Effects of Warning Lamps on Pedestrian Visibility and Driver Behavior

April 2007

EFFECTS OF WARNING LAMPS ON PEDESTRIAN
VISIBILITY AND DRIVER BEHAVIOR

Interim report of work on Non-Blinding Emergency Vehicle Lighting (NBEVL)

Michael J. Flannagan
Joel M. Devonshire

The University of Michigan
Transportation Research Institute
Ann Arbor, Michigan 48109-2150
U.S.A.

Prime contractor:

SAE International
400 Commonwealth Drive
Warrendale, Pennsylvania 15096-0001

Supported by

Department of Homeland Security (DHS), Federal Emergency Management Agency
(FEMA), United States Fire Administration (USFA)

and

US Department of Justice (DOJ), Office of Justice Programs (OJP)

April 2007

EXECUTIVE SUMMARY

This report describes a field study that was performed to provide better information about how warning lamps for emergency vehicles affect the vision and driving performance of surrounding drivers, with special emphasis on understanding any ways in which those lamps might have negative effects on safety. The situations of most concern for this study are those in which an emergency professional is standing or working near a parked emergency vehicle and is therefore at risk of being struck by passing traffic. In such situations, warning lamps on the emergency vehicle can cause glare for the drivers of passing vehicles, possibly reducing their ability to see and avoid collisions with pedestrians near the emergency vehicle. The present study was designed to address questions in three primary areas:

1. *Nighttime glare from warning lamps.* How do warning lamp characteristics such as intensity, color, and flash pattern affect the tendency for the lamps to reduce the visibility of pedestrians in an emergency scene? How are those effects influenced by the degree of retroreflective marking of the pedestrian?
2. *Effects on driving performance.* How do the visual characteristics of warning lamps and of pedestrians affect drivers' behavior, including lateral position, while passing a parked emergency vehicle? Do drivers tend to deviate toward or away from warning lamps based on their photometric characteristics?
3. *Nighttime photometry.* What are the implications of differences in spectral sensitivity between day and night vision for measuring the light output of emergency lamps in a way that will best describe their effects—both intended and unintended—on drivers of other vehicles? When and how is it appropriate to measure light using photometric units designed for daytime light levels (photopic units) versus those designed for nighttime light levels (scotopic units)?

The study was conducted on a closed-course test track. Participants selected from the driving population were asked to drive on the track at night, while attempting to detect pedestrian mannequins that were positioned near a parked vehicle displaying experimental warning lamps. The warning lamps used LED sources and were varied in color (blue, red), flash pattern (steady, flashing in phase, flashing out of phase), and intensity (low, high). Blue and red were chosen because they are the colors that maximize the differences that can be expected between the color sensitivity of human vision when it is adapted to daytime versus nighttime light levels. The

pedestrian mannequins were varied in the level of retroreflective treatment with which they were marked (none, low, high). Participants also made subjective ratings of the attention-getting properties (conspicuity) of the various states of the warning lamps.

Detection distance for the pedestrian mannequins was affected by characteristics of the warning lamps and by the level of retroreflective marking of the mannequins. These results demonstrate and partially quantify the effect that glare from warning lamps can have on reducing the visibility of nearby pedestrians. However, even with no glare at all, the visibility of the pedestrian mannequins without retroreflective markings was very poor. In contrast, with good retroreflective markings, even very high levels of warning lamp glare may not reduce visibility below acceptable levels. The results of this study partially quantify the effects of the photometric variables involved, but they should be integrated with other data before making detailed conclusions.

Differences between the red and blue lamps used in this study suggest that rod and cone photoreceptors may play different roles in the two main tasks used (pedestrian detection and conspicuity rating). These findings have implications for the most effective way to measure the light output of warning lamps of various colors. Conspicuity ratings were not well predicted by the most common way of measuring light (i.e., photopic photometry).

Red and blue lamps were used in this study to maximize the possible differences between visual responses based on rods and cones. Tentative predictions about lamps with colors that fall between red and blue on the spectrum, such as yellow, can be made with some confidence from the present results by interpolating. However, more data should be collected before making specific recommendations for photometry, including data on other colors that are important for warning lamps, including yellow and white.

At least under the test conditions used here, warning lamps did not have substantial effects on participants' driving behavior in terms of the lateral clearance with which they passed the experimental scene. In contrast, greater pedestrian retroreflectivity led to greater lateral clearance.

Two issues appear to stand out as particularly promising extensions of the present study: (1) how would the effects of color observed in the nighttime conditions of this study be altered under daytime conditions, and (2) how well do subjective ratings of conspicuity correspond to objective measures of the effectiveness of warning lamps in alerting drivers of surrounding vehicles.

CONTENTS

INTRODUCTION

Can the safety of emergency vehicle operations be improved by changes in the design or use of warning lamps? By their nature, emergency vehicle operations involve more risk than is involved in most road traffic, and the use of warning lamps to mark emergency vehicles has long been an important countermeasure for that risk. The present research was designed in the context of two major issues that have recently become important for the effectiveness of warning lamps. First, with the use of stronger warning lamps, there has been concern that warning lamps may sometimes be too strong, and that they may have negative safety effects on surrounding drivers through distraction, disorientation, or reduced vision because of glare. Second, in the area of lighting technology, light emitting diodes (LEDs) have become much more attractive as light sources for warning lamps because of large improvements in their light output relative to their cost. Several characteristics of LEDs make them particularly suited to use in warning lamps, including electrical efficiency, virtually instantaneous onset and offset, and the ability to produce strongly colored signals. Because the visual characteristics of LEDs are different from those of other light sources, the increasing availability of LEDs brings new importance to several issues about how warning lamps should be designed and photometered, especially with regard to color.

The research reported here also reflects the results of a series of analyses of crash data that we recently performed in an attempt to describe the overall safety effects of warning lamps, with a special emphasis on investigating the possibility of negative safety effects (Flannagan & Blower, 2005). That work did not produce evidence for negative effects of overly strong warning lamps. However, one of the major limitations that we identified in our analyses of crash data was that they were not able to directly address one prominent class of situations in which effects of warning lamps might lead to crashes: those in which an emergency professional is standing or working near a parked emergency vehicle and is therefore at risk of being struck by passing traffic. In such situations, warning lamps on the emergency vehicle can cause glare for the drivers of passing vehicles, possibly reducing their ability to see and avoid collisions with pedestrians near the emergency vehicle. Such cases are not easy to identify from crash databases because the emergency vehicle, although it maybe an important causal element in the crash, is not a “contact” vehicle and so will not normally be included in the database. Because of the potential importance of nighttime pedestrian cases, and because they were not well addressed by the crash data, we designed the current research to concentrate on the visual effects of warning lamps in those cases.

Overview of research issues

The present study was designed to address questions in three primary areas:

1. *Nighttime glare from warning lamps.* How do warning lamp characteristics such as intensity, color, and flash pattern affect the tendency for the lamps to reduce the visibility of pedestrians in an emergency scene? How are those effects influenced by the degree of retroreflective marking of the pedestrian?
2. *Effects on driving performance.* How do the visual characteristics of warning lamps and of pedestrians affect drivers' behavior, including lateral position, while passing a parked emergency vehicle? Do drivers tend to deviate toward or away from warning lamps based on their photometric characteristics?
3. *Nighttime photometry.* What are the implications of differences in spectral sensitivity between day and night vision for photometering emergency lamps in a way that will best describe their effects—both intended and unintended—on drivers of other vehicles? When and how is it appropriate to use photometric units designed for daytime light levels (photopic units) versus those designed for nighttime light levels (scotopic units)?

Visibility of pedestrians at night

The problem of nighttime pedestrian visibility near emergency vehicles should be seen in the context of nighttime visibility in general. Recent work on crash data has documented that the major safety problem for driver vision in darkness is pedestrian crashes (Sullivan & Flannagan, 2002). These results are consistent with theoretical analyses of the visibility that can be expected with low-beam headlamps. Such analyses indicate that drivers at night are often overdriving their headlamps, in the sense that they cannot see far enough ahead to be able to react in time to unexpected, low-visibility stimuli such as pedestrians. The distance, or time, that a driver needs in order to react depends on many things: speed, driver age, pavement condition, and so on. However, even for reasonably favorable conditions the visibility distances provided by low beams are not very good. For example, in summarizing the evidence from a number of studies

Rumar (2002) concluded that even for young drivers and relatively bright objects, typical low-beams headlamps do not provide adequate seeing distance to allow drivers to react.

Although glare—from either oncoming headlamps or emergency warning lamps—may reduce drivers' vision at night (e.g., Flannagan, Sivak, Traube, & Kojima, 2000), it is important to determine how much of a visibility problem is caused by glare and how much is attributable to the inherent weakness of low-beam headlamps. It is also important to consider a full set of possible countermeasures, especially including retroreflectorization of pedestrians, which has repeatedly been show to have much larger effects on pedestrian visibility than most other photometric circumstances (e.g., Sayer & Mefford, 2003).

Photometry for day and night vision

In the great majority of applications, photometric measurements are made using "photopic" units, meaning that they involve weighting the wavelengths of the physical energy involved by the photopic luminous efficiency function, shown in Figure 1. This kind of photometry is meant to reflect human visual sensitivity to light under relatively bright conditions, including virtually all daytime conditions. The three different types of cone photoreceptors found in the human retina are responsible for this kind of vision, which is characterized by sensitivity to color and sensitivity to fine spatial details in the center of the visual field. The other function shown in Figure 1, the scotopic luminous efficiency function, is used in a less common, more specialized form of photometry that applies to low-light conditions, including many nighttime conditions. The kind of vision that prevails under those conditions is served by the rod receptors of the human retina, and is characterized by insensitivity to differences among colors and insensitivity to fine spatial detail.

