Report # 22-UR-121

NSTSCE

National Surface Transportation Safety Center for Excellence

Crosswalk Lighting Using Narrow Beam Illuminator

Matthew Palmer • Dr. Rajaram Bhagavathula • Andrew Kassing

Submitted: December 9, 2022

Technology
Impairment
Mobility
Infrastructure

Housed at the Virginia Tech Transportation Institute
3500 Transportation Research Plaza • Blacksburg, Virginia 24061

ACKNOWLEDGMENTS

The authors of this report would like to acknowledge the support of the stakeholders of the National Surface Transportation Safety Center for Excellence (NSTSCE): Zac Doerzaph from the Virginia Tech Transportation Institute; John Capp from General Motors Corporation; Terri Hallquist, from the Federal Motor Carrier Safety Administration; Mike Fontaine from the Virginia Department of Transportation and the Virginia Transportation Research Council; and Melissa Miles from State Farm Insurance.

The NSTSCE stakeholders have jointly funded this research for the purpose of developing and disseminating advanced transportation safety techniques and innovations.

The authors would also like to thank the folks at Salex for loaning two of their illuminators for the duration of the project.

EXECUTIVE SUMMARY

Crosswalk safety, especially at night, continues to be a challenge. In 2015, 5,376 pedestrians were killed and 70,000 were injured (National Highway Traffic Safety Administration [NHTSA], 2017). Of these incidents, 74% occurred at night, and of those, 18% were within an intersection. According to another report providing statistics from 2006 (NHTSA, 2008), 59% of pedestrian-involved crashes occurred near or in a crosswalk. For these crashes, where the pedestrian behavior was known, 23% of pedestrians were not visible. In urban environments especially, pedestrians can be difficult to see against the background of lighted building fronts and vehicle headlights (Figure ES1) under current lighting guidelines. Pedestrian visibility can be improved by increasing vertical illuminance (Gibbons, 2008), the light that falls on the vertical surfaces of the pedestrian, but there are diminishing returns.

Figure ES1. Photo. Example of pedestrian visibility in a challenging environment.

This project's main objective was to collect and analyze preliminary data regarding the safety benefits of additional narrow beam crosswalk lighting in a naturalistic environment. Experiment participants operated vehicles while confederate pedestrians (child-sized mannequins) were staged at various positions with or without overhead lighting and crosswalk lighting that used a commercially available narrow beam LED (light emitting diode) luminaire. Salex loaned the crosswalk lighting illuminator (CWI) luminaires to the Virginia Tech Transportation Institute for the experiment.

When used with overhead lighting, the CWI increased the detection distance of the confederate pedestrians in the crosswalk to 297 m while only increasing the power consumption by 5%. This was nearly double the 160-m detection distance for the highest illuminance overhead only baseline condition. The experiment showed no benefit to using the CWI lighting alone.

The results reaffirm that the direction of lighting is significant, but it is only one factor. Merely increasing light levels may not increase visual performance, just as changing the direction may not increase performance. The difference in the location of the illuminators and the overhead lights results in the light coming from different directions and illuminating the pedestrians and the background (roadway) differently than either alone. The effect on pedestrian contrast should be investigated further before setting illuminance levels for CWI lighting. Even with that caveat, the addition of a narrow beam CWI improves driver visual performance at detecting pedestrians in a midblock crosswalk by 88%. This is a powerful finding that should be considered as a safety treatment for midblock crosswalks.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

CAN	controller area network
CCT	correlated color temperature
CWI	crosswalk illuminator
DAS	data acquisition system
DD_m_	detection distance in meters
DF	degrees of freedom
fc	foot-candles
LED	light emitting diode
SSD	stopping sight distance
NHTSA	National Highway Traffic Safety Administration
W	Watts

CHAPTER 1. INTRODUCTION

Crosswalk safety, especially at night, continues to be a challenge. In 2015, 5,376 pedestrians were killed and 70,000 were injured (National Highway Traffic Safety Administration [NHTSA], 2017). Seventy-four percent of these incidents occurred at night, and of those, 18% were within an intersection. According to another report providing statistics from 2006 (NHTSA, 2008), 59% of pedestrian-involved crashes occurred near or in a crosswalk. For these crashes, where the pedestrian behavior was known, 23% of pedestrians were not visible, 41% crossed improperly, and 5% were inattentive. Pedestrian visibility can be improved by increasing vertical illuminance (Gibbons, 2008), the light that falls on the vertical surfaces of the pedestrian, but there are diminishing returns. In addition, pedestrians feel safer and more comfortable in areas that are well lit. In urban environments especially, pedestrians can be difficult to see against the background of lighted building fronts and vehicle headlights (Figure 1) under current lighting guidelines.

Figure 1. Photo. Example of pedestrian visibility in a challenging environment.

