Relationship of Vertical Illuminance to Pedestrian Visibility in Crosswalks

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Twenty-six participants evaluated a series of crosswalk lighting designs by visually detecting objects at each crosswalk location while traveling in a moving vehicle. The research was performed on a closed test track under nighttime conditions while the participants were driving an SUV with regular halogen headlamps. The conditions included several vertical illuminance levels (5, 10, 20, and 30 lux), varied luminaire types (high-pressure sodium (HPS) and metal halide (MH)), and various target object types (pedestrian and surrogate objects). Only one age group of participants (66 years and older) was used for the study, with equal representation of males and females. The participants were asked to detect objects at each crosswalk location when they were confident an object was present. The results indicated that object detection distances changed on the basis of vertical illuminance level, luminaire type, and object type. Object detection distance for HPS was greatest at 30 vertical lux and for MH at 20 vertical lux. However, these results were moderated by the clothing color of the target object. When object color was considered, pedestrians in white clothing were identified earlier under the HPS lighting condition at 20 lux. Under the MH configuration, denim-clad objects were detected earlier than black-clad objects, especially at the 20-lux lighting level. The results suggest that a vertical illuminance level of 20 lux at crosswalk locations provides adequate levels for target object detection. In addition to benefiting from vertical illuminance, target objects that wore white clothing had detection distances superior to other object types of different clothing colors. Recommendations for crosswalk lighting configurations are further discussed.

Collisions and fatalities related to pedestrian visibility at night are particularly serious problems. For example, in 2005 there were 4,881 pedestrian fatalities and 64,000 pedestrian injuries in the United States (1). Of the fatalities, 2,064 (42%) occurred between the hours of 9 p.m. and 6 a.m., a period of time when natural light visibility is reduced. Pedestrian accidents can occur at any point on the roadway and can be a result of pedestrian behavior, driver behavior, or both. A report of the Metropolitan Orlando (Florida) Bicycle and Pedestrian Program noted that, in an investigation of 617 pedestrian–vehicle crashes, 51.6% of this class of crashes happened at night, with an even distribution between lighted roads and unlighted roads (2). However, for fatal crashes, 58.6% occurred at night on unlighted roads and 25.3% occurred at night on lighted roads. The primary cause of these crashes appeared to be the lack of visibility of the pedestrians as they crossed the road. The visibility of the pedestrian is primarily derived from two sources: (a) roadway and headlamp lighting and (b) pedestrian clothing.

Specific guidance in the form of reports and warrants has long been required to assist engineers in developing appropriate lighting at crosswalk and intersection areas. The current version of Recommended Practice for Lighting of Exterior Environments suggests vertical illuminance levels of 20 lux in commercial areas and 5 lux in residential areas (3). The most recent investigation of crosswalk lighting was a result of the European Road Lighting Review and is documented in Hasson et al. (4). In this case, two alternative lighting designs were set up at two locations in Madison, Wisconsin. Flat pedestrian surrogates painted 18% gray were placed in the crosswalk and then revealed to participants for a period of 2 s. The participants were asked to count the number of pedestrian cutouts that were visible. This experiment was performed for both the typical United States designed crosswalk and for one designed to the Swiss requirements of 40 vertical lux. The results showed that at one site detection of the surrogates was not significantly affected by the lighting, while at the other site detection was significantly affected by lighting. In the case for which lighting had a significant impact, it was found that the European lighting design performed better. It is believed that the background of the two sites may have played a role in the results.

The impact of clothing is another factor that has been investigated with regard to crosswalk visibility. For example, Hazlett and Allen used a box 48 in. tall covered in either black, white, or gray cloth as a surrogate for a pedestrian (5). They found that the black object could not be detected with certainty 100% of the time at a safe stopping distance of 13.7 m (45 ft) for a vehicle traveling at 32 kph (20 mph). The gray material was limited to a detection distance at the 100% level of 37.5 m (123 ft), and the white material provided a detection distance of 79.5 m (261 ft). Furthermore, Shinar found that light-colored clothing aided in the visibility of pedestrians when the driver was expecting to see a pedestrian but was not as effective when the pedestrian was not expected (6).