Night driving involves a variety of lighting conditions, from low levels of the range for photopic vision (such as typical pavement just in front of a vehicle, where the low-beam lamps illuminate it strongly), on down to purely scotopic vision. Most stimuli encountered in night driving are in the mesopic range, in which vision is somewhere between purely photopic and purely scotopic.

Warning lamps for emergency vehicles have traditionally been photometered in photopic terms, and this may be reasonable for many purposes. However, given the range of lighting conditions that may be important at night and the various visual tasks that a driver may be faced with, it is not clear that photopic photometry gives the whole story. For example, detecting pedestrians is a task that requires relatively high sensitivity to spatial detail in central vision, and so may depend heavily on cone receptors. In contrast, detecting an emergency vehicle in an unexpected location may often depend on only a low level of spatial detail, and is probably usually done in peripheral vision. Therefore, the conspicuity of emergency warning lamps at night may depend heavily on rod photoreceptors. If these suggestions are correct, then one would expect photopic ("daytime") photometry to be most appropriate for predicting nighttime performance on tasks that involve detecting pedestrians—including measuring the effects of glare in reducing pedestrian visibility—and scotopic ("nighttime") photometry to be most appropriate for predicting the nighttime conspicuity of warning lamps.

The differences between these two forms of photometry can be very large, especially for the strongly colored lamps that are used as warning lamps. As can be seen in Figure 1, the spectral weighting for these two systems of photometry is markedly different. The scotopic system is shifted substantially toward shorter wavelengths (which generally appear as blue) and away from longer wavelengths (which generally appear as red). This difference in spectral sensitivity gives rise to a visual experience known as the Purkinje shift, which can be striking when observed under the right conditions. In a typical demonstration of the Purkinje shift, a blue surface (which reflects mostly short wavelength light) and a red surface (which reflects mostly long wavelength light) are chosen so that they appear about equally bright when seen under normal daytime levels of illumination. When the same surfaces are then observed under low light levels (in the range of moonlight), by people who have visually adapted to those light conditions for 15 minutes or so, the blue surface will appear much brighter than the red surface (and both surfaces will appear silvery gray rather than blue or red). In the work reported here, we used red and blue LEDs to provide a clear contrast between predicted performance based on photopic and scotopic photometry.

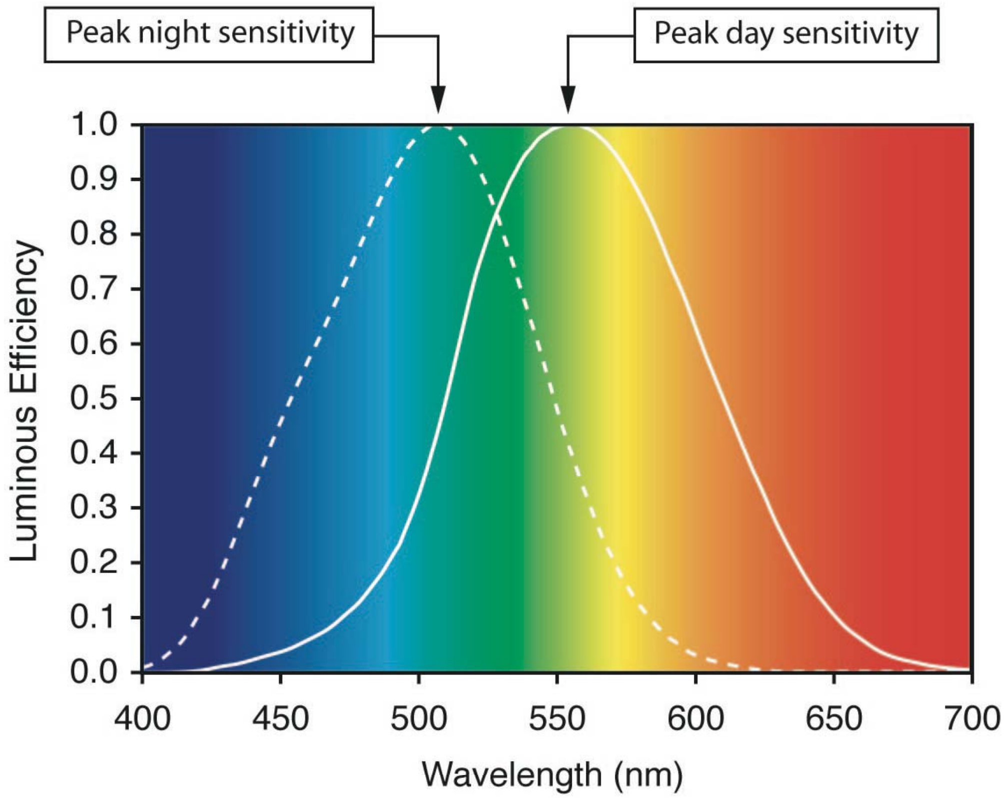


Figure 1. The scotopic (dashed line) and photopic (solid line) luminous efficiency functions, describing the spectral sensitivities of night and day vision, respectively.

Overview of the experimental approach

The primary task that we set for participants in this research was to drive on a closed-course track, at night, and to detect pedestrian mannequins on the side of the road. The mannequins were placed just beyond a parked vehicle that we equipped with very intense warning lamps. We asked the participants to indicate as quickly as possible when they could detect the pedestrian mannequin, and we measured the distance at which they responded. We varied the intensity, color, and flash pattern of the warning lamps, as well as the retroreflective treatment of the pedestrian mannequins.

Because one of the major purposes of this research was to investigate possible negative effects of strong warning lamps, we made the highest photometric levels of the lamps particularly strong. The levels of glare that participants encountered were in the range that would be experienced from typical low-beam headlamps rather than typical current warning lamps.

We sampled the participants from the normal driving population, but to provide a variety of visual abilities and driving styles we selected them from young and old ranges of driver age. We also balanced the groups by gender.

Because we were interested in how warning lamps might affect driving behavior, we had participants drive instrumented vehicles that could record various aspects of how they drove. In order to better control the relevant light levels and reduce safety concerns, we had them drive on a closed-course test track. The use of a track means that they did not encounter the full range of complexity and unexpected conditions that drivers face in the real world, but they still had to perform many of the basic tasks involved in night driving.

METHOD

Participants

Eight people participated in the study. Four were in a younger age group (between 22 and 29 years old with a mean age of 24.8 years) and four were in an older age group (between 63 and 73 years old with a mean age of 68.5 years). Each age group had two men and two women. The participants were recruited from a list of volunteers maintained at UMTRI, and were paid a nominal amount for their participation. All participants were licensed drivers with visual acuity that fell within legal driving limits.

Tasks

In the first part of the experiment, participants were asked to drive on a closed-course test track and to detect a pedestrian mannequin that was positioned on the side of the road near a stationary vehicle. The following instructions were read to each participant at the beginning of the experiment:

> During this study, you will be driving a car for a number of laps around a closed test track. On one straight section of the test track, we have set up a parked car with an experimental set of emergency warning lamps, similar to the lamps used by fire, police, and other emergency vehicles.
>
> On most but not all laps, there will be a pedestrian mannequin on the side of the road just past the parked car. We would like you to report as quickly as possible when you see the mannequin. Please indicate that by saying "now." The experimenter in the car with you will record that point, and we will measure the distance at which you reported seeing the pedestrian.
>
> The lamps will be different from lap to lap, and sometimes they will not be on at all. (However, the tail lamps of the parked car will always be on.)
>
> As you drive down the straight section of track toward the parked car, please try to drive at about 35 MPH (however, please never drive faster than you feel is safe). After you have passed the parked car, you can speed up in order to get around the track faster. We would suggest driving about 50 MPH, but again, never drive faster than you feel is safe.

The second part of the experiment consisted of a magnitude estimation task in which the participants were asked to give ratings of the conspicuity (attention-getting quality) of each of a series of warning lamps. The instructions read to the participants follow:

> Please rate how attention-getting each lamp is, assigning a number from 1 to 10, where 1 is least attention-getting and 10 is most attention-getting. We would like you to fix your gaze on the rear-view mirror for the entire time you are providing ratings.

Test site and materials

The experiment was conducted on a 1.75-mile test track in Ottawa Lake, Michigan (see Figure 2). The track had three 4.6-m (15-ft.) lanes, and consisted of two straight sections and two 7° banked curves. The straight sections were each roughly 0.8 km (0.5 mi) long. All sessions were conducted at night with dry pavement.

Figure 2 also shows the approximate placement of the stationary vehicle and pedestrian mannequin. The stationary vehicle was parked in the same location every evening, half a meter from the outside lane edge. The mannequin was placed further down the track, 10 m from the front bumper of the parked vehicle and half a meter from the lane edge.

Participants drove vehicles from the UMTRI fleet of instrumented vehicles (2003 Nissan Altima 3.5SE sedans, see Figure 3). These vehicles were equipped with standard low and high beam headlamps (only the low beams were used during the study). For each session, two participants, in two separate vehicles, were run on the track simultaneously. A reasonably constant separation was maintained between the two moving vehicles so that the lead vehicle would not cause any visual disturbance for the following participant.

