The Relationship of Vertical Illuminance to Pedestrian Visibility in Crosswalk

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ABSTRACT

Twenty-six participants evaluated a series of crosswalk lighting designs by visually detecting objects within each crosswalk location. The research was performed on a closed test track under nighttime conditions while driving a Sport Utility Vehicle (SUV) with regular halogen headlamps. The conditions presented to each participant included varying illuminance levels (6, 10, 20, and 30 lux), varied luminaires (High Pressure Sodium [HPS], Metal Halide [MH]) and different object types (pedestrian and surrogate objects). The participant was asked to detect objects within each crosswalk location when they were confident there was an object present. The presentation of objects was varied to diminish expectation effects. The results indicated that object detection distances varied based on illuminance level, luminaire type, and object type. Object detection distance for the HPS was greatest at 30 lux and for MH at 20 lux. However, these results were moderated based on clothing color of the object. When object color was taken into consideration, pedestrians in white clothing were identified earlier under the HPS lighting condition at 20 lux. Under the MH configuration, denim-clothed objects were detected earlier compared to black-clothed objects, especially at a 20 lux lighting level. The results indicate crosswalk lighting levels provide adequate object lighting at 20 lux. Furthermore, pedestrians dressed in white clothing have superior detection distances compared to other object types.

INTRODUCTION

Pedestrian visibility and related collisions and fatalities at night is a particularly serious problem. For example, in 2005 there were 4,881 pedestrian fatalities and 64,000 pedestrian injuries in the United States [(1)]. Of these fatalities, 2,064 (or 42%) occurred between the hours of 9 p.m. and 6 a.m., a category of time when natural light visibility is reduced. These numbers generalize the severity of the problem for pedestrian visibility at night. 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 Illuminating Engineering Society of North America (IESNA) Recommended Practice for Lighting of Exterior Environments (IESNA RP-33-99) recommendations for crosswalk lighting states that the crosswalks must have specific lighting with a maintained level of vertical illuminance of 20 lux in commercial areas and then dropping to 5 lux for residential areas.[(2)]

The impact of clothing is another factor that has been investigated with regard to crosswalk visibility. Hazlett and Allen used a 48 in tall box covered in either black, white, or gray cloth as a surrogate for a pedestrian.[(3)] 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).

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.[(4)]

PURPOSE AND SCOPE

The experimental research sought to identify an illuminance level that provided the greatest detection distance for pedestrian objects within crosswalks. During the experimental session, participants drove a vehicle on a closed test track under nighttime conditions. The driver was asked to identify different object types at various locations on the test track. The experimental design included different illuminance levels at the multiple crosswalk locations, different luminaires types, and varied object colors. This project is a follow-on to a previous investigation where the participants were seated in stationary vehicles.

METHODOLOGY

The project required the investigation of pedestrian visibility at crosswalk locations under varying illuminance levels. The task was to identify pedestrians; however, the pedestrian objects varied in clothing color and were presented under different luminaires.

Experimental Design

In an effort to determine the relationship between illuminance levels and object detection, an experimental design was created that examines illuminance levels, luminaire types, and varying object types.

Independent Variables

A series of independent variables were utilized for this phase of research. The independent variables included Lighting Design (vertical illuminance levels of 6, 10, 20, and 30 lux), Lamp Types (HPS and MH) and Object Type (Denim clothed, Black clothed, White clothed, 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 where 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 unique state-of-the-art, full-scale research facility for pavement research and evaluation of vehicle and infrastructure technologies. The facility also includes a variable lighting system and different pavement types that include asphalt and concrete. For this experimental 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 different types of clothed pedestrians were used: one dressed in white, one dressed in denim, and the third dressed in black as seen in Figure 1, Figure 2, and Figure 3. 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 utilized at station four was made from a cardboard cylinder which was 12 inches 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 to minimize any other potential cues that would enhance surrogate detection.

Figure 1. Photo. Pedestrian in Black Clothing.

Figure 2. Photo. Pedestrian in Denim Clothing.

Figure 3. Photo. Pedestrian in White Clothing.