Crosswalks are usually illuminated using street lighting. However, most streetlights are limited in the amount of vertical illuminance that they can produce because they are primarily designed to light the road surface, providing only horizontal illuminance. The challenge then is to provide increased vertical illuminance for pedestrian visibility without increasing driver or pedestrian glare. Pedestrians need to be able to see in order to navigate and avoid obstacles (e.g., curbs). A light source with a narrow beam may prove advantageous in this case. Low light sources, such as lights embedded in the roadway or along curbs, increase vertical illuminance but, unfortunately, also increase the glare to either vehicle operators or pedestrians.

Light emitting diode, commonly known as LED, light sources have many advantages for outdoor lighting, including high efficiency and relatively narrow beam widths that can be tailored. Simulations show that crosswalks can be well lit using LEDs without increasing the glare to drivers or pedestrians by mounting narrow beam LED crosswalk lights at 20 feet high and at a 30-degree angle from vertical (Figure 2). Increased visibility at crosswalks could reduce the 23% of pedestrian-involved crashes where the pedestrian was not visible. The lighting could also reduce the 41% of pedestrian-involved crashes by encouraging crosswalk use via the increased/improved crosswalk lighting.

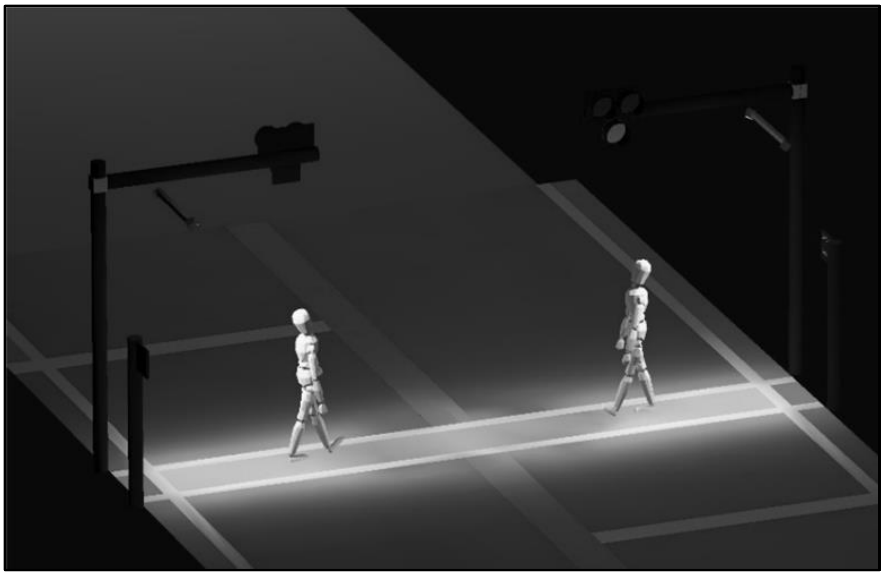

Figure 2. Illustration. Improved LED pedestrian lighting.

The primary objective of this project was to collect and analyze preliminary data regarding the safety benefits of additional narrow beam crosswalk lighting in a naturalistic environment. Experiment participants operated vehicles while confederate pedestrians were staged at various positions with or without overhead lighting and crosswalk lighting that used a commercially available narrow beam luminaire. This project was performed in conjunction with, and adds to, another lighting condition study for pedestrian safety at the Virginia Tech Transportation Institute (VTTI).

Salex loaned the crosswalk lighting luminaires to VTTI for the experiment.

CHAPTER 2. EXPERIMENTAL METHODS

In this experiment, driver visual performance was assessed under different crosswalk lighting designs at both the intersection and midblock stations. The results reported here consider only the portion of the experiment that utilized the special illuminator.

The human factors evaluation was conducted on the Virginia Smart Roads at night in relatively clear weather conditions (no rain, snow, or fog). The Virginia Smart Roads are state-of-the-art, closed test-bed research facilities managed by VTTI in cooperation with the Virginia Department of Transportation. This study used the Highway Section of the Smart Roads; this is a 3.5 kilometer (2.2 mile) long, controlled-access research facility built to U.S. highway specifications. A realistic midblock crosswalk was simulated on the Smart Road. The results of these experiments are highly generalizable and readily applicable to similar conditions on real roads.

A series of crosswalk lighting designs that are representative of currently used designs were developed and installed in conjunction with another experiment. This report only reports on the performance of the Salex luminaire lighting alone and with overhead lighting. Before human factors testing, all crosswalk lighting designs on the Smart Road were photometrically characterized using VTTI's Roadway Lighting Mobile Measurement System, which enables rapid, accurate, low-cost photometric measurements of a variety of lighting sources.

PARTICIPANTS

Twenty-four participants were recruited to take part in the study. Two participant age groups (18–35 years and 65+ years) were used to account for the changes in visual capabilities of the participants as they age. The results were adjusted by the measured visual capabilities. Each age group was also gender balanced. All participants had a valid U.S. driver's license and a visual acuity of at least 20/40 (measured with the Early Treatment Diabetic Retinopathy Study chart with an illuminator cabinet). All experimental activities were approved by the Virginia Tech Institutional Research Board. Participants were paid $30 per hour for their involvement in the study.