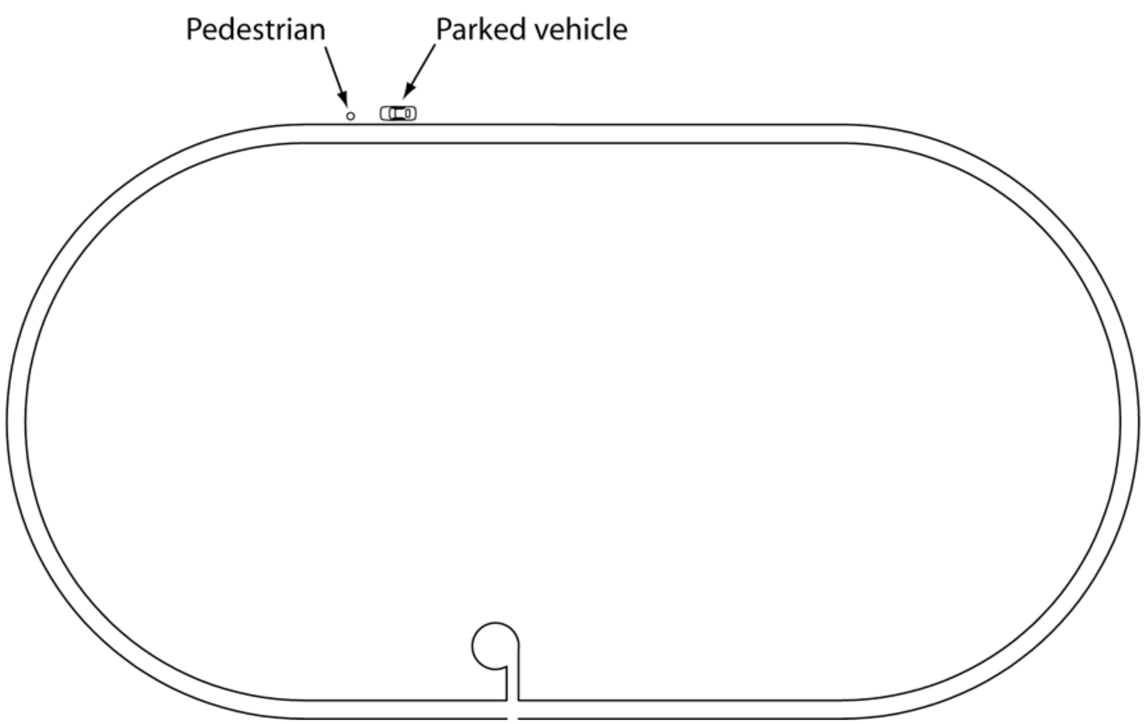


Figure 2. Diagram of the test track showing the approximate locations of the parked vehicle and pedestrian (not to scale). The straight sections on each side of the track were 0.8 km (0.5 mile) long. Participants always drove counterclockwise.

Figure 3. The fleet of instrumented vehicles (2003 Nissan Altima 3.5SE sedans), and a view of the main instrumentation package in the trunk of one of the vehicles.

Figure 4 shows the vehicle that was used as the stationary vehicle (a 1993 Nissan Altima), with the experimental warning lamps mounted on its roof, and a pedestrian mannequin. The stationary vehicle was equipped with standard passenger car rear lamps and red retroreflective markers. The mannequin was inflatable and was attached to a stand so that it would remain upright. Figure 5 shows the parked vehicle and a pedestrian mannequin, as they would be seen by a participant approaching them on the test track.

There were three mannequins, designed for different levels of visibility. All mannequins had the same low-reflectance clothing. One had no retroreflective treatment, and the other two had two different levels of treatment. The retroreflective markings used on the mannequins were based on the specifications in the National Fire Protection Association standard NFPA 1971 “Standard on protective ensemble for structural fire fighting” (NFPA, 1997). The retroreflective strips were applied as shown in Figure 4. All of the strips were the minimum specified width (1.6 cm). The coefficients of retroreflection of the material (R_a) for the two levels of retroreflectivity were 700 and 175 cd/lux/m^2 (observation angle 0.2°, entrance angle -4°). Both of those levels are above the minimum specified by NFPA 1971 (100 cd/lux/m^2). We do not have data on how these values compare to turnout gear in actual use, but we assumed that such gear also at least somewhat exceeds the minimum specifications.

Figure 4. The car that was used as the stationary vehicle, with the experimental warning lamps mounted on its roof, and one of the pedestrian mannequins, showing the retroreflective strips.

Figure 5. The warning lamps and pedestrian mannequin from the driver's perspective.

The experimental warning lamps are shown in Figure 6. The lamps were attached to an adjustable rack that could be positioned at marked locations on the vehicle's roof, as shown in Figure 4. As can be seen in Figure 6, the lamp rack consisted of 4 rows of 8 LED modules (each of which consisted of 3 LEDs). The lamps were purchased from a supplier of emergency lighting equipment. They were made of components that are all currently commercially available, but they were selected to produce a narrower and more intense lighting pattern than would be typical on current emergency vehicles. This was so that the lamps could produce higher light levels at the eyes of approaching drivers than is currently typical. The strategy was made possible by the fact that participants in this experiment would always be approaching the experimental lamps along a relatively constrained path (the designated lane of the test track). In normal applications, there is more concern for the visibility of the lamps from a wide range of angles around an emergency vehicle, and lighting instruments therefore have to distribute light widely.

Each horizontal row of LEDs was a single color, either red or blue. Numbering from the top, rows 1 and 3 were blue, and rows 2 and 4 were red. A 0.50 transmittance neutral density filter sheet was attached to the top of the light rack, such that it could be positioned over the front of the lamps when necessary. The lamps could be operated in twelve different modes, defined by the factorial combinations of color (blue, red), flash pattern (steady, flash-together, flash-alternate), and intensity (with or without the neutral density filter). In the red and blue conditions, all LEDs of the appropriate color were used, and the two colors were never used together. Thus, for the steady patterns both rows of red or blue LEDs were on continuously. The flash-together and flash-alternate patterns are illustrated in Figure 7. In the flash-together conditions, all LEDs of the appropriate color would turn on and off in unison, thus producing all-dark intervals separated by all-on intervals. In the flash-alternate conditions, half of the LEDs of the appropriate color would be on while the other half were off, with that state then switching to one in which the units that had been off were on and vice versa. As shown in Figure 7, the units that were on were always grouped so that the left half of one row would be on with the right half of the other row of the same color, and vice versa. Thus, in the flash-alternate conditions, at any one time half of the LEDs of the appropriate color would be on and half would be off. The two levels of intensity were produced by covering, or not covering, the entire array of lamps with the

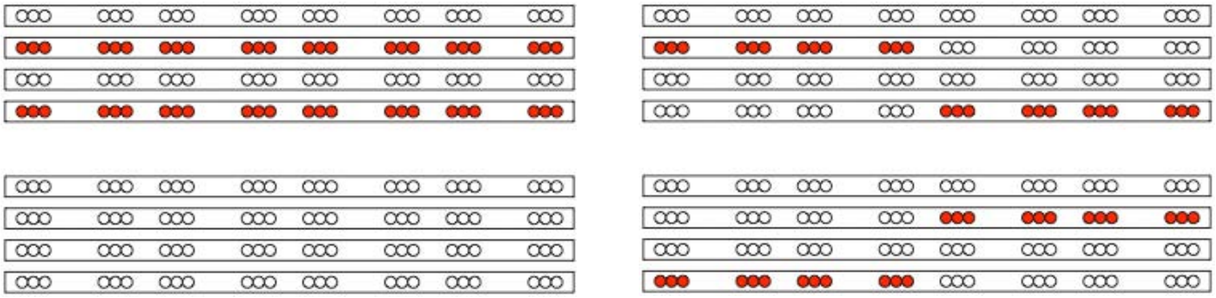
0.50 transmittance filter. For all of the flash patterns, the duty cycles of all the LEDs involved were 0.50 and the flash rate was 2 Hz.

The spectral power distributions for the blue and red LEDs are shown in Figure 8. Other photometric information for the lamps is shown in Table 1 and Figure 9. The blue LEDs had a peak wavelength of 460 nm and the red LEDs peaked at 640 nm. The scotopic/photopic (S/P) ratios were very different from unity: the S/P ratio for the blue LEDs was 16.1, and the S/P ratio for red was 0.053. Table 1 also shows the maximum intensity values that drivers were exposed to during their approaches to the warning lamps on the test track. These values are shown in terms of both photopic candelas (the relatively common, daytime, photometric units), and in scotopic candelas (the photometric units for low-light, nighttime, vision). The values in Table 1 illustrate how these intensity values are related to the S/P ratios.

The maximum intensity values were encountered, for both the red and blue lamps, at 40 m behind the parked vehicle. This was because the lamps were aimed slightly toward the track side of the parked vehicle, so that their axes and maximum intensities would lie as much as possible along the lane in which the participants approached the parked vehicle. Figure 9 shows the illuminance (in photopic lux) from the lamps along the track of a driver's eye approaching in that lane at various distances behind the parked vehicle. These values do not take into account the transmittance of the windshield. Because these are illuminance values, rather than intensity values, they do not peak at 40 m (where intensity was highest) but rather continue to increase at shorter distances, as a consequence of the inverse-square law.

As is evident in both Table 1 and Figure 9, the red LEDs had higher output than the blue LEDs in the more conventional terms of photopic units. However, the relationship was reversed in terms of scotopic units. It would have been desirable for some experimental purposes to have the photometric ranges of the two colors overlap, but because of the great disparity in S/P ratios, and because the relative roles of photopic and scotopic units were in question in this study, that could not be accomplished without very wide ranges of photometric values.

Figure 6. The LED lamp array that was used on top of the parked vehicle.