Crosswalk Placement

For this portion of the study, six test locations were used to evaluate the cross walks. As shown in Figure 4, the crosswalk locations were chosen based on the set-up of the lighting design system on the test track. Four of them (Stations 1, 2, 4 and 5) were within the High Pressure Sodium (HPS) test area. An additional location for the metal halide (MH) testing was establish at the start of the lighting test bed. The luminaires for the lighting systems were on one side with the exception of the MH where luminaire which was in the opposite configuration. Other test locations were also used during the investigation but these results will not be discussed in this paper.

Objects could appear at any of the test locations during the participant experimentation however due to the limitations of the visibility distance on the Smart Road, a the white clothed test object and the surrogate test object only appeared at station 4.

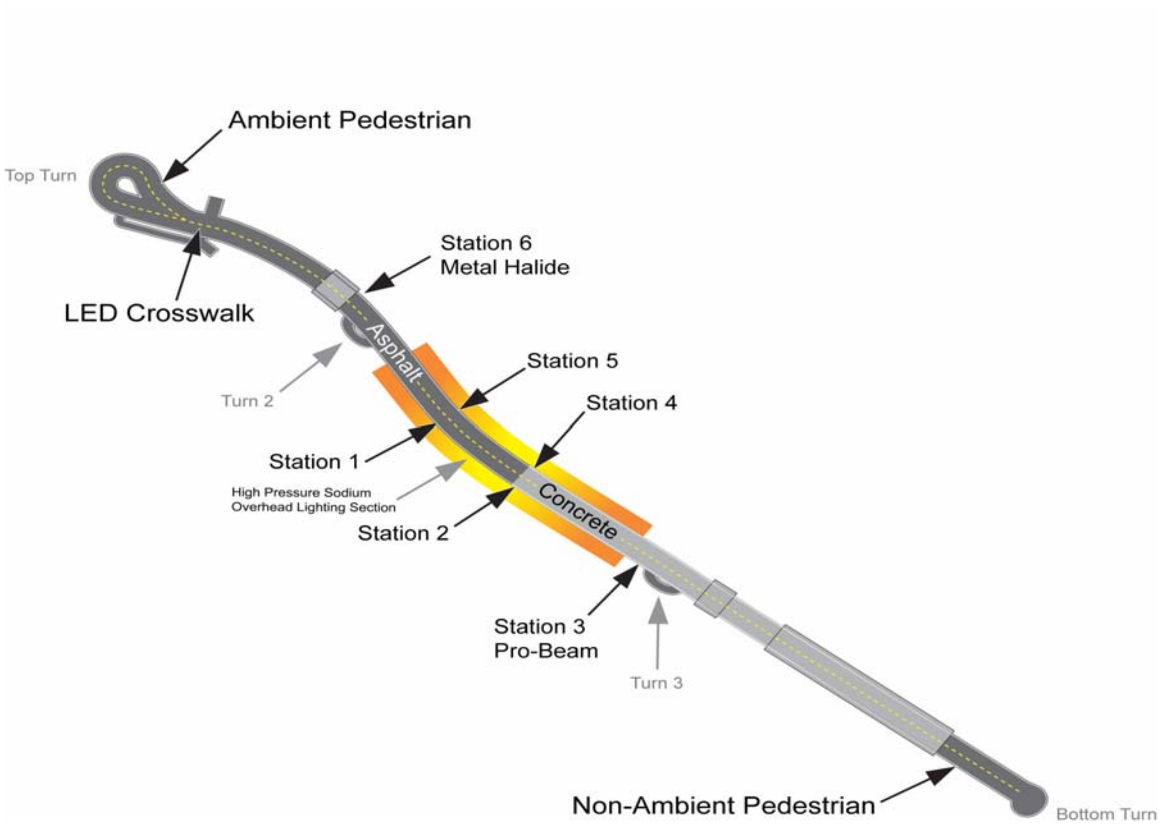

Figure 4. Diagram. Smart Road lighting installation.

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 high pressure sodium (HPS). In addition to the HPS, a MH configuration was adapted to one fixed overhead light standard.

