Research Report: Street Lighting for Pedestrian Safety

FHWA Safety Program

U.S. Department of Transportation
Federal Highway Administration

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A SAFE SYSTEM IS HOW WE GET THERE

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16. Abstract

This document details three separate experiments that coalesce to form pedestrian lighting recommendations that consider the visibility needs of both children and adults. In the first study, participant drivers were evaluated on their ability to detect the presence of child-sized pedestrians under variations of luminaire type (2200 K, 4000 K, and 5000 K), mounting height (road scale and ped scale), as well as variations in luminance and illuminance of the visual target. A second experiment evaluated the ability for walking pedestrians (adults and children) to detect hazards in their path under the same lighting conditions used in the first experiment. The final experiment evaluated the abilities of adults and children to determine when it would be no longer safe to cross a mid-block crosswalk as vehicles approach under varying lighting conditions. The outcomes of this research are presented as recommendations for crosswalk lighting design to include considerations for children, depending on pedestrian volume and road class.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ANSI	American National Standards Institute
CCT	Correlated Color Temperature
CIE	Commission Internationale de L'Eclairage
FHWA	Federal Highway Administration
IES	Illumination Engineering Society
K	Kelvin
LED	Light Emitting Diode
NSC	National Safety Council
Ped	Pedestrian
SPD	Spectral Power Distribution
SRTS	Safe Routes to School
SSD	Stopping Sight Distance

EXECUTIVE SUMMARY

Current research and design guidance for pedestrian lighting has centered on the ability of adult drivers to detect adult pedestrians but ignore the needs for children. This research considered the visibility needs of pedestrians, both adult and child, and evaluated the ability of drivers to detect children as pedestrians. The Safe Routes to School initiative (SRTS) is a program with the goal of increasing the safety of children on their daily routes to school through interventions that improve their visibility and well-being. A product of this research is a set of lighting recommendations that can serve as an intervention for improving the visibility of pedestrians at night, specifically children. The project objectives were: 1) to evaluate the visibility of child-sized pedestrians alongside a lighted roadway at night (Driver Experiment), 2) to evaluate the visibility of trip hazards in a lighted crosswalk at night (Walker Experiment) and 3) to assess the impact of roadway lighting on the decision to cross a roadway (Gap Acceptance Experiment).

The results found that the 2200 K LED light type does not produce the same level of visibility as the 4000 K LED or the 5000 K LED which could be related to the light distribution.

When considering urban versus rural environments, two different lighting designs may be necessary. The results indicated that with more visual clutter as is typical in an urban environment, increased luminance levels may be necessary (2 cd/m^2) while a rural environment can maintain safe visibility with 1 cd/m^2 luminance level. These luminance levels combined with the established minimum illuminance of 9 to 10 lux form a recommended guideline for illuminating pedestrian areas.

The second human factors study evaluated participants; children and adults, acting as walking pedestrians for potential trip hazards while walking at night. The results showed that the lighting systems had a minimal impact on the visibility of trip hazards in the forward view of participants as a majority of detections occurred from at least 40 meters.

The third evaluation sought to determine the impact of various light levels on the decision-making ability of both children and adults when crossing a crosswalk.

Neither light level nor light scale affected the responses of children and adults in regard to when they would no longer attempt to cross a roadway; however, it was determined that the presence of roadway lighting may inform an adult’s perception of depth more accurately.

The results also indicated that children underestimate the acceptable crossing period compared to adults. Adults were more conservative by an average of 30 m (98 ft.) or a range of 2 to 3 seconds with vehicle speeds of 35 and 25 mi/h, respectively.

In addition to the human factors experiments, this research also evaluated vertical and semi-cylindrical methods of illuminance measurement. Vertical illuminance is commonly used as a specification in design guides for roadway lighting; however, semi-cylindrical illuminance, which considers light from a wider angle and may be more applicable in certain scenarios. It was determined that face-height semi-cylindrical illuminances below approximately 9 lux yielded shorter detection distances indicating that at least 9 lux of semi-cylindrical illuminance at face height is warranted for visibility of pedestrians. The results also indicate that beyond 9 lux vertical there was minimal benefit.

Based on these results, the recommended lighting levels are a minimum 2 lux vertical illuminance in areas where pedestrian volumes are low (0-100 pedestrians per hour). Higher pedestrian areas (>100 pedestrians per hour) are recommended to be 10 lux semi-cylindrical. The luminance recommendations for low volume pedestrian zones is 1 cd/m^2 in urban areas. For high volume urban areas, 2 cd/m^2 is recommended and rural areas are recommended to maintain 1 cd/m^2. The color temperature of the light source should be 3000 K are higher. Pedestrian crosswalks should have a minimum of 20 lux vertical as current guidelines suggest.

INTRODUCTION

The design of lighting for pedestrians is critical for the implementation of outdoor and street lighting. In the past, efforts have focused primarily on crosswalk lighting, as crosswalks are typically where pedestrians and vehicles occupy the same space on the roadway. However, sidewalks, non-crosswalk areas used to cross the road, and areas not connected to the road are also in need of lighting design guidelines. Research in this area has been lacking and the current guidelines remain consensus based.

Correctly applied and effective lighting addresses the issues (primarily that of darkness) and safety concerns of both adult and child pedestrians. Research has shown lighting is essential not only for the driver to see pedestrians, but for pedestrians to see their surroundings, with glare control, comfort, ability to detect trip and fall hazards, and promote perceptions of safety and security.

The final consideration is the development of lighting technology. As luminaires and light sources evolve, existing guidelines may become obsolete. For example, solid-state lighting (LED) fixtures have a controlled optical output than traditional sources and as a result, light that was typically emitted to light crosswalks and sidewalks may be limited. Now, recommendations for a suitable pedestrian lighting level are needed for application to pedestrian areas like sidewalks and crosswalks.

Pedestrian Safety

According to a National Center for Statistics and Analysis (2020) fact sheet, the percent of total fatalities involving pedestrians increased from 2009 to 2018 by five percent, as shown in the Percentage of Total Fatalities Column of Table 1. During this time period, there was also an approximate increase of 16,000 injuries. In 2018, 74% of all pedestrian fatalities occurred at non-intersections and 10% occurred on roadsides, shoulders, parking lanes, bicycle lanes, sidewalks, mid-block crosswalks, among other sites. Three-fourths of all pedestrian related fatalities occurred during periods of darkness (76%).

Table 1: Pedestrian Fatalities and injuries as a Percentage of Total Fatalities and injuries in traffic crashes (2009 t0 2018) (excerpted from FARS 2009-2017 National Center for Statistics and Analysis. (2020). Pedestrians: 2018 data. DOT HS 812 850)

Year	Total Fatalities	Pedestrian Fatalities	Percentage of Total Fatalities	Total Injured	Pedestrian Injured	Percentage of Total Injured
2009	33,883.00	4,109.00	12%	2,224,000.00	59,000.00	3%
2010	32,999.00	4,302.00	13%	2,248,000.00	70,000.00	3%
2011	32,479.00	4,457.00	14%	2,227,000.00	69,000.00	3%
2012	33,782.00	4,818.00	14%	2,369,000.00	76,000.00	3%
2013	32,893.00	4,779.00	15%	2,319,000.00	66,000.00	3%
2014	32,744.00	4,910.00	15%	2,343,000.00	65,000.00	3%
2015	35,484.00	5,494.00	15%	2,455,000.00	70,000.00	3%
2016	37,806.00	6,080.00	16%	3,062,000.00	86,000.00	3%
2017	37,473.00	6,075.00	16%	2,745,000.00	71,000.00	3%
2018	36,560.00	6,283.00	17%	2,710,000.00	75,000.00	3%

The age groups of pedestrians killed or injured in traffic crashes in 2018 are shown in Table 3. Children are designated as ages 14 and younger and 17% of all child fatalities and 3% of all injuries were as pedestrians (National Center for Statistics and Analysis, 2020).

Table 2: Total and Pedestrians Killed or Injured in Traffic Crashes, by Age Group, 2018 (National Center for Statistics and Analysis, 2020)

Age Group	Total Fatalities	Pedestrian Fatalities	Percentage of Total Fatalities	Total Injured	Pedestrian Injured	Percentage of Total Injured
<5	344	63	18%	50,000	1,000	2%
5–9	331	58	18%	64,000	3,000	4%
10–14	363	60	17%	76,000	5,000	6%
Children <= 14	1,038	181	17%	190,000	9,000	5%
15–19	2,318	227	10%	254,000	6,000	3%
20–24	3,927	431	11%	334,000	7,000	2%
25–29	3,688	482	13%	310,000	7,000	2%
30–34	3,045	485	16%	244,000	7,000	3%
35–39	2,690	501	19%	219,000	6,000	3%
40–44	2,299	423	18%	191,000	5,000	2%
45–49	2,548	485	19%	190,000	4,000	2%
50–54	2,588	553	21%	183,000	5,000	3%
55–59	2,889	608	21%	170,000	6,000	4%
60–64	2,491	558	22%	149,000	5,000	3%
65–69	1,934	385	20%	102,000	3,000	3%
70–74	1,579	291	18%	77,000	3,000	3%
75–79	1,304	238	18%	46,000	2,000	3%
80+	2,090	361	17%	51,000	1,000	3%
Ages 65+	6,907	1,275	18%	276,000	9,000	3%
Total	36,428	6,209	17%	2,710,000	76,000	3%

A specific focus of pedestrian safety is school-age children as they are travelling to school. These children travel at twilight in both morning and afternoon, creating unique issues. Children are especially vulnerable to traffic. In addition to being small and easily distracted, it is difficult for children to judge the direction of sounds, estimate the speed and distance of oncoming vehicles, and anticipate driver behaviors. In a recent virtual reality simulation, six-year-old children were struck 8% of the time when crossing busy one-lane streets, while the crash rates for eight-, 10-, and 12-year-old children were 6%, 5%, and 2%, respectively. Children's limited ability to judge the available gap at a young age primarily attributes to this difficulty in crossing streets. Younger children also take more time to take the first step in crossing the street, shortening the available gap. However, children's crossing speeds do not differ from those of adults (O'Neal et al, 2018).

When considering all pedestrians in addition to children, one of the factors contributing to the fatality rate at night is lack of lighting. The International Commission on Illumination (CIE) states that the reason roadway fatalities are higher during periods of darkness is mainly due to reduced visibility (National Center for Statistics and Analysis, 2018). Since approximately 90% of the information drivers use to navigate the roads is visual (Hills, 1980), seeing and avoiding pedestrians crossing the street or at an intersection becomes more challenging with less light. In fact, roadway fatalities during periods of darkness are approximately three times greater than those during daylight (National Highway Traffic Safety Administration, 2015).

Nationally, on average about 75% of pedestrian fatalities occur after dark (National Center for Statistics and Analysis, 2018). However, this statistic is more compelling when considering the fact that only about 25% of all traffic volume occurs after dark (Commission Internationale de l'Éclairage, 2010). This means that during the time of day when the least number of vehicles are on the road, the greatest number of pedestrians are killed in crashes. Furthermore, as mentioned earlier, pedestrian fatalities are the only category of traffic deaths that are increasing. This shows a heightened need to add or improve safety measures to protect areas of roadway traffic with high pedestrian volume, especially after dark. Adding lighting to roadways has been shown to be an effective countermeasure against crashes at night (Wortman et al, 1972; Elvik, 1995; Isebrands et al, 2010; Donnell, Porter, & Shankar, 2010; Sasidharan & Donnell, 2013).