Flash-together | Flash-alternate

Figure 7. The flash-together and flash-alternate patterns, illustrated for the red lamps. The filled circles represent lamps that are on. Each cycle consisted of one of the upper configurations succeeded by the corresponding lower configuration, with each configuration being on for half of the cycle.

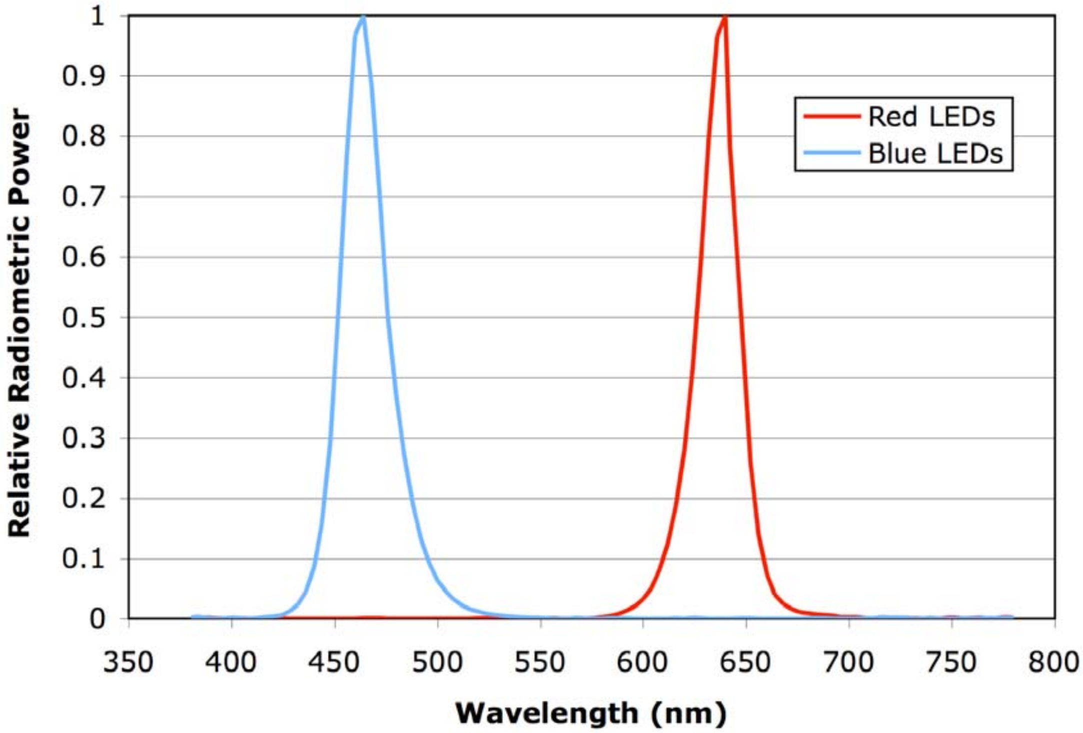


Figure 8. Spectral power distributions for the blue and red LEDs. The blue spectrum peaked at 460 nm and the red spectrum peaked at 640 nm.

Table 1. Photometry for the blue and red LED lamps

LED color	S/P ratio	Peak wavelength (nm)	Peak glare intensity	
			Photopic cd	Scotopic cd
Blue	16.1	460	2,270	36,500
Red	0.053	640	15,500	820

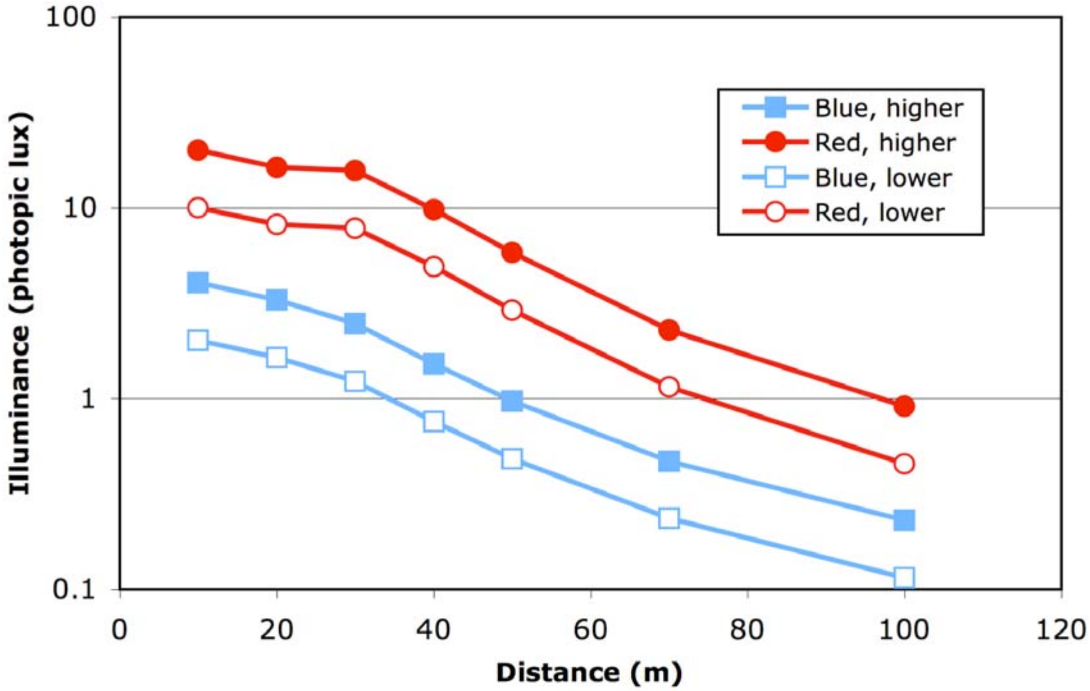


Figure 9. Illuminance (photopic lux) at the subject's eye points at various distances behind the parked vehicle on which the warning lamps were mounted, for the two intensities of each color.

Experimental design and stimuli

There were two parts to the experiment, both of which consisted of a repeated measures factorial design (in which each participant experienced every level of the independent variables). For all subjects, the first part was the pedestrian detection task and the second part was the rating of conspicuity.

In the pedestrian detection task, the independent variables were warning lamp color (blue, red), warning lamp flash pattern (steady, flash-together, flash-alternate), warning lamp intensity (low, high), and pedestrian retroreflective treatment (none, low, high). The combinations of those variable produced 2 x 3 x 2 x 3 = 36 conditions, each of which was run once per subject. In addition, 4 trials were run with the warning lamps off (all with the pedestrian present: 2 without retroreflective markings and one each with the two levels of retroreflective markings), and 4 trials were run with the pedestrian absent, as catch trials for the detection task. Thus, 44 trials were run for each participant. Each trial consisted of one circuit of the test track, which took about two and a half minutes. The order of the 44 trials was randomized for each session.

Because two participants were run in each session, the order of trials was the same within those pairs of participants.

In the conspicuity rating task, the independent variables were those that applied to the lamps: color (blue, red), flash pattern (steady, flash-together, flash-alternate), and intensity (low, high). The factorial combination of those variables produced 2 x 3 x 2 = 12 conditions. Each of those was presented once per session, in randomized order. As with the pedestrian detection task, because two participants were run in each session, the order of trials was the same within those pairs of participants.

Procedure

Each participant took part in one nighttime session, beginning after the end of civil twilight (when the sun is six degrees below the horizon). After arriving at the test location, participants completed a visual acuity screening test and were driven to the closed-course track. The participants then entered the test vehicles, and experimenters read instructions to them and answered any questions. The low-beam headlamps of the test vehicles were turned on at the beginning of the session and left on throughout the session.

The participants were asked to drive continuously around the track in the outermost of the three lanes, traveling about 45-50 mph except in the straight section where the stimuli were located. For each lap, participants were asked to slow down to about 35 mph as soon as they reached the beginning of that straight section. The participants then drove at this speed and indicated, by saying "now," when the pedestrian mannequin was visible. The experimenter recorded this distance by pressing a button and releasing it when the vehicle passed the mannequin.

Each time the second of the two test cars passed the pedestrian, an experimenter near the stationary vehicle changed the stimuli to prepare for the next trial. The experimenter applied these changes by setting the color and flash pattern of the lamps, by applying or removing the neutral density filter that reduced the intensity of the lamps, and by placing the appropriate mannequin in its position.

After all the pedestrian detection trials were completed, the participants were asked to stop their vehicles at a marked point that was 200 meters behind the parked vehicle with the warning lamps. They were then asked to look at the interior rearview mirrors of their vehicles and continue looking there for the duration of the second part of the experiment. This direction of gaze meant that the warning lamps would appear about 45° to the left of the center of their visual fields. The various warning lamp conditions were then presented in random order, and the participants rated the conspicuity of each stimulus by assigning it a number from 1 to 10.

Three experimenters were involved in the experiment. One experimenter sat in the rear seat of each of the two moving vehicles, accompanying each of the participants and marking their detection distances. The third experimenter was positioned next to the stationary vehicle and changed the stimuli between trials.

RESULTS

Detection distance

Detection distances were analyzed with a linear mixed-effects model. The model considered the variables age group (young, old), gender (male, female), color of the warning lamps (blue, red), warning lamp flash pattern (steady, flash-together, flash-alternate), warning lamp intensity (low, high), and pedestrian retroreflective treatment (none, low, high).

The effect of age group was significant, $F(1,4) = 14.5$, $p = .019$. As might be expected, the younger subjects detected the pedestrians, on average, at substantially longer distances than the older subjects (see Figure 10).