For the crosswalk design, the overhead lighting used would be a 400 Watt M-C-II luminaire. In this luminaire designation, the M refers to a Medium Throw, C is a Cutoff luminaires and II represents a type 2 distribution.[(5)] 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. When each of the experimental lighting levels were obtained (e.g., 6, 10, 20, and 30 lux) the appropriate position was marked on the roadway.

Experimental Vehicles

Two identical SUVs were utilized for the research. Each vehicle had identical halogen headlamps, which were aimed prior to the research experiment using a Hoppy® Vision 100 Photometric Headlight Aimer. The headlamps were aligned via the laser targeting system and the onboard alignment software provided horizontal and vertical headlamp aiming corrections. Each of the experimental vehicles was instrumented with a proprietary system created at the Virginia Tech Transportation Institute, which 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 average age of the participants was M = 69.2 years, with age ranges between 66 years and 73 years old.

After an informed consent was given, each participant underwent a visual screening test to ensure participants met the state driving license requirements. The average acuity for male participants was 20/25 and 20/26 for female participants. After the vision test was administered, the participants were 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 at once and they were compensated for their time.

Participant Performance Testing Procedure

During the participant testing, the drivers made 13 laps on the test track. After entering the test road and reviewing the on-road protocol with the in-vehicle experimenter, a familiarization lap was taken where the drivers were shown the test facility and were allowed to be come familiar with the participant testing protocol. During the subsequent laps, the drivers were presented with different objects at the various test locations shown previously. When the driver was able to see an object, they were 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 then mark the location in the data collection. The difference between these is the detection distance of the object.

The participant on-road testing took place in two moving vehicles (SUVs) that traveled different sections of the road at the same time. During the familiarization, the first vehicle proceeded to the bottom turn-around and the second vehicle proceeded to turn-around three. The experimental driving sessions were setup so that neither participant vehicle passed each other on the two lane section of roadway. Each participant vehicle then proceeded to do six loops based on their position (either top or bottom vehicle) before switching. The vehicles would then switch to complete the remaining six laps.

The crosswalk locations were chosen based on the 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 until detection. During each lap, catch trials were introduced where 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 was collected it was then entered into Statistical Analysis System (SAS) and a series of Analysis of Covariance calculations (ANCOVA) were conducted with respect to lighting level, lighting types, 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. The object size will grow more quickly based on approach speed and thus likely would have enhanced target detection. Speed was used in the model to account for this effect.

Illuminance Levels

Detection distances varied based on illuminance levels. The initial section of the results will discuss the illuminance levels at the crosswalks that utilized specific luminaire types and configurations.

High Pressure Sodium

The result for the HPS detection distances based on lighting level is shown in Table 1. In order to analyze detection distances uniformly, a specific object type was chosen for the analysis, in this case denim clothing.

Table 1. HPS ANCOVA results for Illuminance level.

Source	**DF**	**SS**	**MS**	**F value**	**P value**	**Sig**
Level (6, 10, 20, 30)	3	2296321	765440.2	19.92	<.0001	*

* $p < 0.05$ (significant)

Under the HPS lighting conditions the detection distances varied based on the illuminance levels. Further Student Neuman Keuls (SNK) pairwise comparisons were used to identify where these difference occurred. Figure 5 shows the lighting level and detection distances for HPS.