EQUIPMENT

Experimental Vehicles

Participants drove two identical instrumented vehicles (2016 Ford Explorers) equipped with data acquisition systems (DASs) that were connected to the vehicle's controller area network (CAN) and onboard camera systems. The DAS collected kinematic data from the vehicle's CAN system, including vehicle speed, GPS coordinates, four video images (driver's face, forward roadway, left side of roadway, and right side of roadway), driver audio, and inputs from the experimenters. During testing, the participants drove laps on the Smart Road, where they were presented with pedestrians at two stations: a crosswalk at the intersection and a midblock crosswalk.

Visibility Objects

During pilot testing, full- versus child-sized mannequins were evaluated for their suitability. Child-sized mannequins were chosen for the detection task as they are smaller and more difficult (making them a more critical object) to detect than adult-sized mannequins. Each mannequin was 1.2 meters (46 inches) in height. Child-sized mannequins were outfitted in gray-colored scrubs, as shown in Figure 3. Gray was chosen because it is a neutral color and is rendered similarly under different illuminance levels and lighting designs.

Mannequins were located at the entry, middle, and exits of the midblock crosswalk (see Figure 4), very close to the pedestrian-vehicle conflict points. This process continued until the participant encountered all crosswalk lighting designs (for both luminaire placement and light level). Presentation of crosswalk lighting designs and light levels were counterbalanced. The presentation of pedestrians was randomized with “blanks” (i.e., no pedestrian presentation) to keep participants from guessing.

Figure 3. Photo. Child-sized mannequin wearing gray scrubs.

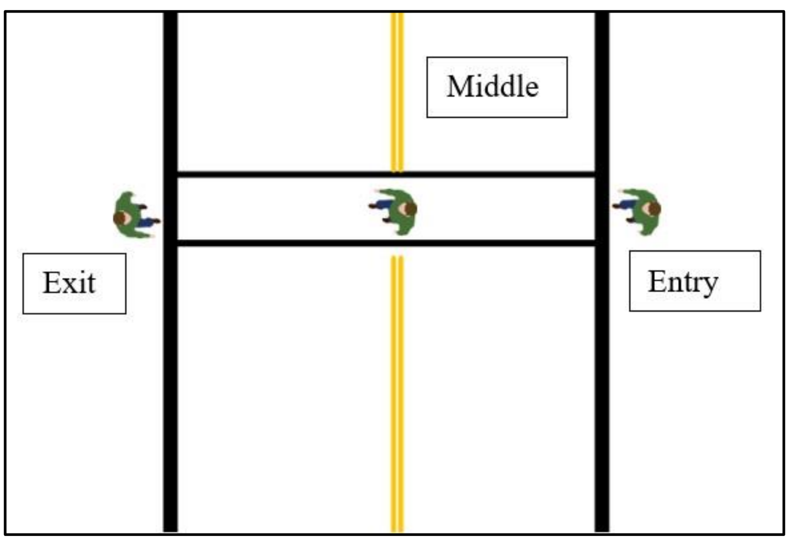

Figure 4. Illustration. Mannequin locations used in the midblock detection task showing entry, middle, and exit locations.

EXPERIMENTAL DESIGN

The experiment evaluated the visual performance at the midblock crosswalk. Table 1 shows the experimental design. The lighting conditions were partially factorial resulting in 10 total lighting conditions.

Table 1. Experimental Design—Independent Variables for Midblock Crosswalk

Independent Variable	Levels
Light level (average vertical illuminance)	• Low—2 lux (0.2 fc)* • Medium—10 lux (0.9 fc) • High—20 lux (1.9 fc)
Crosswalk lighting designs	Overhead Lighting • 3,000 K CCT** • 4,000 K CCT • None Crosswalk illuminators (CWIs) • Salex LED Flood light • None
Participant age	• Younger (18–35 years) • Older (65+ years)

*fc: foot-candles
** CCT: correlated color temperature

INDEPENDENT VARIABLES

Midblock Crosswalk Lighting Designs

Crosswalk Illuminator (CWI)

A commercial flood illuminator product was investigated as a crosswalk illuminator (CWI) as a potential means of improving visual performance of drivers with regards to seeing pedestrians in a crosswalk. The product tested was the Salex LED narrow beam floodlight illuminator (see Figure 5). These are not typically used for crosswalk lighting; however, the narrow beam (5 degrees) makes them a good candidate. The luminaire specifications were 6 Watts, 4,000 K correlated color temperature (CCT), 5 x 30-degree elliptical beam shape, and full glare shield.

Figure 5. Photo. Salex LED floodlight CWI and resulting illumination of pedestrians in the crosswalk when used alone.

The CWIs were mounted on signage near the two ends of the crosswalk at a height of 3.0 m. (10 ft). The beams were adjusted crossed beams so that the illuminator on the right illuminated the pedestrian on the left and the one on the left illuminated the pedestrian on the right.

Overhead Lighting

The crosswalk was illuminated on the approach side by an overhead street lighting luminaire alone and in combination with a CWI on each side of the crosswalk. The overhead luminaire rendered the pedestrian in positive contrast. The overhead luminaires were of type II distribution and had a CCT of either 3,000 K or 4,000 K. The overhead luminaires were mounted at a height of 9.1 m (30 ft).