Safe Routes to School

SRTS is an international approach using engineering, enforcement, safety education, and incentives to encourage children to walk and bike to school. Engineering approaches broadly incorporate design, implementation, operation, and maintenance of infrastructure improvements like traffic control devices or physical devices. Enforcement approaches encompass strategies to stop unsafe behaviors in drivers, pedestrians, and bicyclists. Enforcement strategies also encourage all road users to obey all traffic safety rules and share the road with other road users. Education approaches involve teaching road users the benefits of SRTS and creating awareness about them. Encouragement approaches closely follow education approaches. Their aim is to promote walking and bicycling by getting road users interested in those means of transportation. The U.S. Congress created the Federal-Aid SRTS Program in 2005, providing funding for the implementation of SRTS programs to improve safety and levels of physical activity for students in the form of active transportation to school. These programs can be implemented by a state department of transportation, metropolitan planning organization, local government, school district, or even a school (Terry, Brimley, Gibbons, & Carlson, 2016).

Many studies on the various implementations of SRTS have overwhelmingly concluded that it offers positive benefits. It has been established that the program has been successful in its primary goal and that there has been an increase in the number of children walking and biking to school. A cross-sectional evaluation examined the relationship between urban form changes (SRTS projects such as sidewalks, traffic lights, pedestrian crossing improvements, and bicycle paths; see (Figure 1) and walking and biking to school (Commission Internationale de l'Éclairage, 2010). Surveys were distributed to parents of third through fifth graders at 10 schools near a project with aforementioned features. Subjects were categorized into one of two groups depending on whether or not their children traveled passed the location of an SRTS project on their way to school. Based on responses, children whose travel path utilized some of the features provided through the SRTS project were more likely to show increases in walking or biking than the children who did not travel passed the SRTS project (15% vs. 4%). Governors Highway Safety Association (2017) assessed changes in the rates of active school travel after SRTS projects were implemented. They looked at 48 implementations and the 53 schools affected by them in Florida, Mississippi, Washington, and Wisconsin. A before-and-after analysis concluded that there were significant increases in active school transportation after SRTS projects were implemented. Specifically, walking increased from 9.8% to 14.2% and biking from 2.5% to 3%.

Figure 1. Example of a SRTS traffic improvement project as reported by Commission Internationale de l'Éclairage (2010)

Roadway and pathway lighting focusing on the visibility of children at night can serve as an SRTS intervention as current lighting guidelines focus primarily on the visibility of adult pedestrians. Recommendations for lighting in areas common to children who walk to school, in both rural and urban areas, are provided based on the results of this research. A careful consideration to the characteristics of urban and rural environments must be given as contrast, visual clutter, and multiple light sources impact a pedestrian's visibility. The scope of this research not only includes the visibility of children as pedestrians from the point of view of the driver but also the ability of pedestrians, children, and adults, to detect hazards in their walking path under the same lighting conditions. This method ensures that any recommendation for lighting that benefits the visual performance of a driver also considers the visual performance of pedestrians of all ages.

Objective of Research

The objective of this research was to provide recommendations for lighting for pedestrian safety including lighting methods for improving safe routes to school for children. Lighting recommendations for improving the visibility of pedestrians, both adult and child, from a driver's point of view were developed as a result. Pedestrian visibility, from the pedestrian's point of view, in detecting hazards on walkways and crosswalks are factored into the research method and recommendations.

The findings of the literature review under section 2 reveals the need to develop a luminance standard that would result in optimal visibility for all road users: adult and child pedestrians on sidewalks and in crosswalks, as well as drivers. The luminance standard thus must include both optimal visibility of pedestrians by drivers and the level and type of lighting needed for safe pedestrian travel. A secondary objective is the determination of differences in luminance requirements for adult versus child pedestrians in terms of maintaining good visual performance and perceptions of visibility, comfort, and safety.

The researchers also sought to evaluate the possibility of developing a lighting metric that enhances pedestrian safety per the outcomes of these objectives.

REVIEW OF EXISTING LITERATURE

During the course of this research effort, a literature review considering the visibility needs both for and of the pedestrians was considered. The topics considered in this effort include pedestrian lighting at crosswalks and intersections, urban and rural issues and visibility needs in general. A summary is provided at the end of the review.

Pedestrian Visibility

Studies have shown a positive correlation between well-lit pathways and physical activity, such as running, walking, and bicycling. Through surveys and literature reviews, Lopez and Hynes (2006) concluded that the installation of sidewalk lighting in residential areas encourages physical activity. The same study also noted that comparable research on the relationship of the built environment and health is needed for urban, especially inner city, neighborhoods, as well as for rural areas. Balfour and Kaplan (2002) suggest that the neighborhood environment, including pathway lighting, may influence functional health at an older age. Their study consisted of surveying 883 functionally healthy participants 55 years or older in Alameda County, California, for one year. To determine functional loss, they were asked to rate the severity of neighborhood problems and the difficulty of certain physical everyday tasks. The study found an increased risk to overall functional health in residents who reported living in multiple-problem neighborhoods, where those problems consisted of traffic, noise, crime, trash and litter, poor lighting, and inadequate public transportation, compared to those in non-problem neighborhoods. The study also concluded that neighborhood problems associated with the largest increased risk were heavy traffic, excess noise, and inadequate lighting. Inadequate pathway lighting was not studied as a lone factor, however. In a survey that examined associations between perceived neighborhood characteristics and leisure-time physical activity, Huston et al. (2003) reported that streetlights were positively associated with engaging in leisure or physical activity, but path lighting was not studied specifically.

Hazards for the Pedestrian — Slips, Trips, and Falls

Pedestrian safety hazards are commonly encountered on sidewalks and neighborhood pathways and walkways. A walkway profile survey done in Palo Alto, California, found 50 potential trip points in a 1-mile (0.6-km) stretch (Ayres & Kelkar, 2006). The minimum change in elevation required to be identified as a potential trip point was 0.5 inches (1.3 cm). Based on the walkway profiles, Ayres and Kelkar (2006) concluded that abrupt rises large enough to destabilize a pedestrian appear to be common in residential sidewalks. Potential trip and fall obstacles consist of uneven pavement, holes (in pavement), construction barriers, bicycle racks, and lighting posts, among others (Fotios & Cheal, 2009).

The National Safety Council (NSC) categorizes slip, trip, and fall accidents four different ways: slips and trips without falling, falling on the same level (i.e., tripping on a sidewalk), falling to a lower level (i.e., collapsing structures, falling from ladders or roofs), and jumping to a lower level (i.e., controlled and voluntary movement from one level to another). During 2017, slip, trip, and fall incidents occurred in the United States at a rate of 23.1 per 10,000 full-time workers, accounting for 227,760 occupational injuries (National Safety Council, 2017) and are among the top three occupational injuries (see Figure 2).

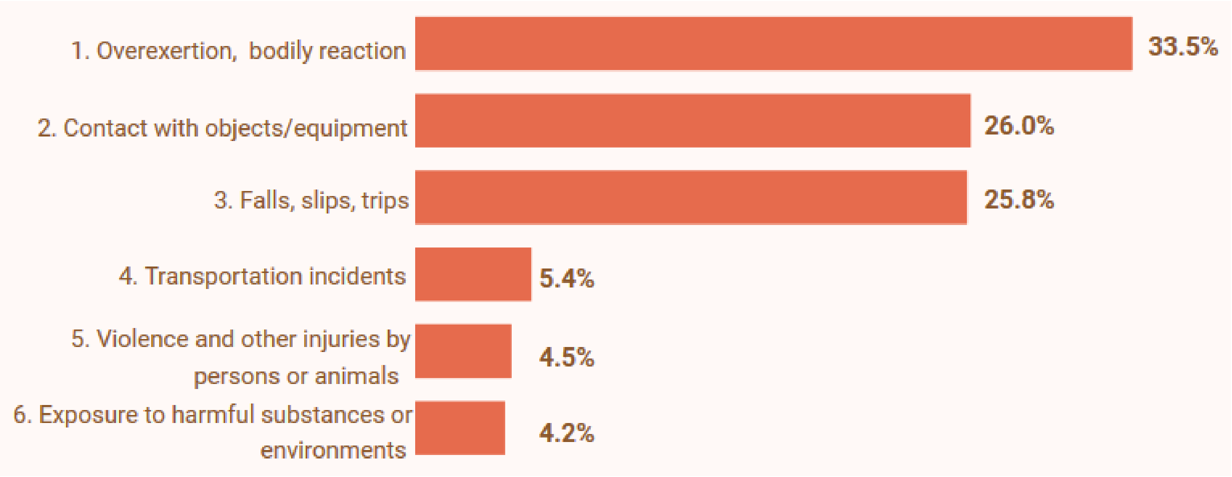

Figure 2. Top six occupational injuries in the United States in 2017 (National Safety Council, 2017)

As reported by the NSC, the demographic most at risk of a slip, trip, or fall accident is people aged 55 or greater. Falls were the leading cause of unintentional-injury death for the elderly in 2013 (National Safety Council, 2013). Fotios and Cheal (2009) found significant differences in performance between young (18–45) and old (60+) participants at low illuminance (0.2 lux). The data showed a significant difference at low illuminance levels; however, the difference decreased in magnitude at higher illuminances, suggesting that obstacle detection ability increases with higher illuminance. The results of this study are bolstered by another study conducted by Bhagavathula and Gibbons (2019), which assessed the detection rates of wheel stops in parking lots and garages). Six different colors of wheel stops were tested: white, blue, gray, yellow, black, and black with yellow stripes. The results of this study showed that increased light levels resulted in higher detection rates of wheel stops (Figure 3). Plateaus in the detection performance (light level where improvement in detection rate was not observed with increasing light level) were observed at the 2-lux average light level in parking lots and 10-lux average light level in parking garages.

Figure 3. Wheel stop in a parking lot (Bhagavathula and Gibbons, 2019)

Pedestrian Lighting at Intersections

Lighting is a significant safety consideration for intersections, a primary road-crossing point for child and adult pedestrians. Pedestrians awaiting to cross at an unsignalized crosswalk must be aware of motorists approaching from multiple directions and understand the concept of time, speed, and distance. Even at signalized crossings, pedestrians must be aware of vehicles turning into one of the lanes they are crossing. Visibility requirements for effectively crossing a roadway hinge on the ability of pedestrians to detect approaching traffic as well as clearly see their pathway across and destination on the other side. Roadway lighting increases visibility, augments vehicle headlamps, and provides more information about the surrounding area for all road users, and consequently can be a contributing factor to reducing automobile crashes (Li, et al, 2020, Hasson & Lutkevich, 2002).