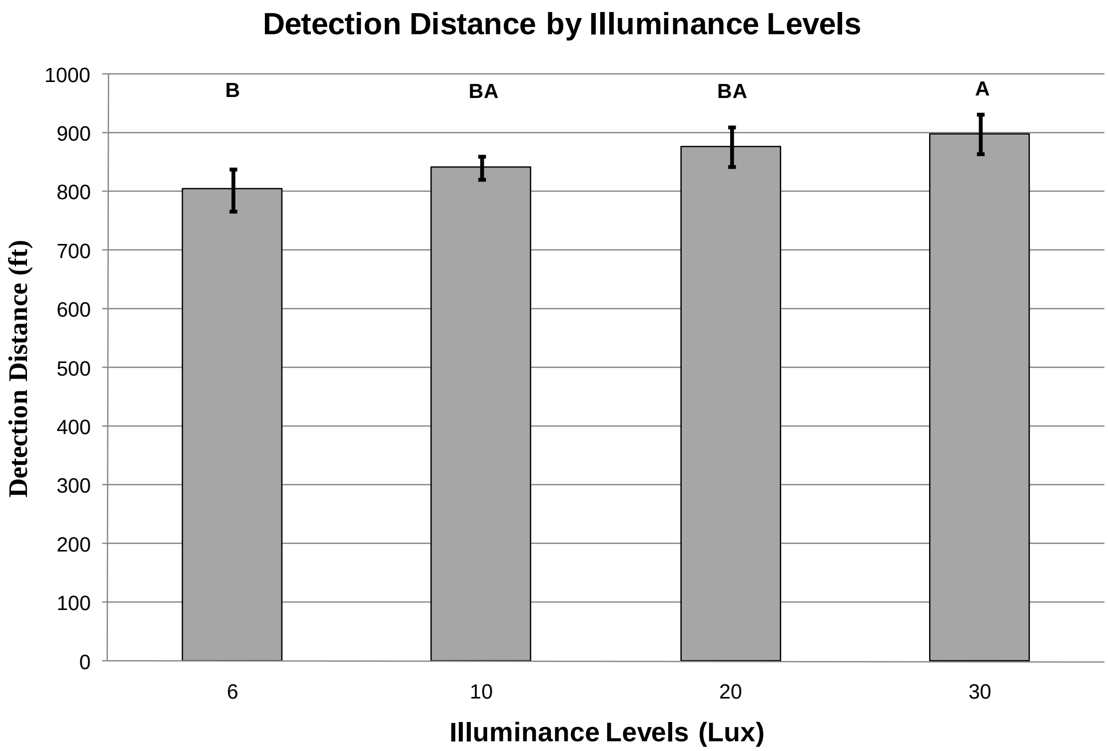

Figure 5. Object detection distances based on illuminance level

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 than the 6 lux. There were no differences between 6,10, 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 illuminance levels of 10, 20 and 30 lux.

Metal Halide

The next analysis included the pedestrian detection distances based on the illuminance levels for the MH luminaire crosswalk. Table 2 below summarizes the ANCOVA results for the illuminance levels and object detection distances.

Table 2. Metal Halide ANCOVA results for Illuminance level.

Source	**DF**	**SS**	**MS**	**F value**	**P value**	**Sig**
Level (6, 10, 20, 30)	3	391325	130441	3.14	0.0351	*

* $p < 0.05$ (significant)

The overall ANCOVA was statistically significant. To identify where these differences occurred, a further set follow-up pairwise comparisons (SNK) were conducted on the simple main effects. Figure 6 shows the lighting level and detection distances for MH condition.

The pairwise comparisons found significant differences between the illuminance 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 earlierat 20 lux than at 6 lux 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. Lastly, there was a significant difference in detection distances when comparing the 30 lux (*M* =793.96 ft) and the 6 lux detection distances. No significant detection distances were found between the 10, 20 or 30 lux illuminance levels.