Lighting Designs

Four designs were evaluated for the midblock crosswalk: 1) CWI only, 2) Overhead 4,000 K CCT only, 3) CWI combined with 3,000 K overhead, and 4) CWI combined with 4,000 K overhead lighting. Figure 6 (a) shows the CWI only configuration (both illuminators on). Figure 6 (b) shows the overhead lighting only configuration, which utilized only the 4,000 K CCT luminaire. Figure 6 (c) shows the configuration of lighting when CWI and each overhead luminaire (either 3,000 K or 4,000 K) were combined.

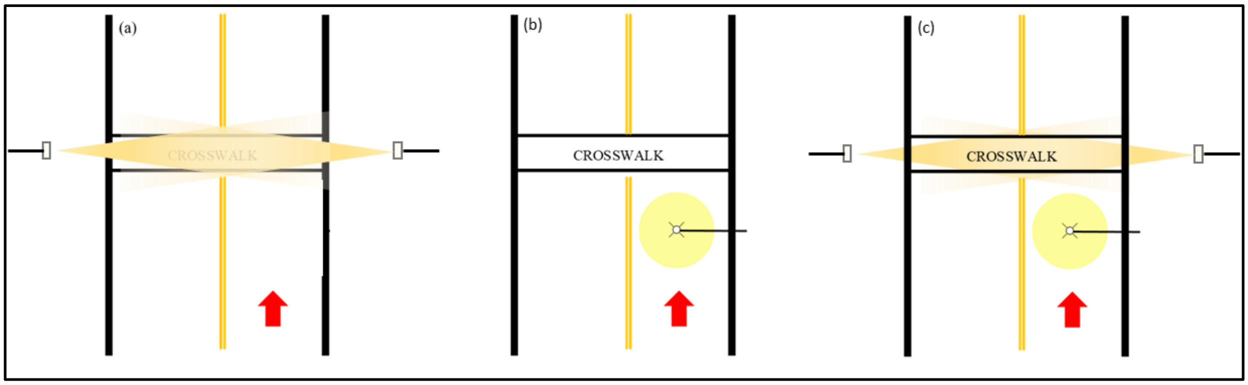

Figure 6. Illustration. Midblock crosswalk positive contrast lighting.
The overhead luminaire was located before the crosswalk. The narrow beam illuminators were located at either end of the crosswalk. (a) Illustrates the CWI only configuration. (b) Illustrates the overhead luminaire only configuration. (c) Illustrates the configuration with combined overhead luminaire and CWI lighting. The red arrow shows the direction of travel of the participant vehicle.

Midblock Crosswalk Light Levels

All overhead crosswalk lighting designs were illuminated to three light levels based on the average vertical illuminance. The low light level was established at 2 lux (0.2 fc). The medium light level was established at 10 lux (0.9 fc) based on research from Bullough (2015). The high light level was established at 20 lux (1.9 fc) based on earlier research from Gibbons (2008).

The lighting levels were measured using a Minolta T-10a meter and a 3 x 1-m grid oriented as shown in Figure 7. Horizontal and vertical illuminance (in the direction of travel) were measured at each point indicated with a red dot.

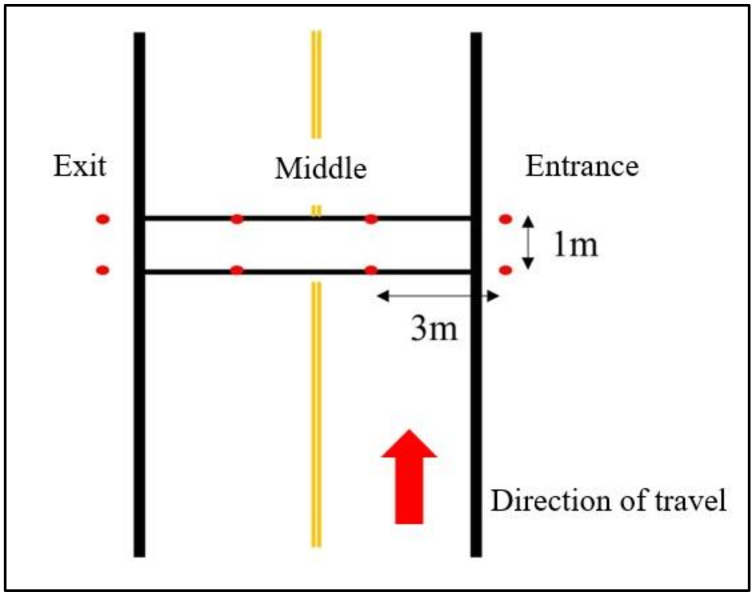

Figure 7. Illustration. Light measurement grid.

Table 2 and Table 3 summarize the horizontal and vertical illuminance measurements of the crosswalk lighting designs, respectively. In Table 3, the four middle measurements (indicated with red dots in Figure 7) were averaged to obtain the "Middle" entry, while the two points at the entrance and two at the exit were averaged for those entries.