PURPOSE AND SCOPE

The experimental research sought to answer a series of questions that included the following: (a) What level of vertical illuminance is required for a crosswalk? (b) What combination of vertical illuminance on the pedestrian in combination with clothing color provides adequate detection and recognition distances? (c) What impact do different luminaire types have on object detection? Finally, it was anticipated that, when the results of these questions were taken

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into account, guidelines and recommendations could be provided for lighting future crosswalk locations.

**METHODOLOGY**

The project required the investigation of pedestrian visibility at crosswalk locations under preselected vertical illuminance levels. The type of objects and vertical illuminance levels were evaluated in a previous phase of research, and the recommendations were adapted to the current project. The task was to identify pedestrians; however, the pedestrian objects varied in clothing color and were presented under different luminaires.

**Experiment Design**

The experiment design was a within-subjects design. Participants observed each of the vertical illuminance levels (6, 10, 20, and 30 lux) at each crosswalk location. In addition, all participants observed the different clothing colors (e.g., white clothing, black clothing, denim clothing, and surrogate object) under the different vertical illuminance levels.

**Independent Variables**

A series of independent variables were used for this phase of research. The independent variables included lighting design (vertical illuminance levels of 6, 10, 20, and 30 lux), lamp type [high-pressure sodium (HPS) and metal halide (MH)], and object type (white clothing, black clothing, denim clothing, and surrogate).

**Dependent Variable**

Each participant was asked to detect objects at different crosswalk locations while driving on the test track. The object detection distance was calculated from the object location to the point at which the driver first detected the object. An in-vehicle experimenter was responsible for marking each data point for each detection distance.

**Equipment**

**Facility**

The testing was performed on the Virginia Smart Road. The Smart Road is a closed, two-lane road that includes a variable-lighting system and different pavement types (e.g., asphalt and concrete). For this experiment design, crosswalk locations were chosen on both concrete and asphalt locations.

**Object Types**

The objects presented to the participants consisted of both the pedestrians and a surrogate pedestrian. Three types of clothed pedestrians were used: one dressed in white, one dressed in black, one dressed in denim, and the surrogate gray target, as shown in Figure 1. The clothing used was colored surgical scrubs purchased from a uniform-supply warehouse. The testing took place over the spring and summer seasons. Each of the experimenter pedestrians wore short-sleeved scrubs.

The surrogate used at Station 4 was made from a cardboard cylinder 12 in. in diameter. The surrogate was painted with 18% reflective Kodak gray paint. The on-road experimenter (i.e., pedestrian) responsible for presenting the surrogate target would hide behind the surrogate in a profile position to minimize any other potential cues that would enhance surrogate target detection.

**Crosswalk Locations**

For this portion of the study, six test locations were used to evaluate the crosswalks. As shown in Figure 2, the crosswalk locations were chosen on the basis of the setup of the lighting design system on the test track. Four of them (Stations 1, 2, 4, and 5) were within the HPS test area. An additional location for the MH testing was established at the start of the lighting test bed. The luminaires for the lighting systems were on one side of the road, with the exception of the MH, for which the luminaires were located on both sides of the road. Other test locations were also used during the investigation, but those results will not be discussed in this paper.

After an initial pilot test in which the researchers asked pilot participants to identify the objects at the test locations, it was found that a ceiling effect was occurring for the white-clothed and surrogate target objects. In an effort to maximize the possible detection distances for these objects, they were placed only at Station 4. The remaining target objects (e.g., black-clothed and denim-clothed objects) could appear at any of the remaining stations but did not appear at Station 4 (Figure 2).

The fixed overhead lighting system was used at the maximum mounting height of 15 m. The mounting height of the fixed system was not included as a variable in the experiment. The lamp type used for the fixed overhead lighting was HPS. In addition to the HPS, an MH configuration was adapted to one fixed overhead light standard.

For the crosswalk design, the overhead lighting used was a 400-W M-C-II luminaire. In this designation, the M refers to a medium

**FIGURE 1 Pedestrian targets dressed in white, denim, and black clothing and grey surrogate target.**
throw, C is a cutoff luminaire, and II represents a Type 2 distribution (7). This luminaire was selected from the existing luminaires on the Smart Road and represents a best practice for roadway lighting. Luminaires from the same manufacturer with the same designation and intensity pattern were used for both the MH and HPS configurations.