To determine the appropriate light level at intersections, a new systems-level approach to intersection lighting design was introduced by Bhagavathula, Gibbons, and Nussbaum (2018). In this study, three intersection lighting designs were evaluated. This evaluation was based on an evaluation of drivers' nighttime visibility using both objective as well as subjective measures. For the objective measure the detection distances of small targets that were placed at the entrances, exits, and middle of pedestrian crosswalks was measured. The subjective ratings measured drivers' perceptions of visibility, safety, and comfort. The results indicated that the design illuminating the intersection box offered better visual performance and had fewest missed target detections with visual performance plateauing between 7 and 10 lux of average intersection illuminance.

A study by Minoshima et al. (2006) also examined the effect of intersection lighting design on subjective ratings of visibility. Subjective ratings of visibility were obtained from drivers exposed to three different intersection lighting layouts (or configurations), each with three levels of illumination (5, 10, and 15 lux). The three intersection layouts were based on the part of the intersection that was illuminated, and used the following three configurations: approach, corner (or box), and both approach and corner. Drivers rated five statements—visibility, danger to pedestrian, ease of driving, brightness, and safety—on Likert-type scales (1 to 5). With 1 being least favorable and 5 being most favorable with 3 being neutral. A mean rating higher than 3 (or the neutral anchor) was used as a measure of effectiveness of an intersection's lighting design. In this study, increases in illuminance levels resulted in higher subjective ratings of visibility. With illuminance levels higher than 10 lux, mean ratings of pedestrian visibility were higher than 3 on the Likert-type scale in all three layouts. Minoshima et al. (2006) also found that ratings (all statements including pedestrian visibility) depended on illuminance level. At the 15-lux illuminance level, the lighting configuration illuminating the approach and corner was rated highest. At the 10-lux and 5-lux illuminance levels, the configuration illuminating the approach was rated the highest. The authors concluded that the approach lighting layout should be used to maintain a mean roadway surface luminance of 10 lux, but if a higher level of average roadway illuminance is needed, then both approach and corner illumination should be used. This study also analyzed the optical properties of intersections where crashes occurred frequently. The results indicate that a uniformity ratio of illuminance (ratio of minimum to average illuminance) of 0.4 makes intersections safer.

The safety effects of lighting at intersections have been given special consideration by both the Illumination Engineering Society (IES) and the Commission Internationale d'Eclairage (CIE). These organizations recommend minimum lighting levels for intersections, with specific levels depending on a number of factors, such as roadway classification, speed, traffic volume, and traffic composition. The light levels recommended for intersections, though, differ substantially from those recommended for roadways. In addition to IES and CIE, other information sources are available for lighting roadways from the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). The intersection lighting guidance and warrants described by these agencies do not obligate state or local governments to provide lighting but do give important insight on when to investigate lighting and how to improve safety at an intersection.

Safety Effects of Lighting at Midblock Crosswalks

Very few studies have been conducted on the topic of crosswalk lighting and pedestrian visibility. One of the earliest studies on pedestrian visibility at intersection crosswalks was by Freedman, et al. (1975), who reported that increasing the intensity of light resulted in an increase in the time available for drivers to respond, and recommended an average horizontal illuminance of 75 lux for crosswalks. This value however is extremely high and is not representative of current technology or responsible lighting practice.

Pedestrian visibility studies conducted in Switzerland showed that rendering pedestrians in positive contrast (i.e., pedestrians are illuminated from the approach side, rendering them brighter than the background), reduced pedestrian-vehicle crashes by two-thirds (Wilken et al., 2001). Pedestrians can be rendered in positive contrast by increasing the vertical illuminance on them. The lighting design that rendered the pedestrians in positive contrast was compared to existing design in a field test (Hasson & Lutkevich., 2002), which showed that the crosswalk lighting design that rendered the pedestrians in positive contrast provided significant benefits over the conventional one. The benefits of positive contrast on pedestrians were also reported in research conducted in realistic nighttime environments. Edwards and Gibbons (2008) measured detection distances of pedestrians under different levels of vertical illuminance and reported that increasing the vertical illuminance on pedestrians increases the distance at which drivers can detect them (Figure 4).

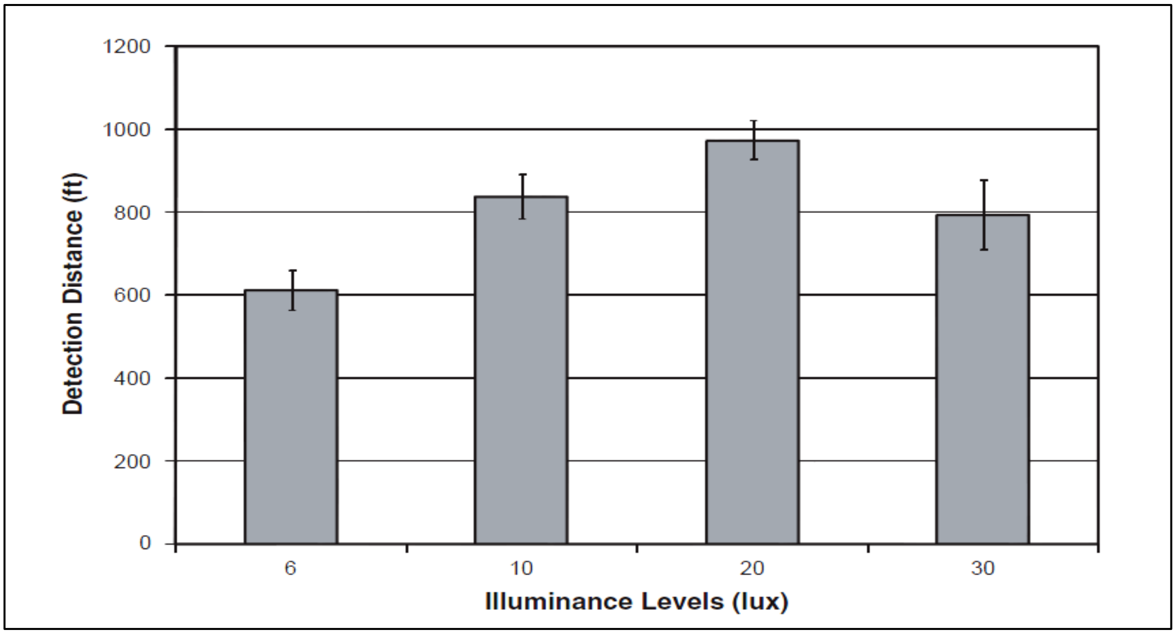

Figure 4. Increase in detection distance with increase in vertical illuminance on the pedestrians as reported by C. Edwards and Gibbons (2008)

The above-mentioned research used fixed overhead lighting to illuminate pedestrian crosswalks; however, some recent research in pedestrian visibility has used bollard-type lights to illuminate pedestrian crosswalks. Bullough et al. (2009) reported a study exploring different ways to illuminate crosswalks for potential improvements in pedestrian visibility and safety. The study consisted of photometric simulations of various crosswalk lighting and a survey of individuals with expertise in the fields of transportation, transit operations, and public safety specifically to analyze the visual performance, glare, and economic impacts of each lighting system. The responses concluded that the bollard-based lighting for crosswalks increased pedestrian illuminance and reduced costs.

Some differences in light levels recommended for optimum pedestrian visibility in crosswalks depend on the approach used for the lighting of pedestrians in crosswalks. Edwards and Gibbons (2008) used conventional overhead lighting for illuminating crosswalks. They reported that a vertical illuminance level of 20 lux at a height of 1.5 meters (5 feet) from the road surface resulted in good driver visual performance at midblock crosswalks (for speeds up to 35 mi/h). Bullough and Skinner (2015), who used a bollard lighting system to illuminate a crosswalk, found that a vertical illuminance of at least 10 lux at a height of 0.9 m (3 ft) on the pedestrian is required to increase contrast and thereby visibility (speeds of the vehicles were not mentioned in the study).

Table 3: Comparison of crosswalk lighting methods and illuminances

Authors	Light Type	Vertical Illuminance	Measurement Height (m)
Edwards and Gibbons (2008)	Overhead Lighting	20 lux	1.5
Bullough and Skinner (2015)	Bollards	10 lux	0.9

It is important to note that pedestrian visibility in bollard-based lighting has never been directly compared to overhead lighting in realistic roadway conditions where the drivers approached the crosswalk in a moving vehicle. Further, bollard-based lighting might increase transient glare for drivers approaching the crosswalk; however, glare control could be improved through use of louvers or baffles (Bullough et al., 2009). Demonstration projects were undertaken with acceptance by surveyed pedestrians in most aspects of the installations however drivers were not surveyed (Christoff, 2013). Another disadvantage of bollard-based lighting is that it involves placing additional fixed objects adjacent to the roadway.

Urban versus rural considerations

Over half of all traffic related fatalities occur in urban areas (53%); however, according to the Census Bureau, 80% of the U.S. population resides in urban areas. Rural fatalities account for 45% of total fatalities with only 19% of the population residing there. These figures reveal that crashes that occur in rural areas are more likely to be fatal, likely due to higher posted speeds and variable terrain, compared to urban areas. In 2018, 79% of pedestrian deaths occurred in urban areas and 18% in rural (3% unknown), despite the higher rate of pedestrians in urban areas (US Department of Transportation, 2015).

Compared to urban, rural related pedestrian fatalities and safety factors are more difficult to quantify due to inconsistencies in data regarding shoulder placement, road classes, sidewalk availability (Boarnet, Anderson, Day, McMillan, & Alfonzo, 2005), and lighting (Stewart, Moudon, & Claybrooke, 2014).

Special Pedestrian Lighting for Children

A study conducted by Wazana et al. (1997) that reviewed risk factors for child pedestrian injuries reported that children are 2.3 times more likely to be injured during darkness than during the day. Loukaitou-Sideris, Liggett, and Sung (2007) reported that to promote safe walking at night, it is important to increase pedestrian visibility by providing lighting. Safety interventions or countermeasures specifically tailored to children could significantly reduce these injuries. Installing special pedestrian interventions such as additional lighting, can promote the use of existing effective transportation safety interventions such as bicycle lanes or sidewalks for children. No specific lighting guidelines to improve the visibility of children currently exist, however, and this research endeavors to inform future guidelines with recommendations based on these empirical findings. Further, almost all the lighting evaluations for current design guides have been conducted from the adult point of view.

Literature Summary

Through the literature review, it was determined that urban and rural zones possess unique characteristics in terms of environmental lighting, pedestrian and vehicle volume, and driver expectation. These are important considerations for pedestrian lighting recommendations for contributing to the body of work under the Safe Routes to School program. Previous research has evaluated pedestrian lighting at intersections and mid-block crosswalks, and design guidelines for those scenarios are specific to pedestrians at adult height. The visibility of children, unaccompanied by an adult, in low-light conditions is a research gap that this multi-evaluation effort serves to fill.

The literature review has shown that the following areas need to be addressed for comprehensive recommendations for lighting midblock crosswalks and intersections to be developed:

- There is a need to develop a light level that results in optimal visibility for all road users (pedestrians and drivers).
- There is a need to understand if there are differences in light level requirements for adult versus child pedestrians in terms of maintaining good visual performance.
- The existing recommended light levels are based on consensus and are not backed by empirical research. Specification of light levels should be backed my empirical research that accounts for all road users (pedestrians and drivers).
- Specifications of light levels and luminaire pole placements for crosswalks at midblock and intersections should be available so that departments of transportation can easily adopt them.
- Finally, there is no universal metric for assessing the safety of a pedestrian. Several metrics have been proposed, such as vertical illuminance (at a specified height - 1.5 m, 0.9 m etc.), semi-cylindrical illuminance, etc. For a lighting designer to be able to optimize a lighting design, a metric that represents pedestrian safety must be developed. This metric can then be used in a design method that can then compare designs and allow for luminaire and layout optimization.