The overhead lighting was unable to achieve 20 lux at full output. Therefore, the experiment was run with a maximum vertical illumination from the overhead lighting of 17.1 lx (1.6 fc). The CWIs were not dimmable and mounted at a much lower height than the overhead lighting, so the light output was not balanced between the overhead illumination and the CWI. Despite the lack of dimming, the average vertical illumination from the CWIs was 10.4 lux (1.0 fc), which was similar to the overhead medium light level condition.

Table 2. Horizontal Illuminance Measurements at the Midblock Crosswalk

Light Type	Light Level	Avg. lx (fc)	Min. lx (fc)	Max. lx (fc)
Overhead Lighting	Low	6.8 (0.6)	5.2 (0.5)	7.8 (0.7)
Overhead Lighting	Medium	31.0 (2.9)	23.8 (2.2)	35.5 (3.3)
Overhead Lighting	High	54.3 (5.0)	41.6 (3.9)	62.2 (5.8)
CWI* Salex		93.4 (8.7)	41.3 (4.8)	127.1 (11.8)

*Crosswalk illuminator

Table 3. Vertical Illuminance Measurements at the Midblock Crosswalk

Light Type	Light Level	Crosswalk Entrance lx (fc)	Crosswalk Middle lx (fc)	Crosswalk Exit lx (fc)	Avg. lx (fc)
Overhead Lighting	Low	2.2 (0.2)	2.5 (0.2)	1.6 (0.1)	2.1 (0.2)
Overhead Lighting	Medium	10.2 (0.9)	10.7 (1.0)	8.6 (0.8)	9.9 (0.9)
Overhead Lighting	High	19.8 (1.8)	19.0 (1.8)	12.6 (1.2)	17.1 (1.6)
CWI Salex		1.7 (0.2)	23.8 (2.2)	5.6 (0.5)	10.4 (1.0)

DEPENDENT VARIABLES FOR INTERSECTION AND MIDBLOCK CROSSWALKS

In the visibility experiment, crosswalk lighting designs were assessed by measuring drivers' detection distance in a detection task. Detection distance is the distance at which pedestrians are visible and identifiable. Effective lighting designs and other pedestrian safety countermeasures increase detection distances. Detection distance can also be compared to the stopping sight distances (SSDs) recommended by the American Association of State Highway and Transportation Officials (2018) to determine whether a certain lighting design provides the driver with sufficient distance to come to a complete stop. However, it should be noted that SSD is calculated assuming a 2.5-second brake reaction time and a certain deceleration rate. SSD is a design value and not necessarily a safety performance indicator. SSDs are longer than the actual distance a vehicle needs to stop in realistic driving conditions. For example, in intersection signal timing, 1 second is used for break reaction time instead of 2.5 seconds.

PROCEDURE

Participants were recruited for three sessions. In the first session, participants signed an informed consent document, and their visual acuities were checked to see if they met the requirements for the study. After the participant provided their consent, the in-vehicle experimenter escorted the participant to the experimental vehicle parked outside. The experimenter had the participant sit in the vehicle's driver's seat and demonstrated the seat and steering wheel adjustments. The experimenter then asked the participant to adjust as needed and to buckle their seat belt.

The in-vehicle experimenter entered the back seat of the vehicle and prepared the data collection equipment. Once the DAS was ready, the experimenter instructed the participant to drive to the Smart Road.

The first lap of the first session was a practice lap. The practice lap was used to familiarize participants with where they would turn around and where the crosswalks were located and to give them an opportunity to see the mannequins so they knew what to look for.

The experimental trials began once participants indicated they were ready. Each time a participant drove through the test area, a different lighting design and light level would be presented at the midblock crosswalk. Additionally, child-sized mannequins appeared at different locations relative to the crosswalks. As the participant drove, they were instructed to say the word "pedestrian," "kid," or "child" (whichever was easiest for them to remember) whenever they saw one of the mannequins. The in-vehicle experimenter pressed a handheld button each time a mannequin was identified. Later analysis of the data would determine the distance between this point and the mannequin, which was reported as the "pedestrian detection distance."

Once the experiment session was complete, participants were asked to drive back to the VTTI building. The participants were then dismissed. Participants drove up to 20 laps during each session. Each session lasted 1.5 to 2 hours in conjunction with another funded crosswalk lighting study. Participants each took part in three experimental sessions, for a total participation time of approximately 6 hours.

ANALYSIS

The detection distance was analyzed relative to the different lighting conditions and combinations. A multivariate least squares regression of the data was performed using a statistical software package. The model details are shown in Table 4 with the resulting significance and means from the analysis. The means and standard errors are shown graphically in Figure 8.