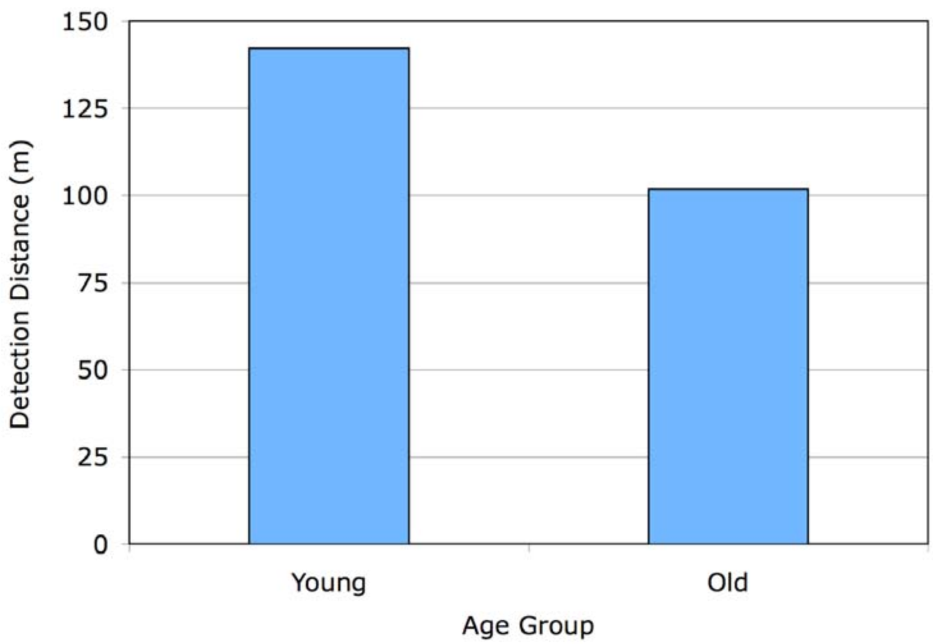


Figure 10. The effect of age on detection distance.

As might also be expected, pedestrian retroreflectivity had a significant, $F(2,10) = 318.6$, $p < .0001$, and very substantial effect on detection distance (see Figure 11).

The effect of lamp activation state also had a significant, $F(2,231) = 59.2$, $p < .0001$, but less dramatic effect of detection distance (see Figure 13). Detection distance was longest when the warning lamps were off, consistent with general expectations based on glare effects. The shortest detection distances were obtained when the warning lamps were continuously on (the steady condition). This also makes sense, considering that the light output, averaged over the duration of a flash cycle or more, was actually greatest in that condition. Both of the flashing conditions involved switching units off half of the time. In the flash-alternate condition, for example, only half of the units were on at any given time. In the flash-together condition, there were times when all the units were on, but half of the time they were all off. This latter pattern is probably responsible for the fact that the second longest detection distances were obtained in the flash-together condition. Participants may have been able to discern the pedestrian mannequin with no glare effects during the parts of the cycle with all of the lamps off.

There was a significant interaction between pedestrian retroreflectivity and lamp activation state, $F(4,231) = 8.3$, $p < .0001$. Figure 13 shows detection distance for each of the combinations of those variables. When the pedestrian has no retroreflective markings, detection distances are critically short even in the absence of glare (and even though the detection task involved very little uncertainty, unlike typical real world driving). For example, Rumar (2002) in a deliberately simple summary of a large body of work on visibility needs in night driving, suggested that, for typical levels of speed and other conditions, the best single estimate for required seeing distance was 150 m. While it could easily be argued that the distance actually required in often shorter, this is a reasonable approximate standard against which to judge the distances in Figure 13. Certainly, the distance for the unmarked pedestrian without glare—under 60 meters—is too short to allow effective response by most drivers in most conditions.

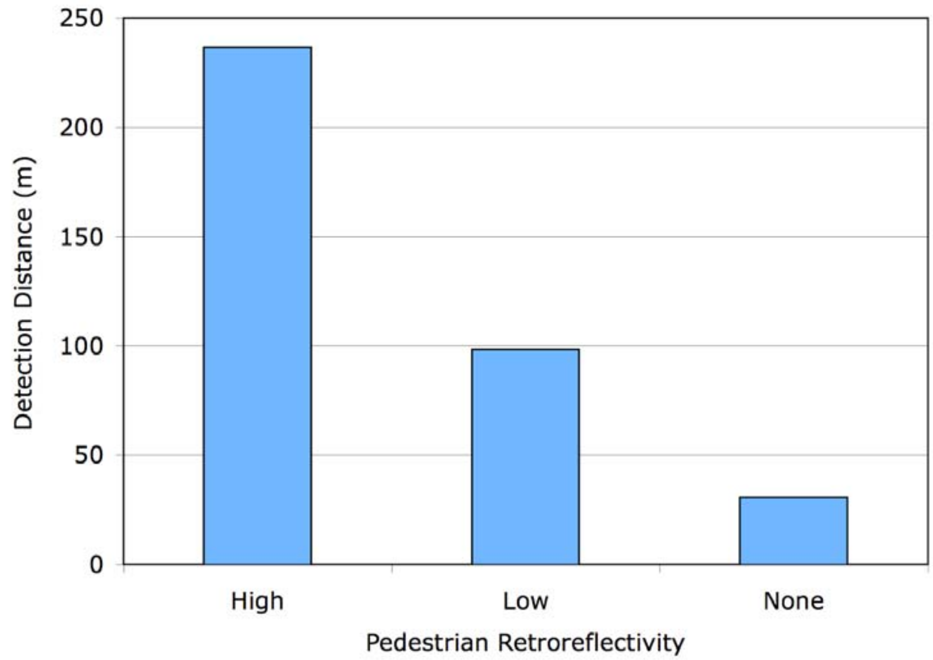


Figure 11. The effect of pedestrian retroreflectivity on detection distance.

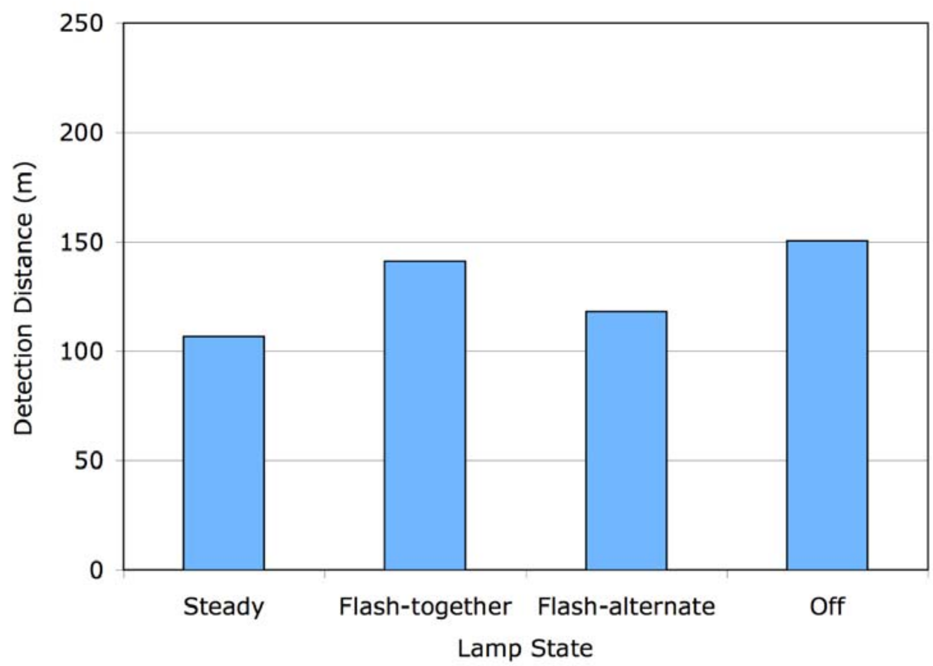


Figure 12. The effect of lamp state on detection distance.

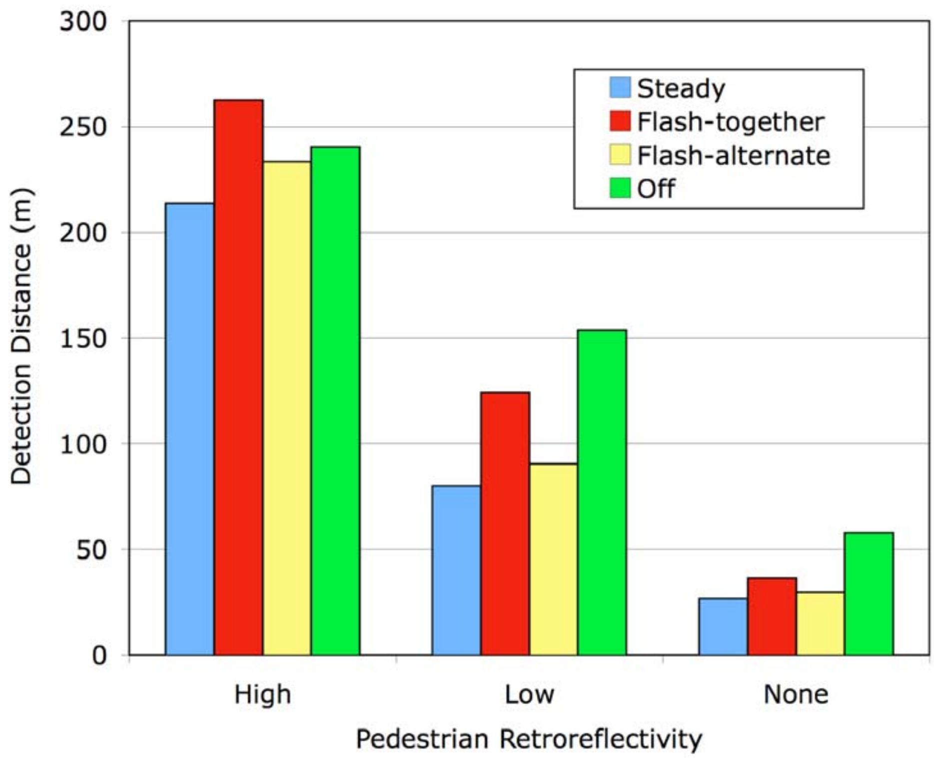


Figure 13. The combined effects of pedestrian retroreflectivity and lamp state on detection distance.