Lighting Design Measurements

To obtain the required lighting levels (vertical illuminance) for the objects at each crosswalk test location, a Minolta T-10 illuminance meter was mounted on a tripod at a height of 5 ft in a vertical orientation. When each of the experimental lighting levels was obtained (i.e., 6, 10, 20, and 30 lux), the appropriate position was marked on the roadway.

Experiment Vehicles

Two identical SUVs were used for the research. Each vehicle had identical halogen headlamps, which were aimed before the research experiment using a Hoppy Vision 100 photometric headlight aiming. The headlamps were aligned via the laser targeting system, and the onboard alignment software provided horizontal and vertical headlamp-aiming corrections. Each of the experiment vehicles was instrumented with a proprietary system created at the Virginia Tech Transportation Institute that recorded driving distance; events (detection distance); and video of the driver, forward roadway view, and side view of object locations.

Participants

A total of 26 individuals participated in the study. Of those 26, 13 were male and 13 were female. The entire participant group consisted of older drivers known for declining visual acuity and difficulty with pedestrian detection at night (8). The average age of the participants was $M = 69.2$ years, with age ranging between 66 and 73 years.

After an informed consent was given, participants underwent a visual screening test to ensure that they met the state driving license requirements (e.g., 20/40 acuity at night). The average acuity for male participants was 20/25, with only two scoring 20/30 and one scoring 20/40. The average acuity for the females was 20/26, with five above the average at 20/30. No participants were disqualified for failing the acuity test. After the vision test was administered, the participant was seated as the driver of the test vehicle and, accompanied by the in-vehicle experimenter, then drove to the test track.

Two participants were tested simultaneously, and they were compensated for their time.

Procedure

During the participant testing, the drivers made 13 laps on the test track. After they entered the test road and reviewed the on-road protocol with the in-vehicle experimenter, the drivers took a familiarization lap, during which they were shown the test facility and allowed to become familiar with the participant testing protocol. During the subsequent laps, the drivers were presented with different objects at the various test locations shown to them previously.
When the driver was able to see an object, he or she was to say "I see something," at which point the in-vehicle experimenter would indicate the detection in the data collection system. When the vehicle then passed the object, the experimenter would mark the location in the data collection system. The difference between these was the detection distance of the object.

The participant on-road testing took place in two moving SUVs that traveled different sections of the road at the same time. Each vehicle drove its respective sections at a requested speed limit of 35 mph. During the familiarization, the first vehicle proceeded to the bottom turnaround and the second vehicle proceeded to turnaround three (Figure 2). The experimental driving sessions were set up so that the participant vehicles did not pass each other on the two-lane section of roadway. Each participant vehicle then proceeded to do six loops on the basis of position (either top or bottom vehicle) before switching. The vehicles would then switch to complete the remaining six laps (Figure 2).

The crosswalk locations were chosen on the basis of lighting-level requirements and positions of the various lighting types. When the pedestrians were presented in the designated crosswalk areas, they remained in a static profile position in the center of the roadway and remained there until detection.

During each lap, catch trials were introduced in which a pedestrian was not present at the crosswalk location. The catch trials were randomized throughout the experiment in an effort to reduce participant expectation.

RESULTS

After the data were collected, they were then entered into SAS and a series of analysis of covariance calculations (ANCOVA) was conducted with respect to lighting level, lighting types, and object types. ANCOVAs were performed to account for variability added by a covariate correlated with the dependent variable, in this case, speed. Speed was chosen due to the object size change as the participant approached each object. Object size grows more quickly on the basis of the approach speed and thus likely has enhanced target detection. Speed was used in the model to account for this effect.

Illuminance Levels

Detection distances varied on the basis of illumination levels. The following two sections discuss the illumination levels at the crosswalks that had specific luminaire types and configurations.

HPS Lighting

The results for the HPS detection distances based on the various lighting levels were statistically significant, $F(3, 221) = 19.92, p < .0001$. To analyze detection distances uniformly, a specific object type was chosen for the analysis, in this case, denim clothing. Under HPS lighting conditions, the detection distances varied on the basis of illumination levels. Additional Student Neuman Keuls (SNK) pairwise comparisons were used to identify where these difference occurred. Figure 3 shows the lighting level and detection distances for HPS.

From the results of the pairwise comparisons, the longest detection distance occurred with the 30-lux level ($M = 898.71$ ft), which was significantly different from the 6-lux results. There were no differences between 6-, 10-, and 20-lux levels ($M = 803.83$ ft, $M = 841.82$ ft, and $M = 877.14$ ft, respectively). Further post hoc pairwise comparisons found no significant object detection differences between the illumination levels of 10, 20, and 30 lux.