Table 4. Least Squares Regression Model Details

Type 3 Tests of Fixed Effects					
Effect	Num DF	Den DF (DF is degrees of freedom.)	F Value	Pr > F	model DD_m_ = Light_Condition|Age / ddfm=kr; (DD_m_ is detection distance in meters.)
Light_Condition	9	207	53	<.0001	random PartNum;
Age	1	22.5	15.71	0.0006	repeated /subject = PartNum type = cs;
Age*Light_Condition	9	207	1.52	0.1427	

Least Squares Means										
Effect	**Age**	**Light Condition**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**	**Alpha**	**Lower**	**Upper**
Light_Condition		4K – Positive – High	159.84	11.398	70.1	14.02	< .0001	0.05	137.11	182.57
Light_Condition		4K – Positive – Low	90.8696	11.7038	76.3	7.76	< .0001	0.05	67.5612	114.18
Light_Condition		4K – Positive – Medium	159.54	9.7679	40.3	16.33	< .0001	0.05	139.81	179.28
Light_Condition		CWI	169.96	11.398	70.1	14.91	< .0001	0.05	147.22	192.69
Light_Condition		CWI – 3K – Positive – High	231.89	11.398	70.1	20.34	< .0001	0.05	209.16	254.62
Light_Condition		CWI – 3K – Positive – Low	183.21	11.7038	76.3	15.65	< .0001	0.05	159.9	206.52
Light_Condition		CWI – 3K – Positive – Medium	206.34	11.7038	76.3	17.63	< .0001	0.05	183.03	229.65
Light_Condition		CWI – 4K – Positive – High	297.45	11.398	70.1	26.1	< .0001	0.05	274.72	320.18
Light_Condition		CWI – 4K – Positive – Low	157.48	11.7038	76.3	13.46	< .0001	0.05	134.17	180.79
Light_Condition		CWI – 4K – Positive – Medium	257.19	11.2562	67.3	22.85	< .0001	0.05	234.72	279.65
Age	O		158.03	11.9015	22.5	13.28	< .0001	0.05	133.38	182.68
Age	Y		224.72	11.8931	22.4	18.89	< .0001	0.05	200.08	249.36

CHAPTER 3. RESULTS

The model shows that the results of the experiment are significantly correlated with the lighting condition and age but not the combination of lighting * age. Age was included as an independent variable to handle the known effect of age on visual performance. As seen in the model details of Pr > F and Pr > |t|, all the light conditions and age categories are significant at 95% confidence with values of less than 0.001. The combination of lighting * age was not statistically significant.

The mean values of the detection distance versus the lighting condition are shown in Figure 8. The bar height is the mean detection distance, and the shades of the bars are used to group the lighting by light type and presence or absence of the additional narrow beam illuminator. The error bars represent the standard error.

Using the CWI alone resulted in detection distances that correlate with, and are not significantly different from, the use of overhead lighting alone at the medium and high vertical illuminance levels (10 and 17 lux). This is expected since the CWI produced similar average vertical illuminance levels alone (10.4 lux). This experiment resulted in no significant difference in the medium and high overhead lighting levels. This finding is somewhat similar to other studies (Gibbons, 2014) where increased lighting levels resulted in diminishing returns in terms of day/night crash rates but dissimilar from other studies on midblock crosswalk lighting levels (Gibbons, 2008). This could be due to lack of experiment statistical power sufficient to distinguish between those two lighting levels.