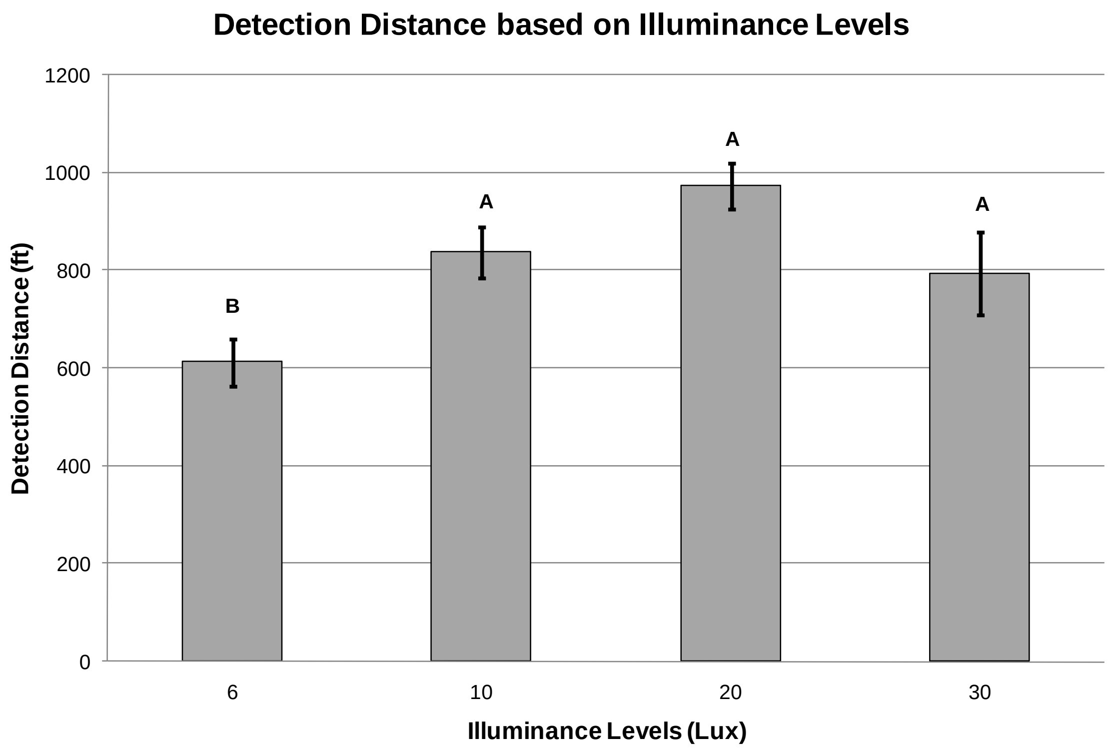

Figure 6. Detection distances based on illuminance levels

Luminaire Comparisons

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

High Pressure Sodium versus Metal Halide

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 denim-clothed objects only. The denim-clothed object was specifically chosen as it appeared at every crosswalk location for the various luminaires (e.g., MH, and HPS).

Table 3 outlines the results obtained when comparing lighting system types and lighting levels for HPS and MH.

Table 3. Lamp Type and Lighting Level ANCOVA results.

Source	DF	Type III SS	Mean Square	F Value	Pr > F	Sig
Level	3	694545	231515	6.22	0.0008	*
Lamp	1	120995	120995	8.02	0.0126	*
Level*Lamp	3	388610	129536	3.32	0.0301	*
Total	7	1204151				

* $p < 0.05$ (significant)

A significant two-way interaction for detection distance occurred between Lamp Type and Lighting Level (see Figure 7). The means showed a difference between HPS and MH at the 6 lux level, with the HPS object detection distances substantially farther (*M* =803.83 ft) compared to the MH distance (*M* = 612.26 ft). At 10 lux the differences between the means were negligible with HPS (*M* = 841.82 ft) and MH (*M* = 837.60 ft). At 20 lux, the mean differences reversed with MH (*M* = 973.41 ft) outperforming HPS (*M* = 877.14 ft). However at 30 lux, HPS (*M* = 898.71 ft) outperformed MH (*M* = 793.96 ft) for object detection distances.