RESEARCH METHOD

The pedestrian lighting study that forms the basis for this report incorporated three human factors-based experiments to achieve the project objectives. The project objectives were: 1) to evaluate the visibility of child-sized pedestrians alongside a lighted roadway at night (Driver Experiment), 2) to evaluate the visibility of trip hazards in a lighted crosswalk at night (Walker Experiment) and 3) to assess the impact of roadway lighting on the decision of when to cross a roadway (Gap Acceptance Experiment). Each of the evaluations compared different light types and mounting heights, and the two pedestrian experiments (Walker and Gap Acceptance) included children as participants. The output of this project is a set of lighting recommendations that consider the visibility of pedestrians (child and adult) to drivers as well as the visibility of drivers and trip hazards to pedestrians. The three experiments are described in greater detail below.

Driving and Detection Experiment (Driver Experiment)

In this experiment, the research team considered the visual needs of the driver with the goal of determining the lighting levels necessary to detect and identify a child-sized pedestrian offset from the roadway in a sidewalk or crosswalk simulation scenario. Metrics considered include vertical illuminance, semi-cylindrical illuminance, and roadway luminance. The environment was also a special consideration; the test trials included a rural setting with only a guardrail behind the pedestrian and a second setting with more visual clutter, as would be common in an urban environment.

Table 4 summarizes the independent variables of the driver experiment. The vertical illuminance levels varied due to the differences in spectral power distribution (SPD) of the light types and the luminance levels selected; however, the vertical illuminance levels were matched across light types and luminance levels. A high, medium, and low area of illuminance was selected under each condition. Along the route were four locations where a child-sized pedestrian (mannequin) could appear in a rural setting and one location in the urban setting.

Table 4. Independent variables and levels for driver experiment

Independent variable	Rural environment	Urban environment
Light spectral power distribution (SPD)	2200 K LED 4000 K LED 5000 K LED	4000 K LED
Road Luminance	High (2 cd/m^2) Medium (1 cd/m^2) Low (0.5 cd/m^2)	High (2 cd/m^2) Medium (1 cd/m^2) Low (0.5 cd/m^2)
Semi-cylindrical illuminance on pedestrian (dependent on SPD and luminance)	High 13–17 lux Med. 10–13 lux Low 7–10 lux	High 6–40 lux Low 3–22 lux
Visual background	Highway setting (guardrails)	Street setting (clutter)
Light source scale (height)	Highway scale 50 ft (15.2 m)	Road scale 30 ft (9.1 m) Ped scale 18 ft (5.4 m)
Age	Young (25 to 45 years), old (65 and older)	Young (25 to 45 years), old (65 and older)

Each of the three experiments used a repeated measures design to assess the effects of light spectral power distribution (SPD), luminance, and surround ratio on driver and pedestrian visual performance. Descriptions of each independent variable for this experiment can be found in Appendix B: Independent Variables.

Driver Experiment Procedure

In the driver experiment, participants drove a vehicle through a course and detected child-sized mannequins on the shoulder of the roadway by saying "kid" or "child" aloud when a mannequin is spotted. Participants were instructed to scan and search for child-sized pedestrians on their route and announce when they could detect them. An in-vehicle experimenter pressed a handheld button after the participant's verbalization to flag the moment in the data stream. Using the vehicle's data acquisition system, which captures audio, video, and experimenter input, and continuous differential GPS, the exact moment of detection was pinpointed during data reduction procedures. The distance from the point of detection to the mannequin is considered the detection distance. Figure 5 illustrates this concept in greater detail.

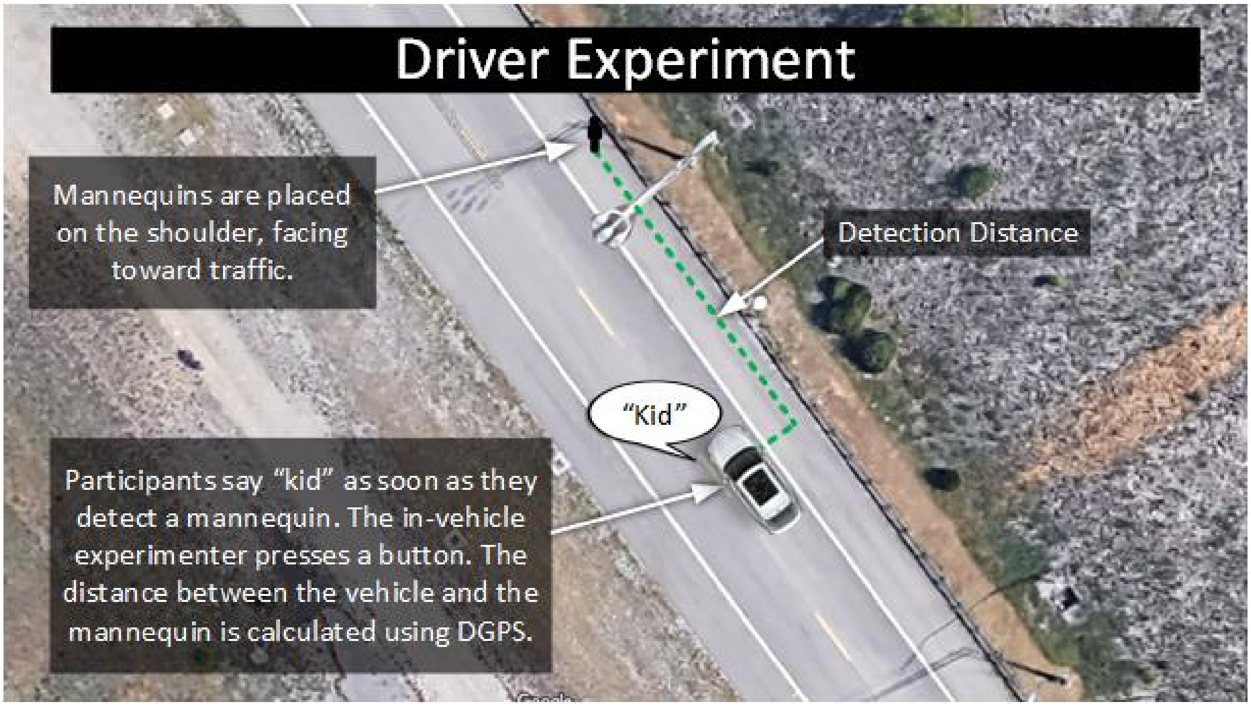

Figure 5. Diagram of driver experiment procedure

The dependent variable is detection distance (i.e., the distance between the driver and the target object at which the driver detects the object). Detection distance is commonly used as a measure of visual performance in nighttime roadway visibility studies (Bhagavathula & Gibbons, 2013; Bhagavathula, Gibbons, & Nussbaum, 2017; Mayeur, Bremond, & Bastien, 2010; Shinar, 1985). Detection distance of a visual target can also be directly compared to the stopping sight distance (SSD), which is used as a design standard for sight distance in road design by the American Association of State Highway and Transportation Officials (2011). SSD is the minimum distance required for a driver travelling at the design speed to come to a complete stop. If the detection distance is lower than the SSD, the driver will not be able to avoid a collision with the object under the given conditions.

The study incorporated the use of cylindrical cardboard tubes (Figure 6) as catch trials to encourage participants to announce only they had seen a child-sized mannequin 45 in (1.14 m) tall when they were sure. This height correlates with the average height of a 6-year-old, an age on the lower end of ages of children walking to school. In a nighttime setting, both the mannequins and the tubes appear as silhouettes from a distance beyond approximately 246 ft (75 m), the distance headlamps typically reach. At this distance, the tubes and mannequins could appear similar. Participants were encouraged to announce a detection only when they were sure it was a mannequin and not a tube.

Figure 6 also illustrates where the vertical illuminance measurement was taken on the mannequin. This measurement was taken to ensure each position along the test course was matched for vertical illuminance. Three vertical illuminance levels (high, medium, and low) were used for the rural road test, and two high and low), for the urban road test.

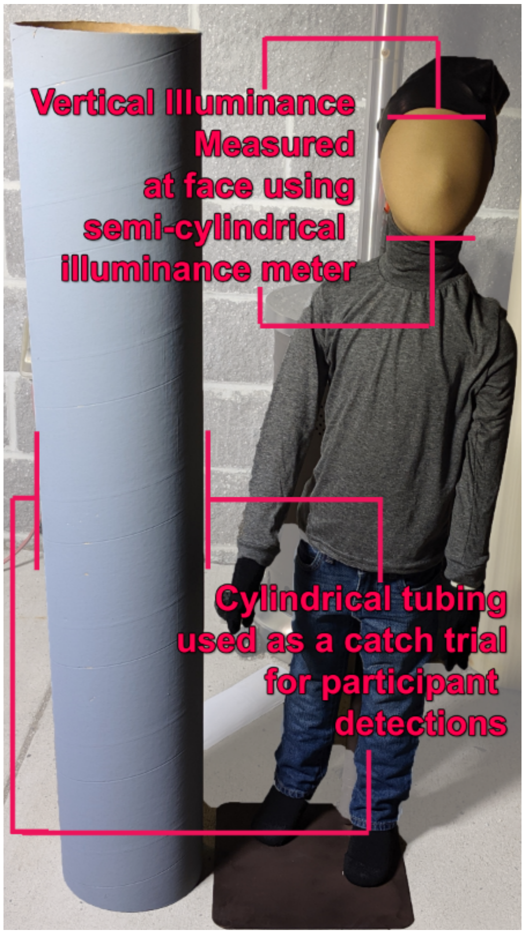

Figure 6. Cylindrical tube and child-sized mannequin

The mannequins were positioned approximately 5 to 7 ft (1.5 to 2 m) to the right of the driving lane. This distance coincides with the positioning of a sidewalk where roadway lighting would be required to also illuminate a sidewalk. Distances closer to the roadway are more illuminated; therefore, an offset distance represents a worst-case scenario.

It can be argued that detecting a pedestrian at a high degree offset (5 to 7 ft (1.5 to 2 m), is not always important to the driving task; however, the behaviors and decision making of children are not predictable. The safety of a child in proximity to a roadway increases when the driver is aware of the child. Researchers placed the mannequins in relation to the luminaire to establish a variety of vertical and semi-cylindrical illuminance conditions for detection.

Pedestrian Walking and Detection Experiment (Walker Experiment)

This experiment explored the visibility needs of pedestrians at roadway-scale and pedestrian-scale street lighting. In this case, the visibility needs under consideration were those of the pedestrians to walk and move safely. Pedestrian participants were exposed to a visual environment where they were tasked with identifying a potential trip-and-fall hazard in their path ahead. For the experiment, the experimental variables included lighting metrics such as vertical and horizontal illuminance, roadway uniformity, luminance, contrast, and surround ratio were recorded and described in Appendix B: Independent Variables..