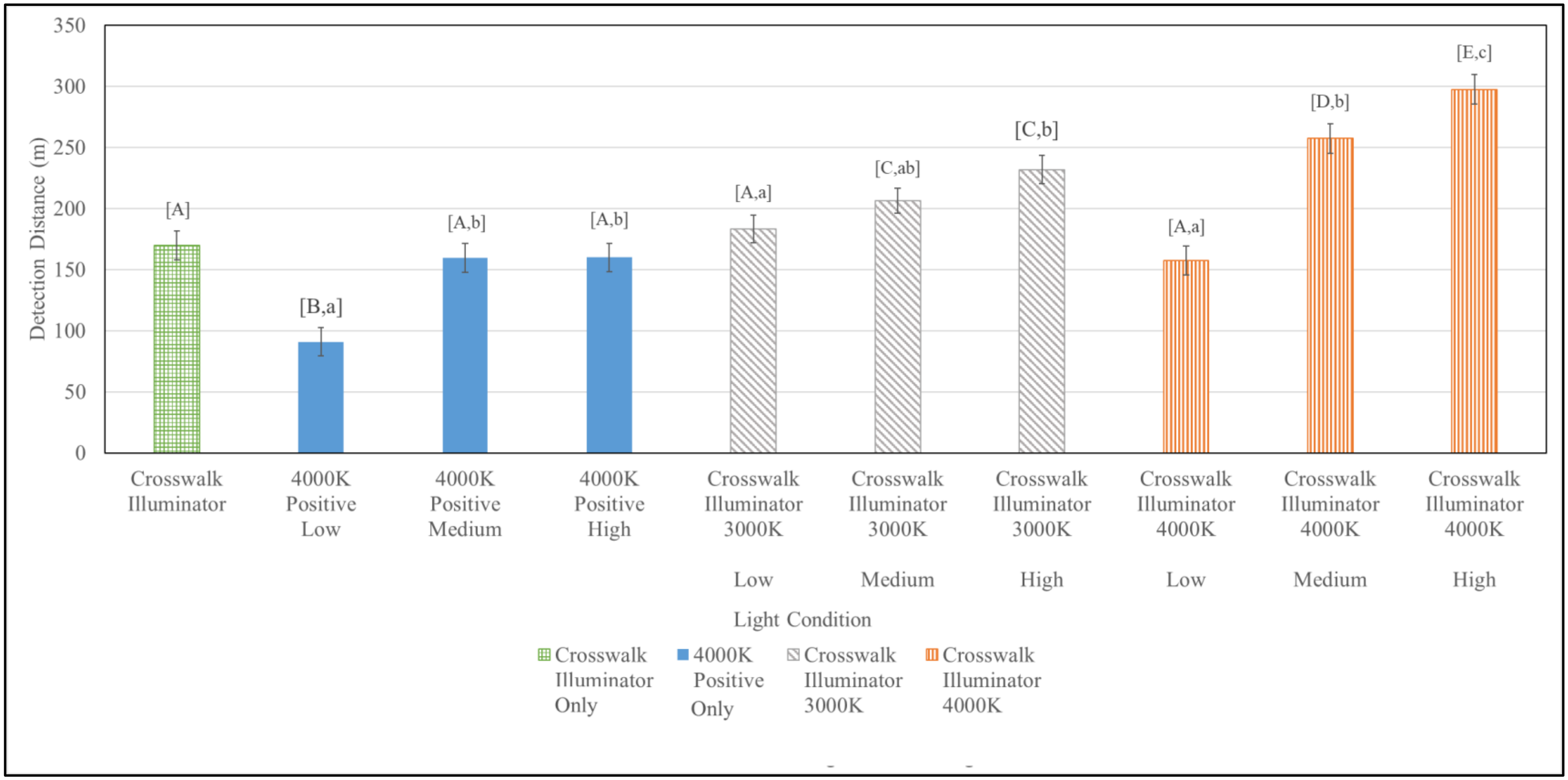

Figure 8. Column chart. Detection distance vs. lighting condition.
The colors/patterns group the lighting conditions into the CCT and presence or absence of the CWI. The letters above the columns denote statistically significant differences from pairwise analyses. The uppercase letters denote pairwise comparison across all light conditions (all columns). The lowercase letters denote pairwise comparison within a lighting grouping (same color/pattern). Differing letters indicate statistically significant differences

The highest performing lighting condition was the 4,000 K CCT high and CWI combination. This lighting condition almost doubled the detection distance (300 m) versus the overhead lighting alone conditions at medium and high levels (160 m each). The next highest combination was the 4,000 K CCT medium and CWI, and third was 3,000 K CCT high and CWI.

A pairwise analysis was performed across all the light conditions and within each grouping of different CCT levels and in the presence or absence of the CWI. In Figure 8, the uppercase letters denote the significant differences between all the lighting conditions. The lowercase letters denote statistically significant differences within the subgroupings.

The pairwise analysis showed that the 4,000 K medium and 4,000 K high detection distances were not significantly different from each other or from the CWI only condition. Neither were the combined CWI+4,000 K low nor CWI+3,000 K low conditions statistically different from those three conditions, indicated by the capital letter "A" in Figure 8. The lowest performing lighting condition (4,000 K low, no CWI) was different from all other lighting conditions and the difference was statistically significant, indicated by the capital letter "B."

The conditions with the three highest detection distances were all statistically significantly different: CWI+3,000 K high, CWI+4,000 K medium, and CWI+4,000 K high, indicated by the letters "C," "D," and "E." These results indicate a high confidence that the increase in detection distance was not random noise.

The remaining combined condition of CWI+3,000 K medium was statistically different from the CWI and overhead lighting (4,000 K) only conditions, but not statistically different from the condition of CWI+3,000 K high.

There is minimal error bar overlap of the detection distance measurements, even for the lighting conditions that are not statistically significantly different from one another. This suggests that further study is warranted to see if increasing the power of the experiment with additional trials or participants will show a statistical difference between the lighting conditions with the capital A markings.

Analysis of the visual performance relative to the age categories confirmed that there was a reduction in visual performance, on average, for all conditions for the older age group versus the younger age group (Figure 9). This aligns with the body of literature regarding the effects of aging on visual performance, helping to validate the results of this study.