The general analysis showed a significant effect of color on detection distance, $F(1, 4.96) = 20.8$, $p = .0062$, which is displayed in Figure 14. However, it is not very informative to compare the outcomes for the two colors without considering the photometric levels involved. As shown in Table 1, the expected direction of the effect of color depends on which form of photometry is used. Using photopic values, the red lamps are considerably more intense than the blue ones, and detection distances should be shorter for red, because of increased glare effects. Alternatively, using scotopic values, the blue lamps are considerably more intense than the red ones, and the predicted effect on detection distances is also reversed. The fact that the outcome shows greater detection distance for blue suggests that predictions based on photopic photometry are more appropriate.

We will return to a more detailed analysis of the effect of color on detection distance, considering details of photometric levels, but first it is useful to review the results of the conspicuity rating task in order to illustrate a striking difference in how color affects the two dependent variables.

The conspicuity ratings were analyzed using the same independent variables as for the detection distance analysis, except for pedestrian retroreflectivity, which did not apply because the pedestrians were not part of the rating task. Color had a significant effect on conspicuity ratings, $F(1,4) = 12.6$, $p = .024$. The effect is shown in Figure 15. Just as for the effect of color on detection distance in Figure 14, it is not very informative to look at the effect of color on conspicuity ratings without considering the photometric values. Referring again to the values in Table 1, there are alternative predictions based on photopic and scotopic photometry. The photopic values show the red lamps to be much more intense than the blue ones, suggesting that they should be rated as more conspicuous; in contrast, the scotopic values would suggest that the blue lamps should be rated more conspicuous. In fact, conspicuity ratings were higher for the blue lamps, suggesting that in this case the scotopic photometric values are more appropriate for predicting the experimental outcome. This is opposite the conclusion in the case of pedestrian detection distance, in which it appeared that the photopic values led to the better prediction.

In summary, for the light levels used in this study, the blue lamps appeared to be weaker than the red lamps in terms of their effects on detection distances (in the sense that they appeared to cause less reduction in detection distance through glare), while at the same time they appeared to be stronger than the red lamps in terms of their effects on ratings of conspicuity. Taken together, the divergent effects of color on these two dependent variables seem to indicate that the effects of color depend on the nature of the task involved. That is consistent with the ideas involving rods and cones that were discussed earlier. It may be that detection of pedestrians depends primarily on cone photoreceptors, and therefore is better predicted by photopic photometry, while conspicuity of warning lamps at night depends primarily on rod photoreceptors, and therefore is better predicted by scotopic photometry.

Lamp activation state also had a significant effect on ratings of conspicuity, $F(2,8) = 40.5$, $p < .0001$, which is shown in Figure 16. The flash-together condition was rated most conspicuous, probably because it involved the greatest transitions in light levels, between periods in which all units were off and periods in which all units were on. Although the flash-alternate condition did involve some transitions, in contrast to the steady condition which did not, it was rated the least conspicuous. This may have been because the transitions were weaker than in the case of the flash-together condition, involving changes in which units were active but no change in the number of active units, and because the amount of light emitted by the whole array of lamps was twice as great in the steady condition compared to the flash-alternate condition.

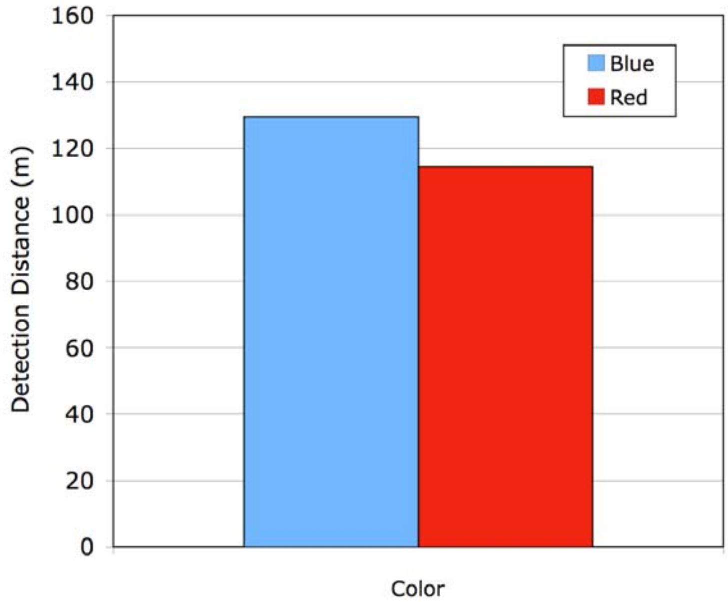


Figure 14. The overall effect of color on detection distance. This summary does not take into account the actual photometry of the blue and red lamps. See text for details.

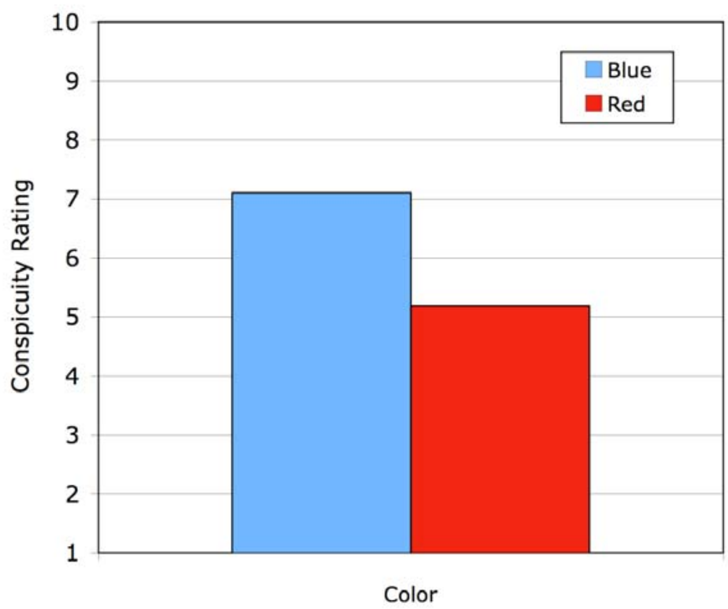


Figure 15. The overall effect of color on conspicuity ratings. This summary does not take into account the actual photometry of the blue and red lamps. See text for details.

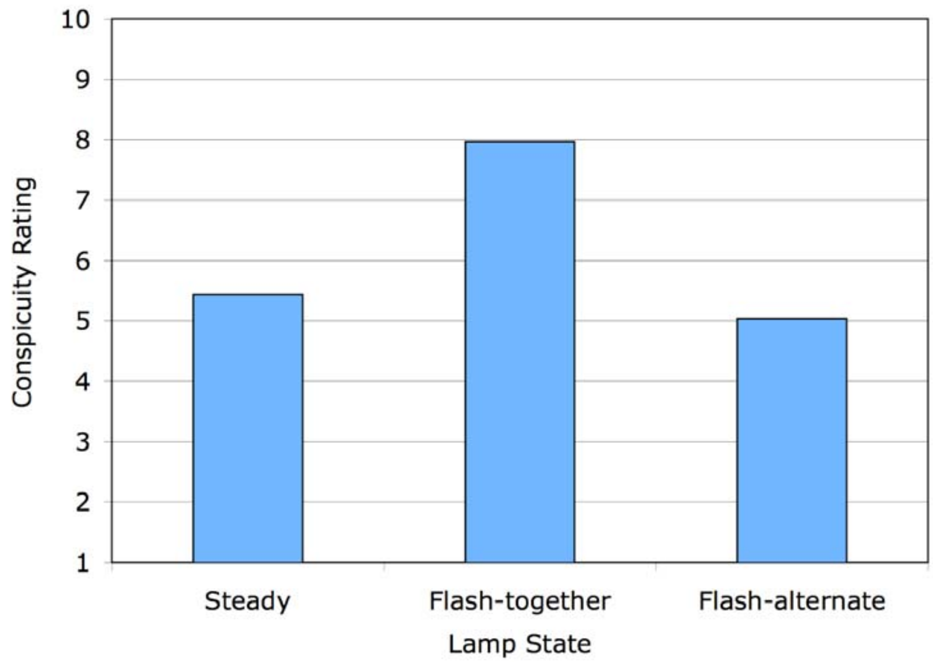


Figure 16. The effect of lamp state on conspicuity ratings.

Figure 17 and Figure 18 show more detailed analyses of detection distances and conspicuity ratings, including a breakdown by the levels of intensity produced with the 0.50 transmittance filter. In both figures, the dependent variables have been graphed against both photopic and scotopic candela values. The patterns in these figures can be used to develop slightly more detailed versions of the arguments suggested above in connection with the results in Figure 14 and Figure 15.