Walker Experimental Design and Procedure

Table 5 shows the variables, levels, and classifications for the walker experiment. Many of these variables and levels remain consistent from the driver experiment, including luminance and light type. The differences include the visual target types (tripping hazards) and vertical illuminance at ground level for the targets.

Table 5. Walker experiment design

Independent variable	Levels
Light spectral power distribution (SPD)	4000 K LED
Surface Luminance	High (2 cd/m^2) Medium (1 cd/m^2) Low (0.5 cd/m^2)
Vertical illuminance on tripping hazard	High: (Ped 22–24 lux; Road 19-22 lux) Medium: (Ped 10–13 lux; Road 6-9 lux) Low: (Ped 6–7 lux; Road 3-5 lux)
Tripping hazard height	0.5 inch 1 inch
Age	Old (65 and older) Young (25 to 45 years) Child (8 to 12 years)
Light Type	Road scale (Overhead) Ped scale
Lane	Furthest from roadside lighting Nearest to roadside lighting

Walker Experiment Procedure

For the walker experiment, two participants observed targets placed inside their own lane on the surface of an intersection ahead (Figure 7). The participants started 61 meters (200 feet) from the intersection and began walking toward the intersection. When they could detect an object in their lane within the intersection, they stopped walking and the distance was measured to determine from which they could detect the object. The detection distance was the dependent variable for this experiment.

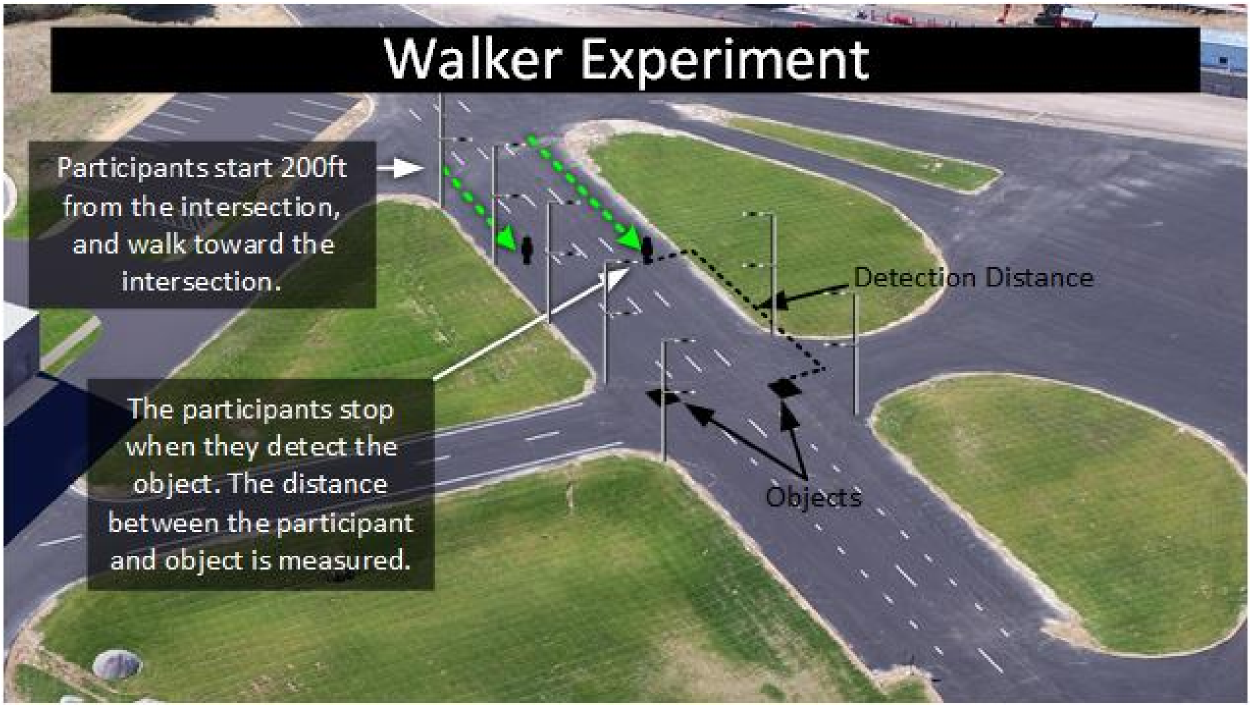

Figure 7. Walker experiment method

Pedestrian Crosswalk Gap Acceptance Experiment (Gap Experiment)

The third experiment was a gap acceptance scenario in which a child and adult (sometimes the child’s parent) each indicated separately at what point they would still consider crossing the street as a vehicle approached at various speeds and in different lanes.

Gap Acceptance Experimental Design and Procedure

Table 6 shows the variables and levels for the gap experiment. Many of these variables and levels remain consistent from the walker experiment, including luminance, light type, and age. The differences are the lanes of travel and the speeds of the vehicles operating in the trials. Descriptions of these independent variables are in Appendix B: Independent Variables..

Table 6. Gap acceptance experiment design

Independent Variable	Levels
Light spectral power distribution (SPD)	4000 K LED
Surface Luminance	High (2 cd/m^2) Medium (1 cd/m^2) Low (0.5 cd/m^2)
Lane	Nearest: (3.6 m (12 ft) from participants) Furthest: (10.9 m (33 ft) from participants)
Speed	25 mph (40 km/h) 35 mph (56 km/h)
Age	Old (65 and older) Young (25 to 45 years) Child (8 to 12 years)
Light type	Road scale Ped Scale

Gap Experiment Procedure

The walker and gap experiments were conducted on the same nights with the same participants. After the completion of the walker experiment, participants moved behind the jersey barriers indicated in Figure 8. Participants were each provided a handheld button they could press with their thumbs. Participants were instructed to press their button at the moment they would no longer feel safe attempting to cross the road. It was emphasized that to cross the roadway, they would be walking and not running, and that they needed to make it all the way across the road before a vehicle reached the crosswalk.

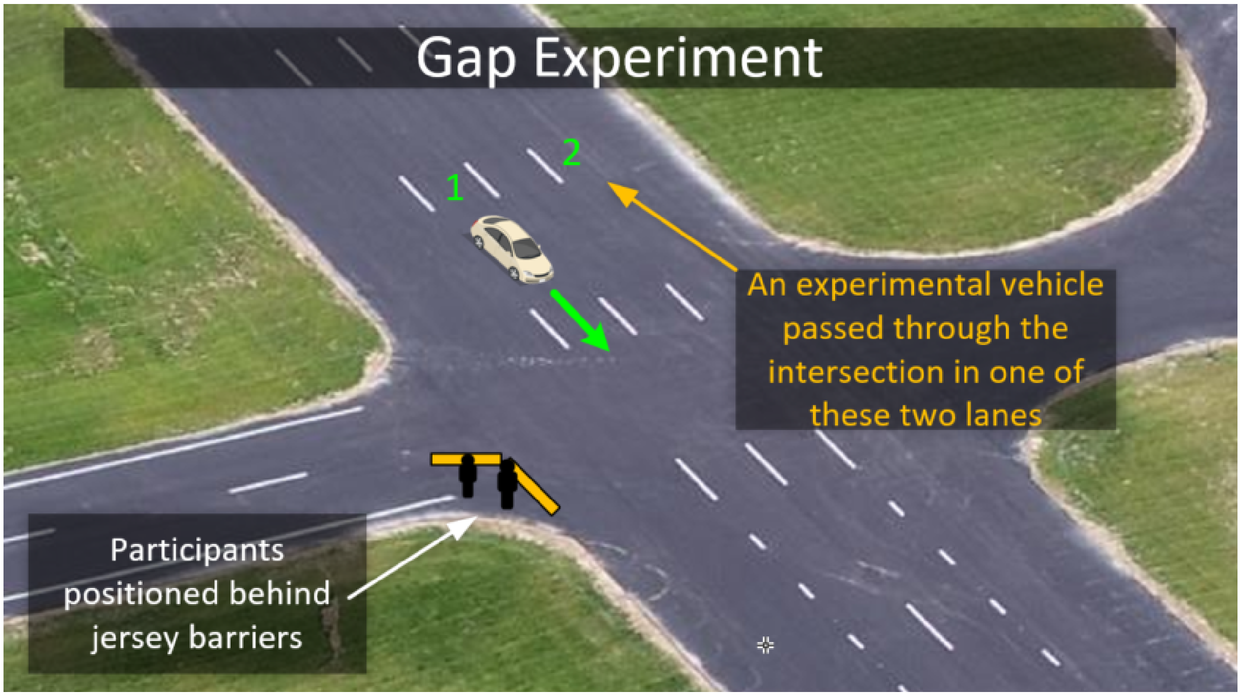

Figure 8. Gap experiment setup

A total of 28 trials that included combinations of each light scale (ped and road), each luminance (high, medium, and low), each lane (near and far), and each speed (25 mph and 35 mph). There were four trials when no roadway or pedestrian lighting was on.

The dependent variable for this task is the distance between the vehicle and the participant at the instant when participants pressed the button. This data would indicate the position just beyond the last accepted point a participant would consider crossing the road.

RESULTS DISCUSSION IN BRIEF

This chapter will provide a brief summary of findings from the analysis of the three experiments. For the full analysis, including charts and descriptions of interaction effects, refer to Appendix D: Analysis and Discussion of Experimental Results.

Semi-Cylindrical and Vertical Illuminance

Comparisons of semi-cylindrical and vertical illuminance measurement methods showed a strong correlation. Due to the wider angle of the semi-cylindrical measurement instrument, light from multiple sources can contribute to the illuminance values. Due to this, the research team believes the use of semi-cylindrical in an urban environment where more light sources are present is an appropriate measurement method. For rural environments where there are not light sources in addition to the roadway or pedestrian lighting, the vertical illuminance method can be used as a wider-angle consideration is not necessary.

For semi-cylindrical illuminance, there appears to be a shift at approximately 9 to 10 lux where detection distance begins to plateau (as shown in Figure 27 in Appendix D: Analysis and Discussion of Experimental Results). This was especially apparent for the road- and pedestrian-scale lighting systems. As this area was an urban environment, and therefore a worse-case scenario for contrast in terms of the visibility level of an object, the researchers believe that this range where the shift occurs is a minimum lighting requirement for semi-cylindrical illuminance at face height.

Driver Experiment

A learning effect was determined through analysis where participants’ performance improved after the first two laps and plateaued for the remaining eight laps. Due to this, and because the study’s design was balanced across participants for the configurations they would experience first, the results are broken into expected versus unexpected detections.

During the trials, when participants were unsure of when to expect a pedestrian, the results were truer to reality. After two laps, the repetition increased familiarity with the course and where the mannequins might appear despite balancing the experiment and including catch trials. Most “unexpected” detections occurred between 45 and 65 m (148 and 213 ft) from the pedestrian. At a speed of 45 mph (72 km/h), that is a range of 2.2 and 3.2 seconds compared to the 3.4 to 4.7 seconds of detection during later laps in the experiment.