MH Lighting

The next analysis included the pedestrian-detection distances based on the illumination levels for the MH luminaire crosswalk. The overall ANCOVA was statistically significant $F(3, 27) = 3.14, p = .0351$. To identify where these differences occurred, further set follow-up pairwise comparisons (SNK) were conducted on the simple main effects. Figure 4 shows the lighting levels and detection distances for MH condition.

The pairwise comparisons revealed significant differences between the illumination levels. To begin, there was a significant difference in detection distances between 20 lux ($M = 973.41$ ft) and 6 lux ($M = 612.26$ ft). Participants identified the object earlier at 20 lux than

![Figure 3](image_url)
6 lx under the MH luminaire. Furthermore, there was a significant difference in detection distances between 10 lux ($M = 837.60$ ft) and 6 lux. Again, participants saw objects at a greater distance at 10 lux than at 6 lux. Last, there was a significant difference in detection distances when the 30-lux ($M = 793.96$ ft) and the 6-lux detection distances were compared. No significant detection distances were found between the 10-, 20-, and 30-lux illuminance levels.

**Luminaire Comparisons**

A second level of analyses was conducted to compare the type of luminaire with the respective illuminance levels to gauge differences in object detection distances.

To compare the effects of lamp types and lighting levels on detection distances of the objects, an ANCOVA was conducted. The comparison was across lighting levels and lamp types for a denim-clothed object only. The denim-clothed object was specifically chosen as it appeared at every crosswalk location for the various luminaries (i.e., HPS and MH). Table 1 outlines the results obtained when lighting system types and lighting levels for HPS and MH were compared.

**Object Types**

Additional analyses were conducted to review the influence of object type (e.g., object color and surrogate). These analyses are presented in more detail below.

**HPS Object Types**

This analysis compared object types (e.g., color and surrogate object) on the basis of illuminance levels for the HPS crosswalk setup. The ANCOVA showed a two-way interaction for object type and illuminance levels (Table 2).

From the detection distances for object type, it was apparent that the white-clothed object outperformed all other object types at each illuminance level (Figure 6). However, at 20- and 30-lux illuminance levels, the disparity between the white-clothed object and the surrogate object was less dramatic than at the 6- and 10-lux illuminance levels. Moreover, the surrogate object detection distances outperformed both the denim-clothed and black-clothed objects at every illuminance level. Interestingly, the black-clothed and denim-clothed objects were not differentiated greatly at any of the illuminance levels. The denim-clothed object had greater detection distances at each level than the black-clothed object, yet the disparity between
FIGURE 5. Lamp-type comparison based on denim object detection distance (ft) and vertical illuminance level (lux).

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum-of-Squares</th>
<th>Mean Square</th>
<th>F-Value</th>
<th>P-Value</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>3</td>
<td>32,958,867</td>
<td>10,986,289</td>
<td>242.11</td>
<td>&lt;.0001</td>
<td>*</td>
</tr>
<tr>
<td>Level</td>
<td>3</td>
<td>2,296,321</td>
<td>765,440.2</td>
<td>19.92</td>
<td>&lt;.0001</td>
<td>*</td>
</tr>
<tr>
<td>Color×level</td>
<td>9</td>
<td>3,380,944</td>
<td>375,860.4</td>
<td>8.61</td>
<td>&lt;.0001</td>
<td>*</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>38,636,132</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p < 0.05 (significant).

FIGURE 6. HPS pedestrian detection distances (ft) based on object type and clothing color for various vertical illuminance levels (lux).
TABLE 3  MH Illuminance and Color ANCOVA Results

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum-of-Squares</th>
<th>Mean Square</th>
<th>F-Value</th>
<th>P-Value</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1,140,915</td>
<td>1,140,915</td>
<td>23.63</td>
<td>&lt;.0001</td>
<td>*</td>
</tr>
<tr>
<td>Level</td>
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<td>391,325</td>
<td>130,442</td>
<td>4.8</td>
<td>0.0064</td>
<td>*</td>
</tr>
<tr>
<td>Color*Level</td>
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<td>556,473</td>
<td>185,491</td>
<td>3.14</td>
<td>0.0351</td>
<td>*</td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td>2,088,713</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*p < 0.05 (significant).