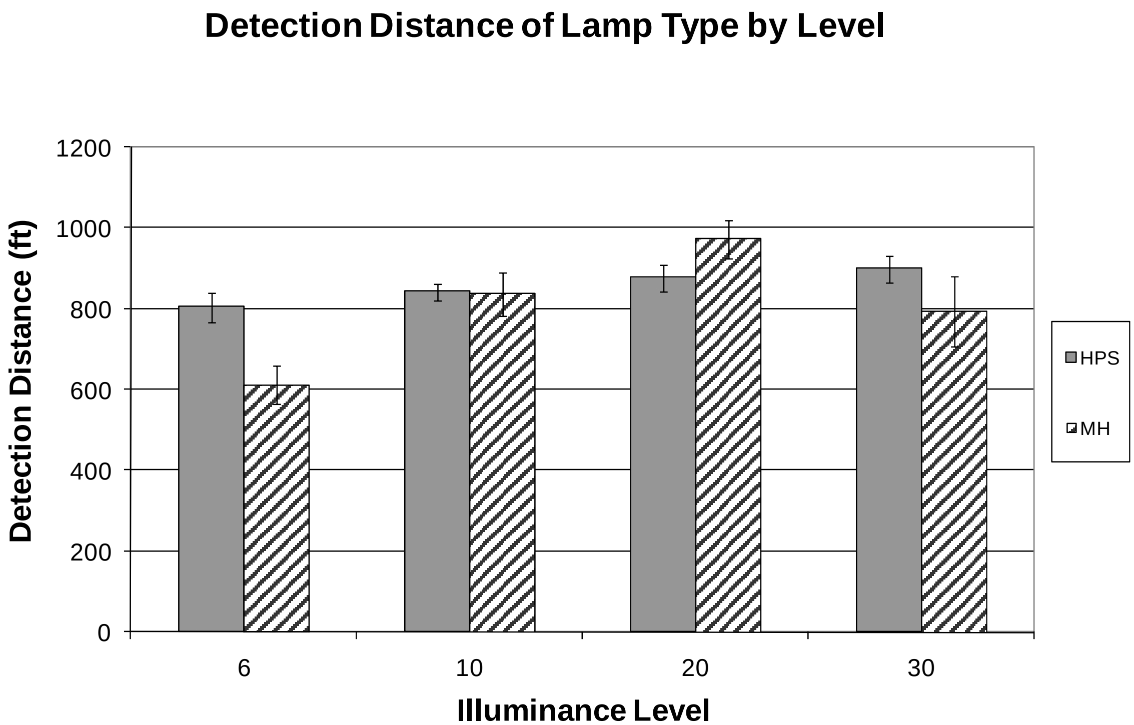

Figure 7. Detection distance by lamp type and lighting level

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) based on illuminance levels for the HPS crosswalk setup. The ANCOVA showed a two-way interaction for object type and illuminance levels, which is shown in Table 4 below.

Table 4. HPS Illuminance and Color ANCOVA results.

Source	DF	SS	MS	F value	P value	Sig
Color	3	32958867	10986289	242.11	<.0001	*
Level	3	2296321	765440.2	19.92	<.0001	*
Color*Level	9	3380944	375660.4	8.61	<.0001	*
Total	15	38636132				

* $p < 0.05$
(significant)

From the detection distances for object type it is apparent that the white-clothed object outperformed all other object types at each illuminance level (see Figure 8). However, at 20 and 30 lux illuminance levels, the disparity between the white-clothed object and surrogate object is less dramatic than at the illuminance levels at 6 and 10 lux. Moreover, the surrogate object detection distances outperformed both the denim-and black-clothed objects at every illuminance level. Interestingly, the black-clothed and denim-clothed objects did not differentiate greatly at each of the illuminance levels. The denim-clothed object had greater detection distances at each level compared to the black-clothed object, yet the disparity between the two object types was not as great when comparing them to the white-clothed object. From the data, it also appears that the white-clothed object had a ceiling effect as far as detection distance was concerned, as there was not a dramatic increase in detection distances as illuminance levels were increased.