The data shown in Figure 9 highlights the concept of unexpected versus expected appearance of objects. Each participant drove one practice with mannequins or objects of detection presented before driving the ten experimental laps. The data here shows that on the first two experimental laps, when participants were first exposed to the mannequins, their detection distances were shorter. On the third lap and beyond, a learning effect is shown to plateau the detection distances, across all lighting configurations and scenarios, most likely due to expectancy. This highlights a potential for weighted importance of the data from the first two laps, as an ordinary driver on any highway would come across a pedestrian unexpectedly. The data also shows that younger drivers detected the child pedestrian consistently from a greater distance than older drivers, even during the first two laps before familiarity with the experimental trials improves their awareness of mannequin placement.

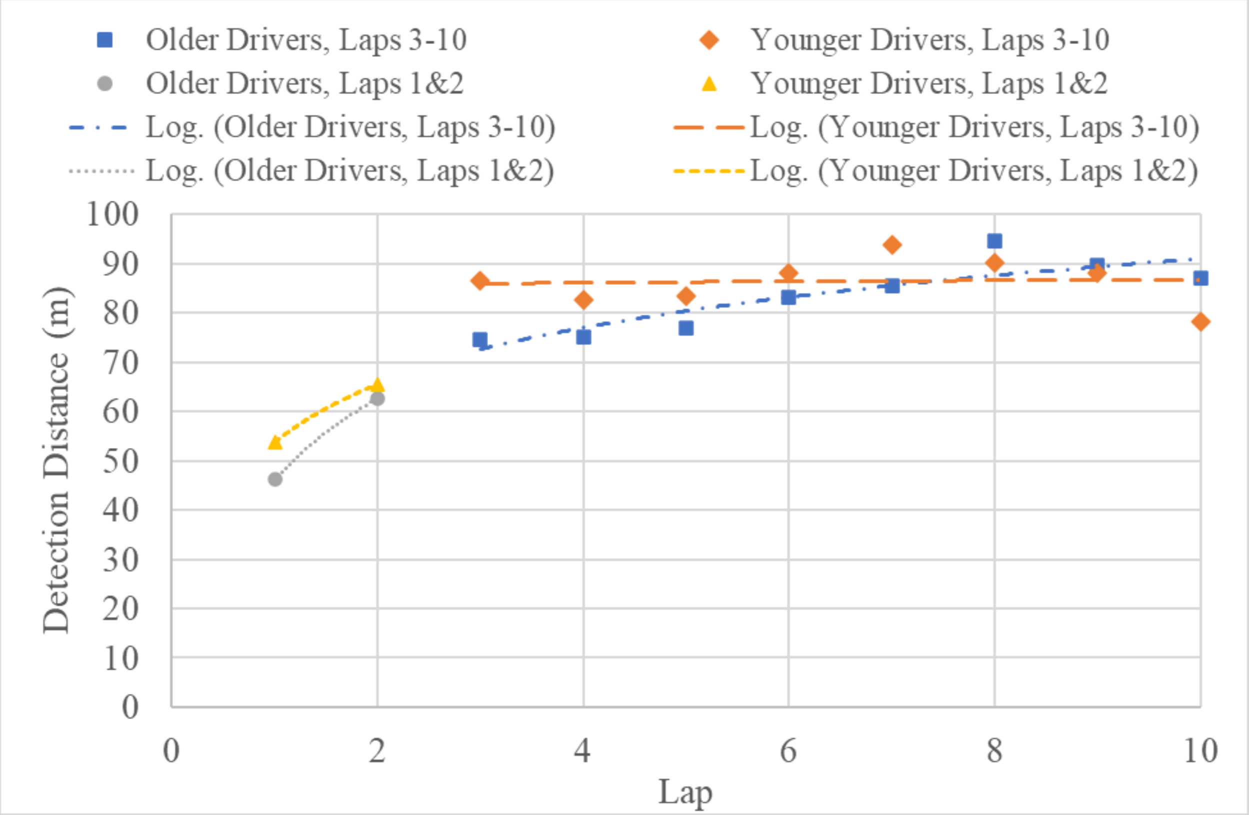

Figure 9. Age by detection distance per lap

Ped scale and road scale lighting comparisons may indicate that semi-cylindrical illuminance levels below 8 lux have shorter detection distances than when semi-cylindrical illuminance is greater than 20 and as high as 40 lux (Figure 10). But between 10 and 20 lux, no discernible difference is found either for the two scales of lighting compared here or the three light types (2200 K, 4000 K, or 5000 K). Based on these results, there is a visual plateau at approximately 10 lux.

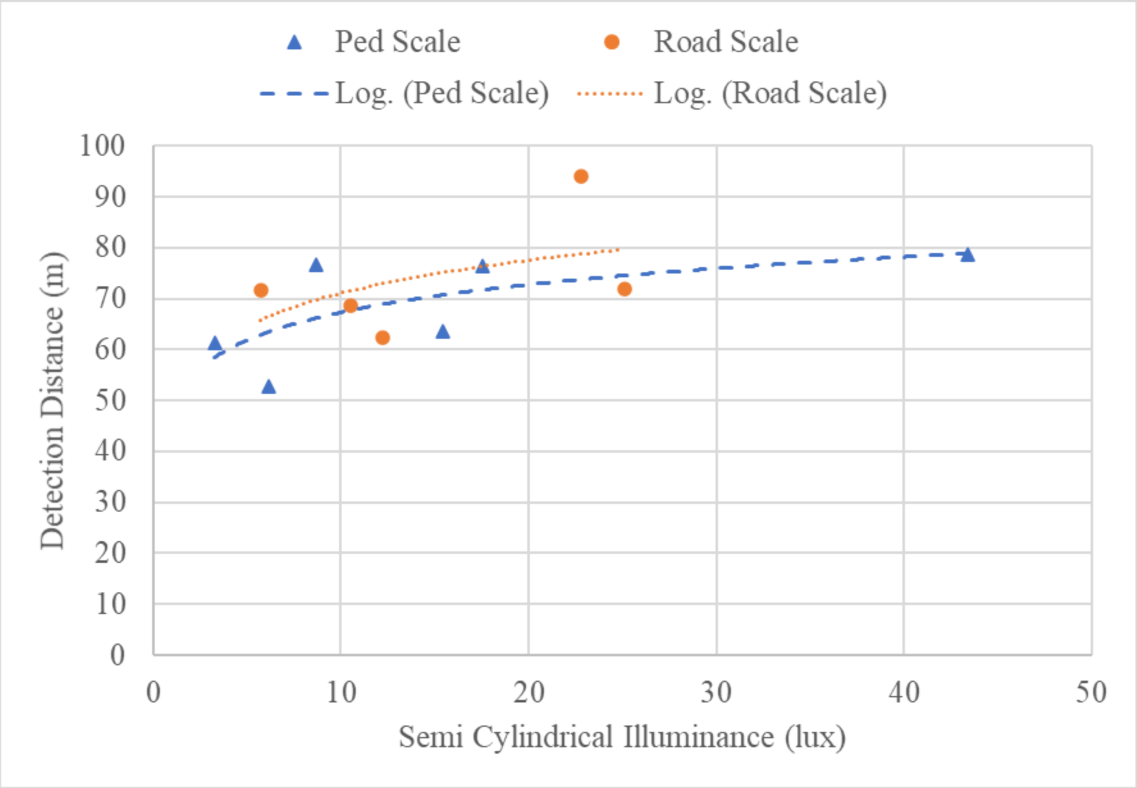

Figure 10. Detection distance by semi-cylindrical illuminance for each light type (ped scale, road scale)

Figure 11 shows the relationship between the luminance level (cd/m^2), semi-cylindrical illuminance (lux), and detection distance (m). The average illuminance correlates to each luminance level, as expected, and the trend is apparent in the detection distance as well. In general, higher light levels result in longer detection distances.

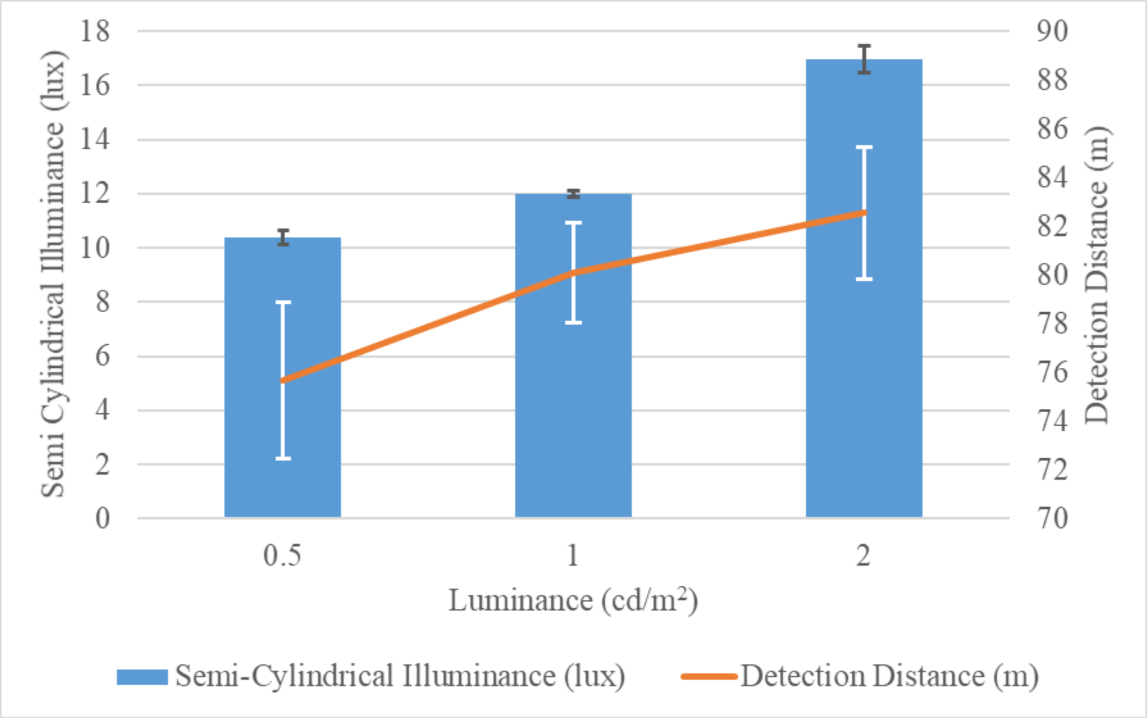

Figure 11. Luminance (cd/m2) and illuminance (lux) across detection distance (m)

A correlation was found between luminance level and detection distance for the first lap when the general location of the mannequins was completely unfamiliar to participants. As this scenario captures the truest response from drivers, a weighted emphasis is placed on this result. Thus, the 2 cd/m^2 luminance level was the most preferred as during the first lap participants were able to detect the child-sized mannequins an estimated 7 m (22 ft) further than at 1 cd/m^2 and 17 m (56 ft) further than at 0.5 cd/m^2 (as shown in Figure 9 in Appendix D: Analysis and Discussion of Experimental Results).

In the rural highway locations, researchers compared three light types consisting of 2200 K LEDs, 4000 K LEDs, and 5000 K LEDs. The 2200 K LEDs could not achieve the higher luminance of 2 cd/m^2, as did the other two light types. Results determined the detection distances under the 2200 K LEDs for both luminance levels (0.5 and 1 cd/m^2) were significantly shorter than 4000 K and 5000 K under the same luminance levels (Figure 12).