For detection distance, greater intensity of the warning lamps should lead to shorter detection distances (because of the role of the warning lamps as glare sources). If photopic photometry entirely predicts the effects of both the blue and red lamps, then the data plotted against photopic intensity (the filled symbols in Figure 17), should fall on a single line, with negative slope. This is approximately the case, except that the data points for the blue lamps appear a bit too low, indicating that the effect of the blue lamps is stronger than the effect of the red lamps even after photopic intensity is taken into account. However, what is most clear is that the scotopically plotted points (the open symbols in Figure 17) are not even nearly aligned with a single function with a negative slope. As before, it appears that photopic photometry is a better way to predict effects on pedestrian detection than scotopic photometry.

The results in Figure 18 can be discussed in a similar way. If scotopic photometry entirely predicts conspicuity ratings, then the data plotted against scotopic intensity (the open symbols in Figure 18) should all fall on a single line, with positive slope. This is approximately what the data show, although there is a small deviation in that the average conspicuity ratings for the two intensity levels of the red lamps are reversed from what would be expected. It is difficult to devise an explanation for why a less intense lamp would be rated as more conspicuous than a more intense lamp, with all other qualities equal. This specific difference is not statistically reliable, and—given how surprising it is—it may best be attributed to chance. As in Figure 17, the overall comparison of scotopic and photopic predictors is clear. For conspicuity ratings, the scotopic values seem to predict reasonably well, while the photopic values (the filled symbols in Figure 18) lead to an overall pattern with a negative slope, opposite what would be expected for conspicuity.

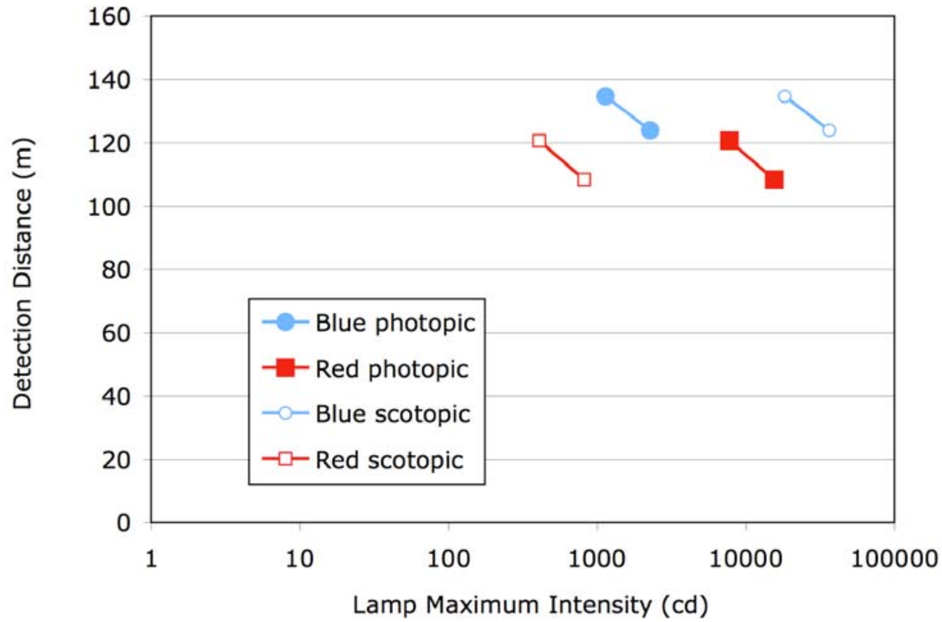


Figure 17. Detection distances as functions of alternative photometry (photopic and scotopic) for the red and blue LEDs.

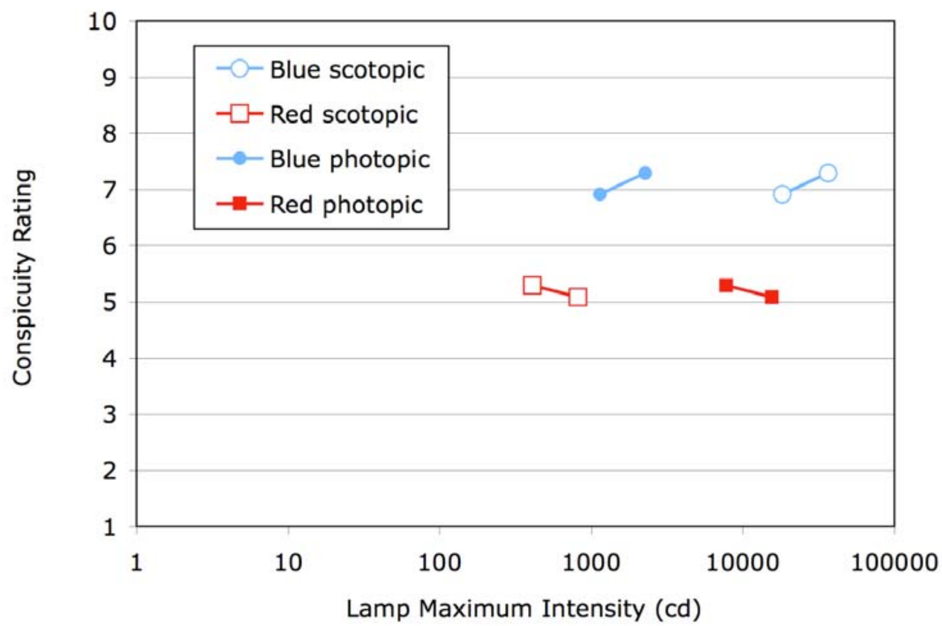


Figure 18. Conspicuity ratings as functions of alternative photometry (photopic and scotopic) for the red and blue LEDs.

An analysis was made of the lateral clearance between the participants' vehicles and the parked vehicle at the point that the parked vehicle was passed. The dependent variable was the distance between the two closest parts of the vehicles. The independent variables in the analysis were the same as for the analysis of detection distance. There was a significant, $F(2,10) = 24.6$, $p < .0001$, and substantial effect of pedestrian retroreflective markings, as shown in Figure 19. There were no main effects of lamp variables (color, flash pattern, and intensity) on lateral clearance. As one illustration of the lack of effects, Figure 20 shows lateral clearance values for the higher and lower intensity levels of the blue and red lamps.

It appears that warning lamp characteristics, at least under these conditions on a closed-course test track, do not have substantial effects on drivers' lateral control. The participants in this experiment did not show a tendency to be closer or further from the parked vehicle as they passed it based on the type of warning lamps it was displaying. However, they did pass the vehicle with greater clearance when the pedestrian mannequin was more strongly marked with retroreflective material. It is not clear why they did this, although it may be because they detected the mannequin earlier when it was better marked and so were able to alter their course to be further to the left at the point of passing. (The range of retroreflective treatment—from none at all to well above the minimum requirements of NFPA 1971—was large, and clearly had a strong effect on detection distance, as shown in Figure 11.) If the pedestrian were an actual person, such a strategy might be attributable to a desire on the part of the participants to provide a wider safety margin for that person. However, it was clear to all of the participants in this study that the mannequin was in fact not a real person. Furthermore, although they were told that the mannequin would not always be present, they all probably quickly understood that it would usually be present (on 91% of the trials). Given that it was always a good bet that the pedestrian mannequin would be present, and that the presence or absence of the mannequin did not objectively affect the appropriate level of concern for safety, it may be that something about the immediate visual appearance of a person-like object had an influence on the participants' behavior.

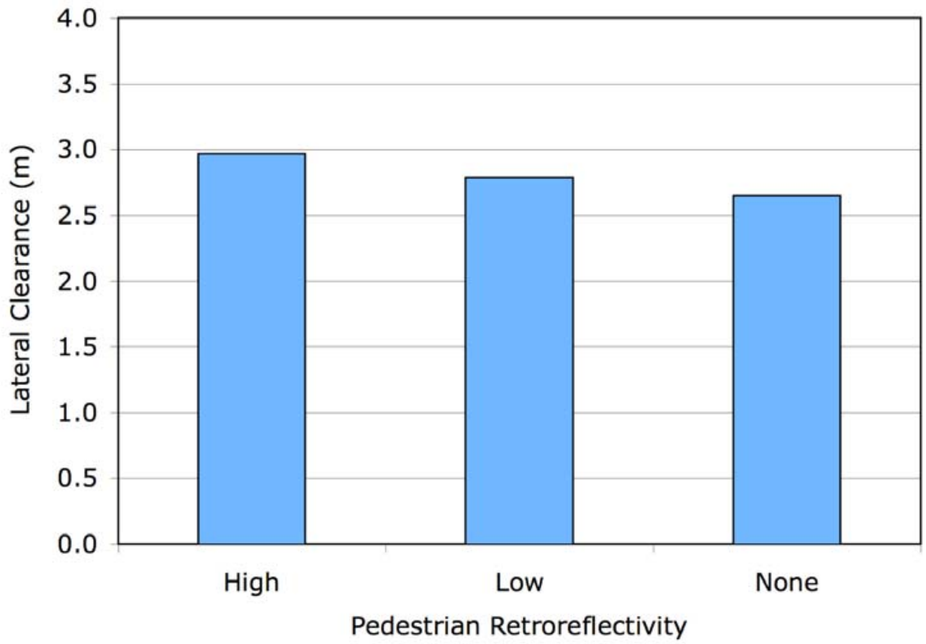


Figure 19. The effect of pedestrian retroreflectivity on lateral clearance.