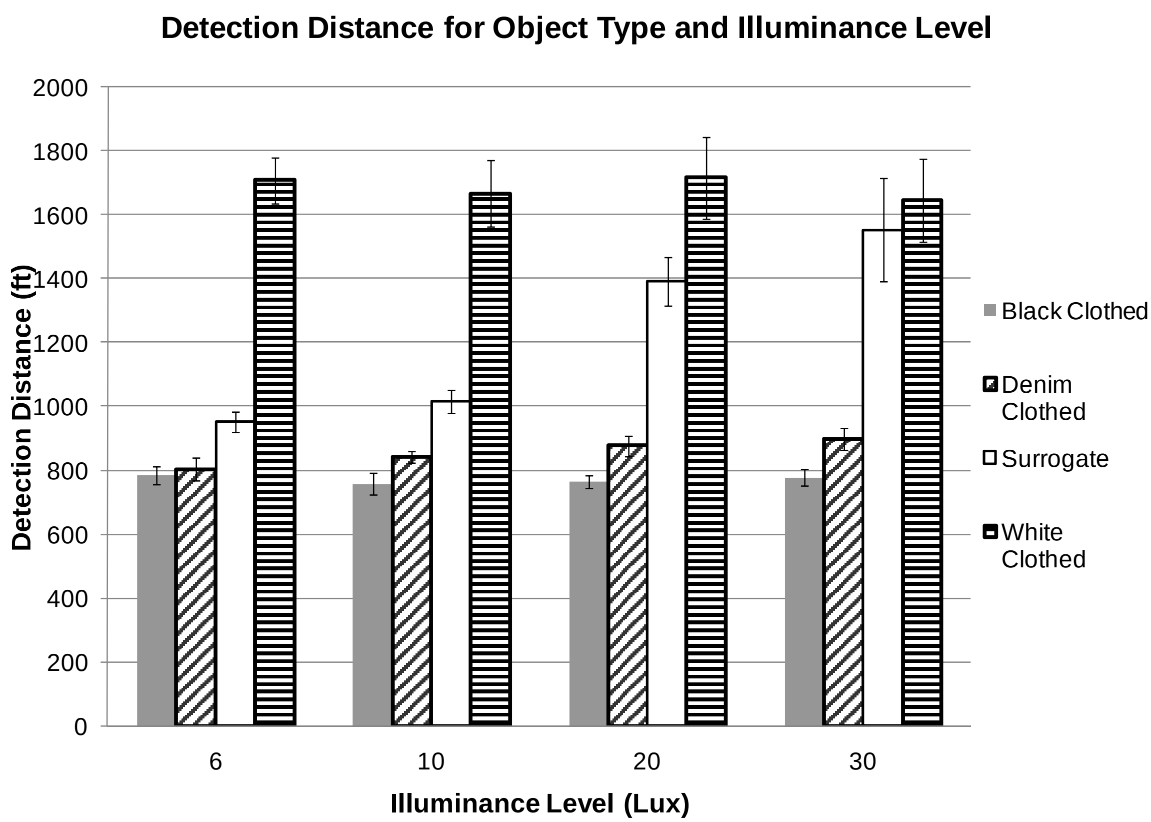

Figure 8. HPS pedestrian detection distances based on clothing color and lighting level

Metal Halide Object Types

Only two object types, namely denim-clothed and black-clothed, were analyzed for the MH crosswalk setup. In Table 5, the ANCOVA showed an interaction between both object type (e.g., denim clothing, black clothing) and the lighting level.

Table 5. MH Illuminance and Color ANCOVA results.

Source	DF	SS	MS	F value	P value	Sig
Color	1	1140915	1140915	23.63	<.0001	*
Level	3	391325	130442	4.8	0.0064	*
Color*Level	3	556473	185491	3.14	0.0351	*
Total	7	2088713				

* $p < 0.05$
(significant)

The results show that under the 6 lux illuminance level, neither color of clothing performed better than the other (see Figure 9). However, when the 6 lux lighting level was increased to 10 and 20, the detection distance for the denim-clothed pedestrian increased substantially. However, under the 30 lux condition, it appears that the increased lighting level aided in the black-clothed pedestrian detection distance. An interesting decrease in detection distance occurred for the denim-clothed pedestrian. This result is to be expected as the MH lighting system has a higher blue component than the HPS system.