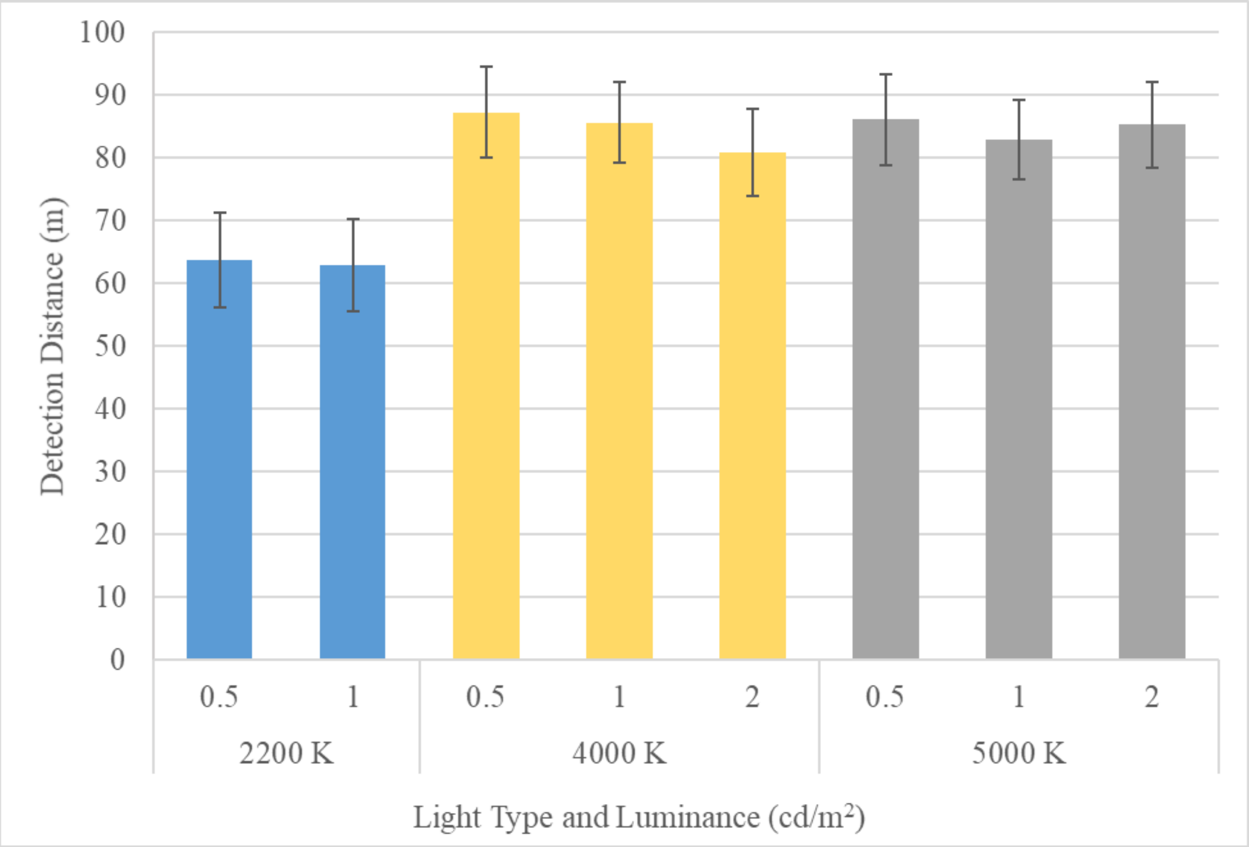

Figure 12. Detection distance for rural highway by light type and luminance

When compared to the 4000 K and 5000 K light types, the 2200 K produced much lower detection distances by approximately 20 m (66 ft), but luminance (cd/m^2) had no impact on detection for highway lighting. When comparing the ped-scale and road-scale lighting (urban environment), however, the higher luminance produced a greater detection distance.

This may be explained by the complexity of the environment. Again, the 2200 K, 4000 K, and 5000 K light types were on the rural highway section of the course and the Ped Scale and Road Scale were on the urban section with visual clutter positioned in the vicinity of the mannequin. When comparing the rural and urban environments, the mannequins placed in the rural locations were detected further for each luminance. Results indicate a higher luminance may be necessary in environments with visual clutter (signs, light poles, and other common street-side objects) for drivers to discern a child-sized person from their background. In rural environments where the background is a guardrail or consistent darkness, there is less impact of luminance level.

Walker Experiment

The results of this experiment showed that pedestrians could detect small objects from significantly further away under ped-scale lighting than road scale by an estimated average of 7 m (22 ft). While all participants identified the obstacle in their path well before it would become a threat to their safety, this difference does indicate that ped-scale lighting positively impacted visual performance.

Results indicated that for both light types (ped scale and road scale) the higher luminance (2 cd/m^2) produced longer detection distances. Again, while the distances at which participants recognized and identified hazards were much longer than necessary for a real-world trip and fall scenario, it does show that acuity is improved under higher luminance levels. While the task for this study was to identify a small object several meters ahead, visual acuity may be necessary for more immediate threats not considered in this experiment.

Figure 13 shows the two-way interaction between light type and luminance for ped scale lighting. There is an expected trend downward from higher luminance levels (2 cd/m^2) to medium (1 cd/m^2) to low (0.5 cd/m^2). For road scale, the higher luminance produced longer detection distances as expected, but low and medium averages were not significantly different.

Significant differences in detection distance exist between ped scale 2.0 cd/m^2 and ped scale 0.5 cd/m^2 (adjusted p-value = <0.0001) of approximately 10 meters (32.8 ft). Road scale 2 cd/m^2 was significantly different from both 1 cd/m^2 (adjusted p-value=0.0008) and 0.5 cd/m^2 (adjusted p-value = 0.0395).

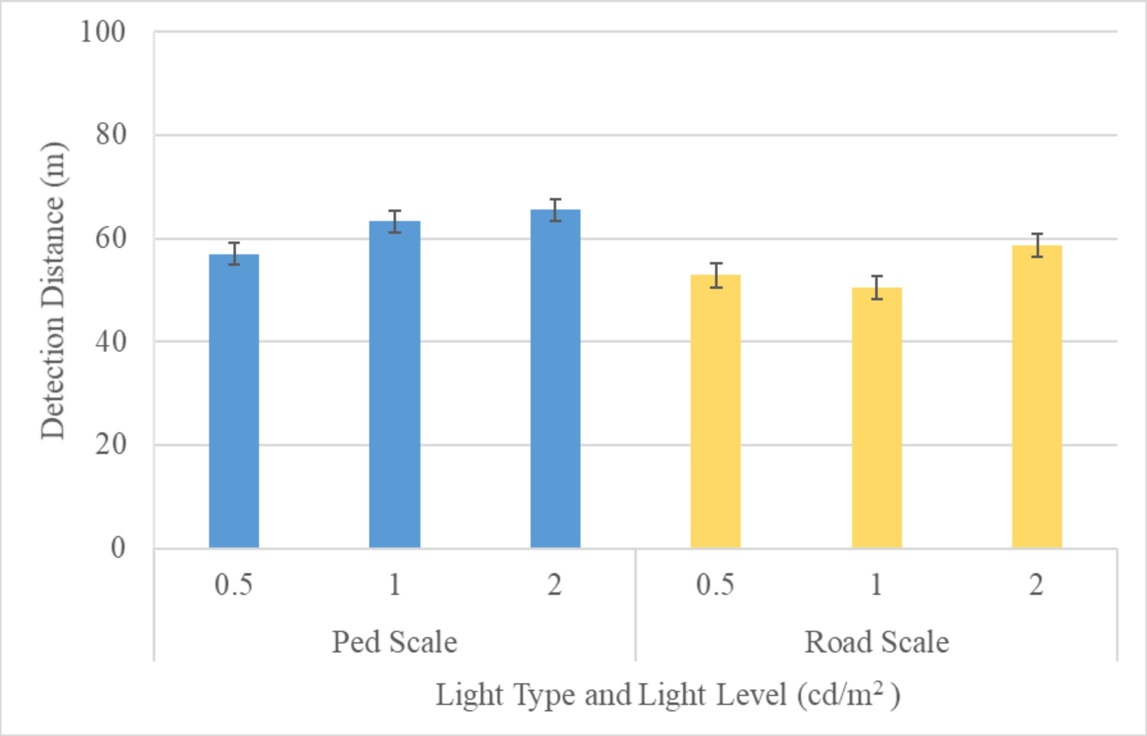

Figure 13. Detection distance by light type and luminance

Gap Acceptance Experiment

Due to differences in adult and child walking speeds, it is difficult to determine if the responses provided by participants, were safe choices. In most cases, crossing the road would be considered a safe decision if after a person crossed a roadway, the next vehicle did not reach the crosswalk until several seconds later. The task was for participants to indicate when they would no longer consider walking across, however, so their answers cannot be based on if the decision was a safe choice. Rather, all decisions made by the participants should be considered as “just unsafe" and cannot be compared to a correct "safe" answer. Therefore, the responses only indicate how conservative (or not) participants were with estimations of danger.

In terms of safe stopping distance, the responses provided by participants were more than adequate. Assuming a vehicle traveling 25 mph (40 km/h) began to stop immediately as a pedestrian entered the crosswalk, that vehicle would come to a complete stop within approximately 17 meters (82 ft). At 35 mph (56 km/h) this distance increases to 29 m (95 ft). In either case, 17 m (82 ft) and 29 m (95 ft) are far less than the average distance vehicles were in the responses, which were approximately 97 m (318 ft) for children and 127 m (417 ft) for adults.

When broken down by light type, it was found that adults were more conservative with their responses when no roadway lighting was present (Figure 14). For adults, the no-lighting condition was statistically significant from both the ped scale (adjusted p-value= <0.0001) and road scale (adjusted p-value=0.0418*)*. There were no significant differences between ped scale and road scale overall, even when the no-lighting condition was removed from the model.