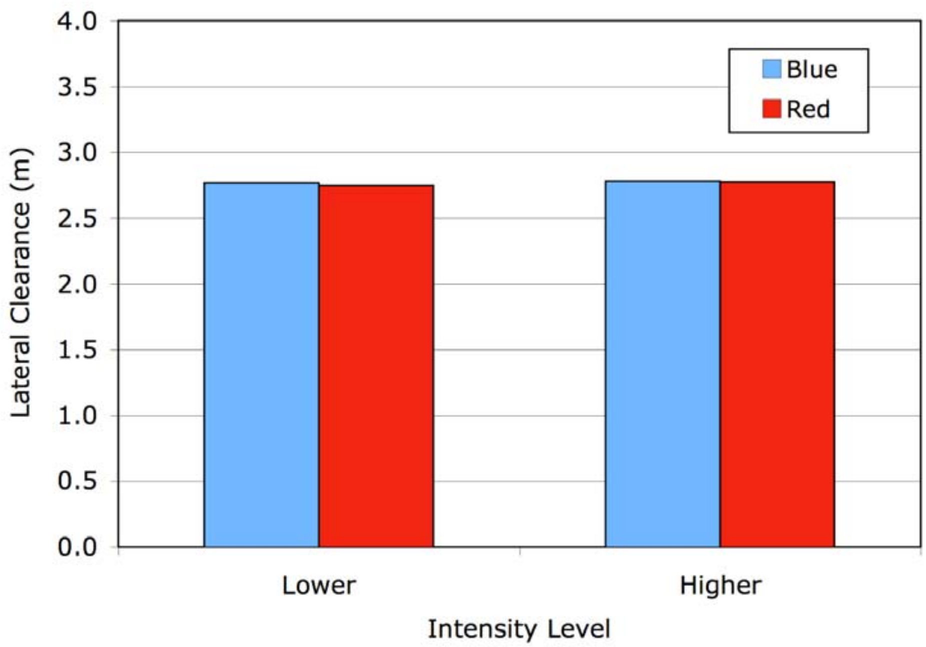


Figure 20. Lateral clearance for each combination of color and intensity level. There were no significant differences among these conditions.

DISCUSSION AND CONCLUSIONS

The results of this study have a number of implications for the effectiveness of emergency vehicle warning lamps and for the safety of pedestrians near emergency vehicles at night. However, all of these implications should be seen within the context of the experimental situation that was used: a closed-course test with reasonably alert and cooperative subjects. Conclusions about basic visual performance, based on the measurement of detection distance, are probably the simplest to evaluate. Conclusions based on ratings of the subjective conspicuity of the warning lamps should be regarded as more tentative. Although previous methodological research on warning lamps has shown good correlations among subjective ratings, detectability in peripheral vision, and photometric values (Howett, 1979), there may be ways in which subjective ratings do not fully correspond to the objective effectiveness of warning lamps. Conclusions based on the driving behavior of the participants in this study should probably be regarded as suggestive of what may be happening in real traffic situations, but should not be regarded as conclusive. The subjects in this experiment knew that they were driving under conditions that were very controlled and, compared to the world of real traffic, very safe.

The measurements of detection distance in this study confirmed the already well-established importance of retroreflective markings for pedestrian visibility with low-beam headlamps. Warning lamps, at least at the very high light levels used in this study, can measurably reduce the visibility of pedestrians in an emergency scene by causing glare for passing drivers. However, even with no glare at all, the visibility of pedestrians without retroreflective markings was very poor. Also, if pedestrians have good retroreflective markings, even very high levels of warning lamp glare may not reduce visibility below acceptable levels. The results of this study partially quantify the effects of the photometric variables involved, but they should be integrated with other data before making detailed conclusions.

For the two LED colors used in this study (red and blue), photopic photometry appears to correlate reasonably well with the tendency of warning lamps to reduce pedestrian visibility through glare. Scotopic photometry—rather than photopic photometry—appears to correlate reasonably well with subjective ratings of the attention-getting properties of warning lamps. These findings suggest that cone photoreceptors (which serve daytime, or high-light-level, vision) may be most important for the visual task of detecting pedestrians under the conditions used in this study, and that rod photoreceptors (which serve nighttime, or low-light-level, vision) may be most important for determining how noticeable warning lamps are under the conditions used in this study.

Red and blue lamps were used in this study because those colors maximize the difference between photometric values for the lamps in terms of photopic and scotopic forms of photometry. In principle, the effects of lamps of other colors (e.g., yellow, white) should be predictable by interpolation based on the results for red and blue. However, given the exploratory nature of the present study, it would be valuable to make direct tests of other colors.

A possible practical consequence of the effects of color observed in this experiment is that, at least for nighttime conditions, the blue lamps used in this study showed both higher conspicuity and lower glare effects than the red lamps. This can be seen directly by comparing Figure 14 and Figure 15. Blue thus appears to be a better choice than red in terms of either variable. Any conclusion from these results about the overall benefits of blue versus red (or other possible colors) should be considered tentative, but these results are consistent with other suggestions that there may be advantages to blue lamps. The New York State Police began using blue lamps visible to the rear of their vehicles in 2006 as a countermeasure for the vehicles being rear-ended, partly based on indications that the blue lamps had a visibility advantage over red at night (H. Litardo, personal communication, December 2006). Also, a series of day and night tests of innovative lighting systems conducted in Florida (Wells, 2004), showed an advantage of blue over red at night relative to day. Figure 21 shows two of the lighting conditions that were evaluated in the Florida work. (In addition to the roof-mounted red and blue lamps, a variety of other lamps, were tested, including the yellow lamps visible in the rear window of the vehicle shown in Figure 21.)

Figure 21. Blue and red lamps used in the study by Wells (2004).

At least under the test conditions used here, which include reasonably alert drivers, there is no evidence of a tendency for driving behavior to be affected by the characteristics of warning lamps. The dominant influence on drivers' lateral position while passing the experimental scene appears to have been the visibility of the pedestrian mannequin, with drivers allowing greater lateral clearance when the pedestrian was more visible.

Flashing lamps have long been used because of their attention-getting qualities. The present results appear to indicate that flashing also has benefits in reducing the negative effects of glare. The flash-together pattern used in this study (i.e., all lamps flashing in phase) had less effect of the visibility of pedestrians than steady burning lamps. This is probably because the dark periods in the flash pattern permitted drivers to see without glare. Flashings lamps also received higher subjective attention-getting ratings. In this study, the duty cycle of flashing lamps was always 50%. Even shorter duty cycles, with the extreme being strobes, would probably be even better in this way. Further work would be necessary to evaluate the effects of duty cycle more quantitatively, and to consider the many issues involved in whether and how to coordinate flashing among multiple warning lamps.

Recommendations for future research

Two issues appear to us to stand out as particularly promising extensions of the present study: (1) How would the effects of color observed in the nighttime conditions of this study be altered under daytime conditions? Standard photometry for day and night vision suggests that the differences in conspicuity between blue and red lamps that were seen in this study should be quite different in the day; in fact, the difference for these specific lamps should be reversed, with red being more conspicuous than blue. (2) How well do subjective ratings of conspicuity correspond to objective measures of the effectiveness of warning lamps in alerting drivers of surrounding vehicles? Subjective ratings of conspicuity are simple and easy to obtain, and there is some evidence that they agree with other possible measures of conspicuity, such as peripheral detection and photometry (Howett, 1979). But the work by Howett did not address color systematically. It would be useful to test whether those findings can be extended to lamps of different colors.

REFERENCES

Flannagan, M. J., & Blower, D. F. (2005). *Inferences about emergency vehicle warning lighting systems from crash data.* Ann Arbor, Michigan: The University of Michigan Transportation Research Institute.

Flannagan, M. J., Sivak, M., Traube, E. C., & Kojima, S. (2000). Effects of overall low-beam intensity on seeing distance in the presence of glare. *Transportation Human Factors*, *2*, 313-330.

Howett, G. L. (1979). *Some psychophysical tests of the conspicuities of emergency vehicle warning lights* (NBS Special Publication 480-36). Washington, D.C.: National Bureau of Standards.

National Fire Protection Association (NFPA). (2006). *NFPA 1971 Standard on protective ensemble for structural fire fighting* (1997 ed.). Quincy, Massachusetts: NFPA.

Rumar, K. (2002). *Night vision enhancement systems: What should they do and what more do we need to know?* (Report No. UMTRI-2002-12). Ann Arbor: The University of Michigan Transportation Research Institute.

Sayer, J. R., & Mefford, M. L. (2003). *High-visibility safety apparel and the nighttime conspicuity of pedestrians in work zones* (Report No. UMTRI-2003-29). Ann Arbor: The University of Michigan Transportation Research Institute.

Sullivan, J. M., & Flannagan, M. J. (2002). The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. *Accident Analysis and Prevention*, *34*, 487-498.

Wells, J. D. (2004). *Florida Highway Patrol emergency lighting research & prototype evaluation* [unpublished research report].

ABOUT THE AUTHORS

Michael J. Flannagan is a Research Associate Professor at the University of Michigan Transportation Research Institute (UMTRI). He has been at UMTRI since receiving his Ph.D. in experimental psychology from the University of Michigan in 1989. His research experience is in the human factors of driving, with an emphasis on visual perception. His recent work has been on how driver vision can be improved by innovations in traditional vehicle systems, such as automotive lamps and mirrors, and by the introduction of new systems, such as infrared night vision systems and camera-based rear vision systems.

Joel M. Devonshire is a Research Associate in the Human Factors Division of the University of Michigan Transportation Research Institute (UMTRI). He received a B.S. in psychology from Eastern Michigan University in 2001. His work has included human factors studies of lighting and visibility systems, as well as studies of the driver interfaces for technologically advanced driver assistance and safety systems, such as warning systems for lane departures and forward collisions.