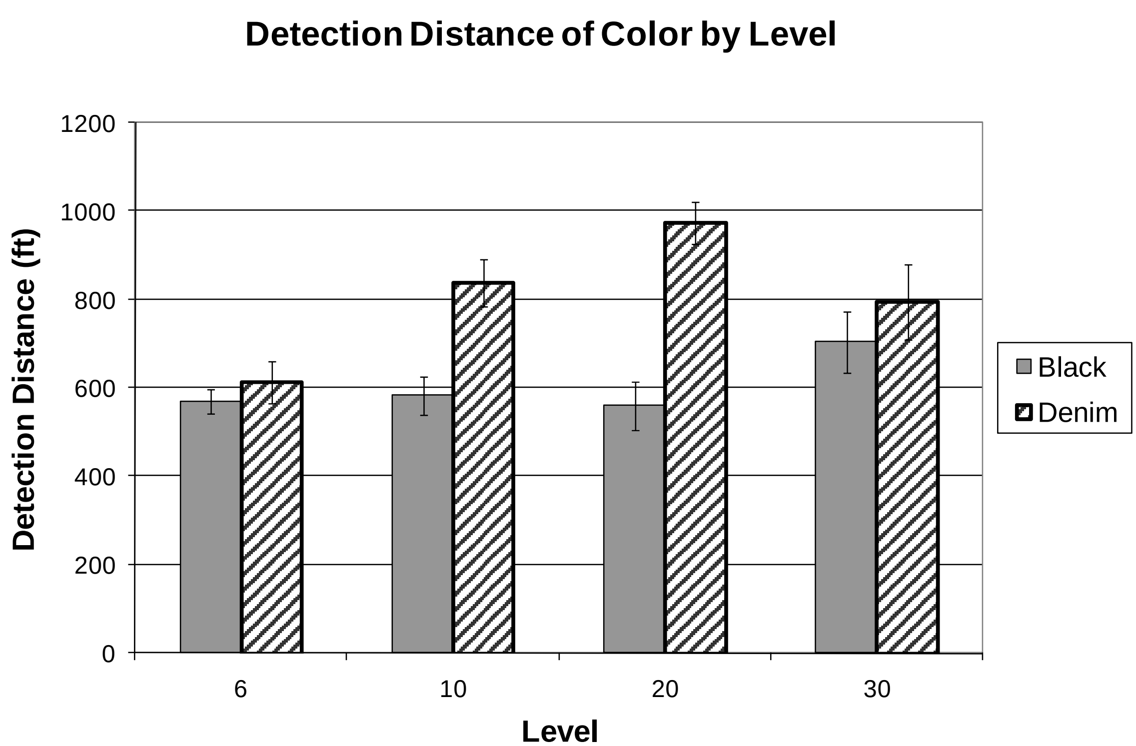

Figure 9. Pedestrian detection distances based on clothing color and lighting level

Discussion and Conclusions

The objective of the research was to analyze object detection distances based on the vertical illuminance level present, the type of lamp configuration and also the type of object present 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 only showed a significant difference between the highest and lowest illuminance level; there were no appreciable difference 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 appears that HPS and white-colored clothing is superior for detection purposes, thus suggesting that pedestrians be encouraged to wear white-colored clothing to maximize visibility. Black-clothed pedestrians had the shortest detection distances when compared across all illuminance levels. When compared to MH using only denim-colored clothing, HPS appears to return only slight gains in visibility detection distance as the illuminance level increases.

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 would suggest for denim-clothed pedestrians that an average lighting level of 20 lux is sufficient to provide adequate detection in crosswalks illuminated by MH. Again, when compared to 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, denim-clothed pedestrian again outperformed the black-clothed pedestrian at every level, however detection distances improved for the black-clothed pedestrian at 30 lux.

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 lighting design level of 20 vertical lux.

- The farthest object detection distance was obtained by the white-clothed pedestrian. The detection distances were substantially longer than either the denim-clothed or black-clothed pedestrian.

- The surrogate target had a higher detection distance than the denim-clothed or black-clothed pedestrian.

- High Pressure Sodium outperformed Metal Halide for object detection distances; however, this was dependent on the clothing color of the object.

- For metal halide, denim-clothed pedestrians had the farthest detection distance at a vertical illuminance of 20 lux.

- Covariates should be addressed in dynamic situations to remove potential influence and confounding the results.

Study Limitations

There were a few study limitations in the research design.

The participants involved in the research were perhaps highly motivated to identify the targets. Despite the presence of catch trials in the task, participants were asked to identify targets in the crosswalk locations and the driver was only searching for potential targets and no supplemental search tasks occurred during the experiment. This suggests that actual real-world detection distances may vary based on driver inattention and variation in scanning patterns.

Lastly, the crosswalks were "ideal" locations with little extraneous clutter to distract a driver's attention. Further research using supplemental targets and signage is suggested for the future.

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