurations, have been demonstrated by Bullough et al. (2012) for fixed roadway lighting systems, as well as for sign legibility (Goodspeed and Rea, 1999; Schnell et al., 2009).

The results also suggest that although vehicle lighting and fixed roadway lighting can sometimes interact to reduce the overall visibility relative to when only one of these systems is present, that new headlamp technologies such as those evaluated in the present study can provide greater resistance to these effects than conventional static forward lighting systems. By their nature, vehicle lighting produces relatively high illuminances on vertical surfaces of hazards such as pedestrians ahead of the vehicle. These illuminances increase as a vehicle approaches the hazard. Thus, maintaining targets in positive contrast (with the hazard or target being brighter than its surrounding background) is beneficial for vehicle lighting. Fixed lighting systems have different geometric properties and because they primarily illuminate downward, they can often illuminate the background as much as, or even more than, the target of interest, potentially reducing the visual contrast of the target. By providing generally higher vertical illuminances on targets of interest, such as pedestrians, new headlamp technologies such as HID or adaptive lighting systems reduce the likelihood of contrast reductions that would in turn reduce visibility of hazards such as pedestrians. This may be especially important in less familiar road geometries such as those resulting from the implementation of roundabout intersections.

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