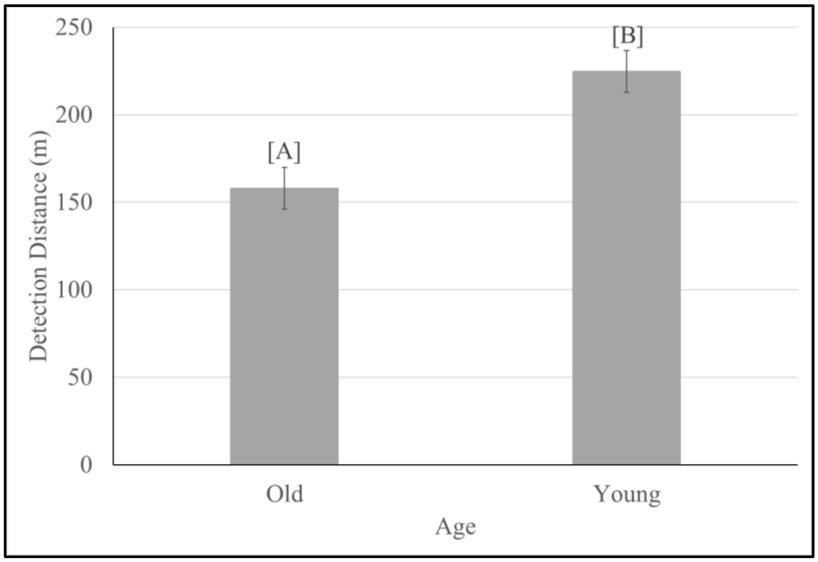

Figure 9. Column chart. Difference in detection distance vs. age group.

DISCUSSION

Increasing roadway lighting typically has a diminishing effect on visual performance of the drivers, and this can be seen in the three overhead only conditions in this experiment where the high light level and medium light level resulted in similar visual performance. The CWI+4,000 K high condition nearly doubled drivers' visual performance versus either lighting condition alone. This condition corresponds to a vertical lux of 27.5 lux vertical illumination (light is additive), which is not quite double the 4,000 K high lighting condition, but more than double the 4,000 K medium light level and CWI alone. The energy consumption was increased from 240 W to 252 W (6 W each for the CWI), which is only a 5% increase for double performance. This CWI achieved similar visual performance to the 4,000 K medium condition while using only 12 W of power versus approximately 120 W, respectively. The data shows that simultaneously lighting the pedestrians from different directions increases the visibility of the pedestrian more than increasing the lighting level of the overhead lighting. The additional illumination also provided a significant increase in participants' visual performance versus overhead lighting at 4,000 K medium and at 3,000 K high.

What is interesting is that the additional CWI lighting provides increased and statistically significant differentiation between the 4,000 K lighting condition levels. Without the CWI, there is no significant difference between the 4,000 K CCT medium and 4,000 K CCT high light levels. The mean detection distances for the 4,000 K medium and high alone are within 0.3 m for this experiment. With the addition of the CWI, the 4,000 K CCT medium and high light levels are statistically significantly different with a 40-m difference, even if still showing some diminishing improvements. The increased visual performance resulting from the CWI was statistically independent of participants' age grouping.

These results illustrate that vertical illuminance can be produced more efficiently from a CWI than a typical overhead lighting design because the beam is much narrower, which is expected. The CWI also produced a higher horizontal illuminance in the crosswalk, but because of the narrow beam, it was also limited to crosswalk vicinity. The overhead lighting is more efficient at producing horizontal illuminance over a wider area and farther from the base of the luminaire. The angle at which the lighting strikes the pedestrian seems to play an important role in the visibility of the pedestrians, with an advantage given to lighting from two different directions as in the combination of the CWI with the overhead lighting. This means that the pedestrian contrast with the background (roadway and horizon, etc.) could be different when the CWIs are used with overhead lighting. The overall luminance of the pedestrians may have also increased since there should have been some overlap in the light falling on the pedestrians from the overhead lighting and CWIs.

CHAPTER 4. CONCLUSIONS

The results reaffirm that the direction of lighting is significant but only one factor of importance. Merely increasing light levels may not increase visual performance, just as simply changing the direction of lighting may not increase performance. The difference in the location of the illuminators and the overhead lights results in the light coming from different directions and illuminating the pedestrians and the background (roadway) differently than either alone. The effect on pedestrian contrast should be investigated further before setting illuminance levels for CWI lighting.

Even with that caveat, the addition of a narrow beam CWI improves driver visual performance at detecting pedestrians in a midblock crosswalk by 88%. This is a powerful finding that should be considered as a safety treatment for midblock crosswalks.

REFERENCES

American Association of State Highway and Transportation Officials. (2018). *A policy on geometric design of highways and streets* (7th ed.).

Bullough, J. D., & Skinner, N. P. (2015). *Demonstrating urban outdoor lighting for pedestrian safety and security*. University Transportation Research Center – Region 2. http://www.utrc2.org/sites/default/files/Final-Report-Demonstrating-Urban-Outdoor-Lighting-Pedestrian-Safety.pdf

Gibbons, R. B., Edwards, C., Williams, B., & Andersen, C.K. (2008). *Informational report on lighting design for midblock crosswalks* (FHWA-HRT-08-053). Federal Highway Administration.

Gibbons, R. B., Guo, F., Medina, A., Terry, T. N., Du, J., Lutkevich, P. J., & Li, Q. (2014). *Design criteria for adaptive roadway lighting* (FHWA-HRT-14-051). Federal Highway Administration.

National Highway Traffic Safety Administration. (2008). *National pedestrian crash report*. United States Department of Transportation. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/810968

National Highway Traffic Safety Administration. (2017). *Traffic safety facts 2015 data: Pedestrians* (DOT HS 812 375). United States Department of Transportation. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812375