The two object types was not as great when they were compared with the white-clothed object. From the data, it also appeared that the white-clothed object had a ceiling effect in relation to detection distance, as there was not a dramatic increase in detection distances as illuminance levels were increased.

MH Object Types

Only two object types, denim-clothed and black-clothed, were analyzed for the MH crosswalk setup. In Table 3, the ANCOVA showed an interaction between both object type (i.e., denim clothing, black clothing) and lighting level.

The results showed that under the 6-lux illuminance level, neither the denim nor the black color of clothing performed better than the other (Figure 7). However, when the lighting level was increased to 10 and 20 lux, the detection distance for the denim-clothed pedestrian increased substantially. However, it appeared that, under the 30-lux condition, the increased lighting level aided in the detection distance for the black-clothed pedestrian. An interesting decrease in detection distance occurred for the denim-clothed pedestrian. This result was to be expected as the MH lighting system had a higher blue component than the HPS system.

DISCUSSION OF RESULTS, CONCLUSIONS, AND STUDY LIMITATIONS

Discussion of Results

The objective of the research was to analyze object detection distances on the basis of vertical illuminance level, the type of lamp configuration, and the type of object at the crosswalk locations. This analysis was conducted under dynamic conditions with object detection distances as a measure of driver visual performance.

The HPS design showed a significant difference between the highest and lowest illuminance levels only; there were no appreciable differences between the lowest and midrange levels (e.g., 20 lux). These results were also only for a specific object color (i.e., denim); however, when compared across object-type colors, it appeared that HPS and white-colored clothing were superior for detection purposes, thus suggesting that pedestrians be encouraged to wear white clothing to maximize visibility. Black-clothed pedestrians had the shortest detection distances across all illuminance levels. When compared with MH lighting and pedestrians with only denim-colored clothing, HPS appeared to return only slight gains in visibility-detection distance as the illuminance level increased.

![FIGURE 7  Pedestrian object detection distances (ft) based on clothing color and vertical illuminance level (lux).](image-url)
Detection distances for the denim-clothed pedestrian when viewed under varying illuminance levels for MH showed increases as the vertical illuminance increased. However, at 20 lux, there appeared to be a ceiling, and further increases in vertical lux beyond this level (e.g., 30 lux) had diminished detection distances. This result would suggest that for denim-clothed pedestrians an average lighting level of 20 lux was sufficient to provide adequate detection in crosswalks illuminated by MH. Again, when compared with HPS, there were diminished returns past the 20-lux lighting level, where there was still a small increase in detection distance for HPS. When the object type was compared for MH, a denim-clothed pedestrian again outperformed a black-clothed pedestrian at every level; however, detection distances improved for the black-clothed pedestrian at 30 lux.

Conclusions

The conclusions from this experiment are as follows:

- The best practice for the visibility of the pedestrian object in a crosswalk was found to be at a vertical illuminance level of 20 lux.
- The surrogate target had a higher detection distance than the denim-clothed or black-clothed pedestrian.
- HPS outperformed MH for object detection distances; however, this result was dependent on the clothing color of the object.
- For MH, denim-clothed pedestrians had the farthest detection distance at a vertical illuminance of 20 lux.

Study Limitations

There were a few limitations in the research design. The participants quickly learned each location at which a potential pedestrian may appear, and practice effects likely influenced the detection distances. Catch trials were used during the study, so that a pedestrian was not present at one or more crosswalk locations. However, participants were asked to identify targets in the crosswalk locations; the driver was searching only for potential targets; and no supplemental search tasks occurred during the experiment. Pedestrian detection distances in the real world (e.g., without practice effects) are going to be shorter than those gathered in the present study due to driver inattention and variation in scanning patterns.

In addition, the position of each pedestrian within each crosswalk location was predetermined by the lighting level achieved (e.g., different positions for 5, 10, 20, and 30 lux). This condition may have influenced the detection on the basis of the position of the pedestrian; however, the pedestrian location was always in the center of the roadway.

Last, the crosswalks were ideal locations, with little extraneous clutter to distract a driver’s attention. Further research using supplemental targets and signage is suggested. In addition, comparisons based on front-lit pedestrians versus back-lit pedestrians are an interesting future research direction.

REFERENCES


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