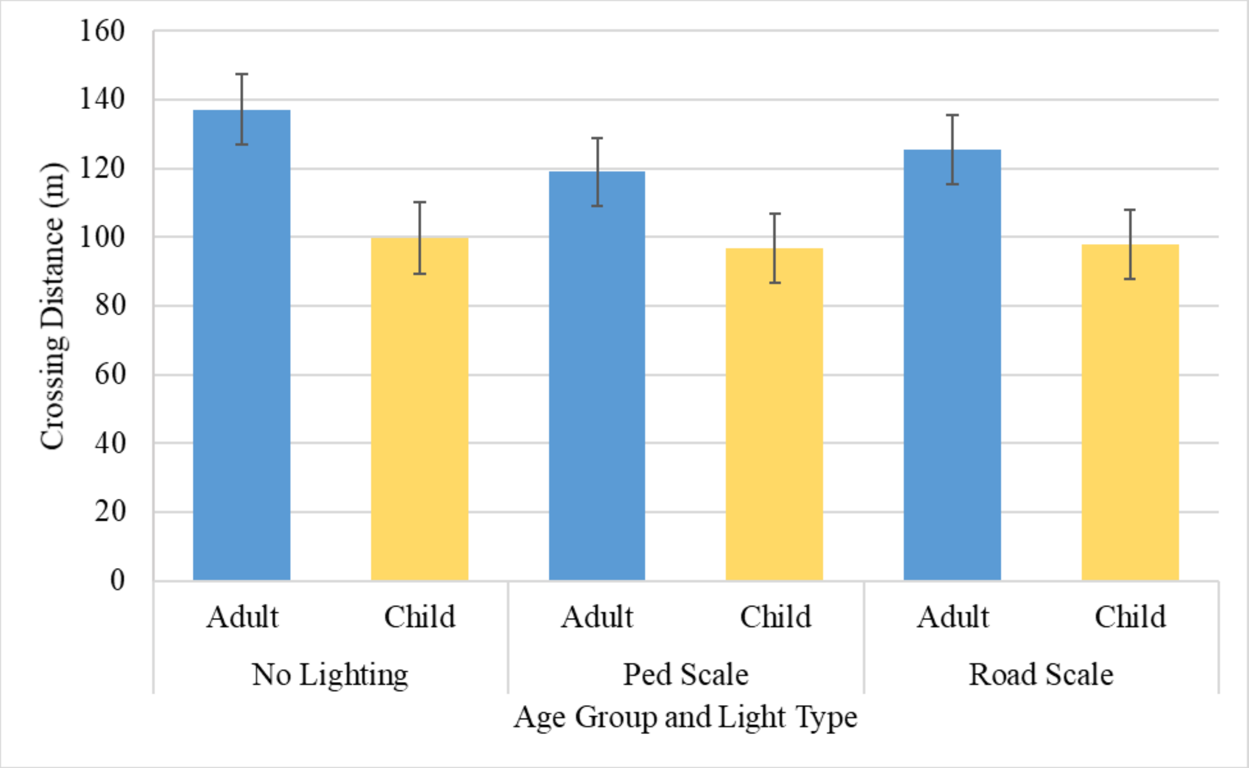

Figure 14. Crossing acceptance distance for gap experiment by age and light type

Figure 15 shows data charted from a three-way model including age group and light type by luminance. There was no significance found between luminance levels, and aside from the differences determined in the age groups already highlighted, there are no notable or practical trends between luminance.

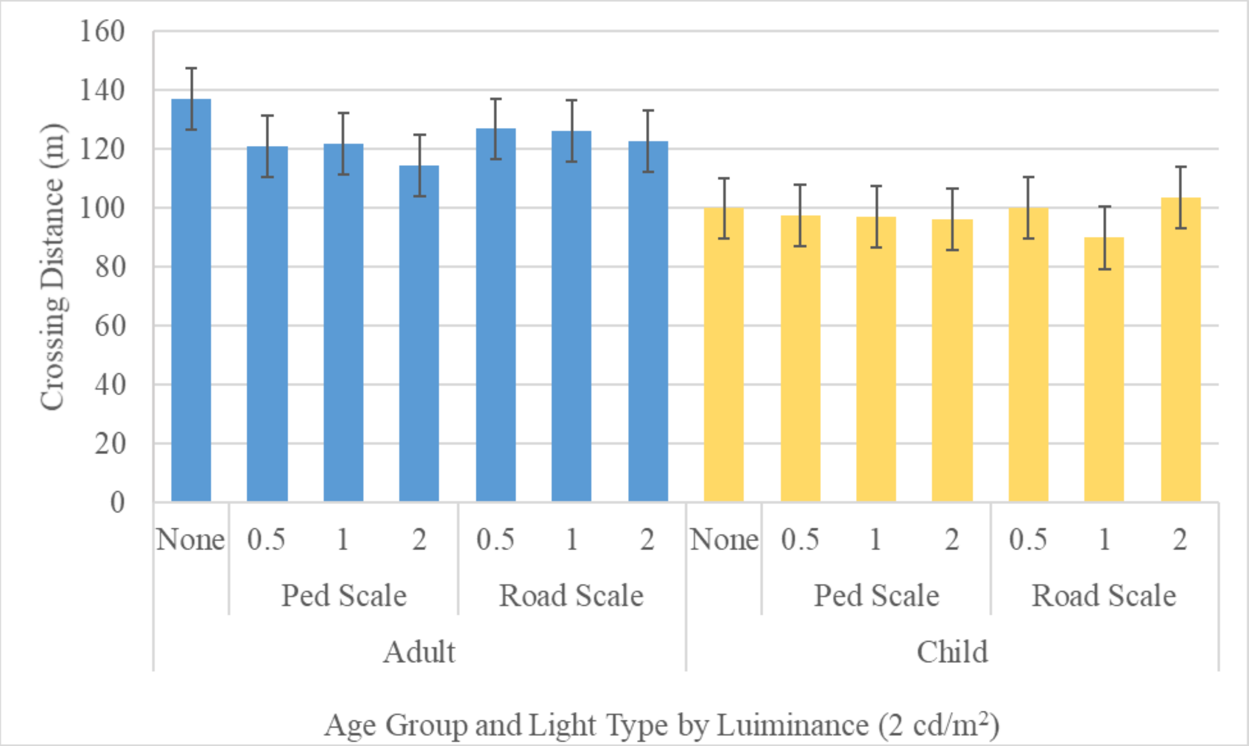

Figure 15. Crossing acceptance distance for gap experiment by age group

No significant effects determined for the speed of the vehicles. For each lighted condition, adults responded to each speed within three meters of the other speed. In general, the responses of children were more widely varied.

The results of the gap acceptance experiment primarily showed that children are less conservative than adults when judging when it is safe to cross a roadway with oncoming traffic. This finding was consistent across light types and luminance levels, indicating the lighting did not affect their decisions.

In the absence of light, however, adults were more conservative with crossing choices than on a lighted roadway, a phenomenon that could be attributed to the lack of certainty in relation to depth perception experienced in area with no roadway lighting. It is unclear if adults were choosing to cross sooner in the unlighted condition due to uncertainty with the vehicle's location. If so, then perhaps the addition of lighting aided depth perception, resulting in a more confident and less conservative choice. In general, neither light type nor level influenced when people would choose not to cross.

LIGHTING RECOMMENDATIONS

Lighting for Pedestrian Areas

The research results show a correlation between the lighting level on the roadway and visibility of pedestrians. The research indicates that at a level of 9 lux semi-cylindrical or 3 lux vertical illuminance, additional light does not increase visibility. A higher lighting level is needed for high visual clutter on a roadway, however, which seems to indicate that a luminance level of 2 cd/m2 is required for visibility in urban settings. As there is a stronger link between the roadway luminance and the semi-cylindrical illuminance, it has been determined that the more stringent criteria for pedestrian lighting shall be used in the areas which have high pedestrian volumes and potential uncertainty in pedestrian behavior. These areas might include school zones or roadways with pedestrian levels of 100 pedestrians per hour which is drawn from existing Lighting design standards (IESNA RP-8-18, 2018).

A grid of calculation and measurement points aligned along the side of the roadway for adjacent sidewalks or along the pedestrian walkway for separated pedestrian paths should be illuminated to a minimum level based on a line of calculation points along the path and spaced at no more than 2 m (6.6 ft.).

Crosswalk Lighting

Current research shows that crosswalk light levels should be at 20 lux vertical illuminance or higher. Recognizing that this level is significantly higher than the levels recommended along the side of the roadway, these facilities are in the roadway and the path of the vehicle and as such a higher lighting level is recommended. Further research is being developed for these criteria.

In terms of lighting for pedestrians at crosswalks, results of this research indicated that neither light level nor light scale impacted the responses of children and adults in regard the point at which they would no longer attempt to cross a roadway; however, it was determined that the presence of roadway lighting may inform an adult’s perception of depth more accurately. Most crosswalks are lit for the primary purpose of allowing pedestrians to be seen. The results of this study also indicate a benefit to the pedestrian in being able to make a more confident decision regarding the vehicle’s distance from the crosswalk. The decision-making abilities of children are not improved with the addition of lighting, nor are they impacted by the lane positioning or speed of approaching vehicles.

Luminaire Height

On roadways, pedestrian lighting is typically provided by the roadway lighting system itself. However, pedestrian-scale lighting is used for some roadways and pathways. Typically, pedestrian scale lighting is mounted at a lower height and provides high levels of vertical illumination. Roadway lighting is mounted at a higher elevation and provides a higher level of horizontal illuminance. The other issue with a lower mounting height is that luminaires which direct vertical illuminance towards the pedestrian also typically have higher glare rating for both the person and vehicle drivers. As a result, the roadway luminance needs to increase to overcome the potential for disability glare.

Recommendations

Based on the research results above, the criteria in Table 7 are recommended for areas where the pedestrian lighting is provided by a roadway scale luminaire (6.5 m or 20 ft or higher). For pedestrian scale lighting (6.5m in height or lower) an additional 2 lux vertical and 0.5 cd/m2 are required to be added to the criteria to overcome the glare from the lower mounting height.

The average of the rural and urban recommendations can be considered for suburban areas.

Note that while these recommendations can be applied to any light source, the Color temperature recommendation typically applies to LED light sources only.

Table 7. Recommended Light Level Criteria for Pedestrian Facilities

Pedestrian facility characteristics	**Pedestrian lighting minimum**	**Rural (Average Surface Luminance)**	**Urban (Average Surface Luminance)**
Low/medium pedestrian volumes (0-100 Pedestrians per hour)	2 lux vertical	No luminance recommendation; use the typical road luminance	1 cd/m^2
High pedestrian volume/ school zones (>100 Pedestrians per hour)	10 lux SC	1 cd/m^2	2 cd/m^2
Pedestrian crosswalk	20 lux vertical (minimum average)	No luminance recommendation; use the typical road luminance	No luminance recommendation; use the typical road luminance

The spectral characteristics of the light source are recommended to be 4000K CCT however other spectral contents can be considered if concerns for the surrounding areas are raised. This light source should be a minimum of 3000K CCT.

Other Considerations

Along with these design recommendations, other roadway lighting criteria must also be met. This includes consideration of both glare, surround ratio, light trespass, and environmental concerns.

Disability glare, which is intensity from a light source that limits a road user's ability to see, and discomfort glare, where light from a luminaire causes discomfort for the driver and pedestrians, should be limited. IESNA RP-8-18, 2018 provides guidance for both of these. For disability glare adherence to a ratio of veiling luminance to the roadway lighting level is evaluated and must meet a design criterion. Similarly, recommendations for the selection and placement of luminaires for discomfort glare control are also provided.

Another consideration is that of surround ratio. Current research has shown that lighting at least one lane width outside of the roadway driving lanes at 0.8 of the lighting level in the driving lanes provides significant benefits for the detection of objects and pedestrians in both in and beside the roadway. Surround Ratio must be balanced with the needs of the areas adjacent the roadway and considered as light trespass.

Light trespass is a term used to describe light leaving the roadway right of way (ROW) and falling on the adjoining properties. This should, whenever possible, be minimized and is typically evaluated based on a calculation of a vertical illuminance level at the edge of the ROW. For pedestrian lighting however, if the pedestrian way (sidewalk or path) is outside the ROW, there may be an exception where the light would leave the ROW to light the pedestrian facility.

The final consideration is areas where the environment must be considered. Certain plant species and most animal species are impacted by roadway lighting. Roadway lighting emitted outside of the roadway can has been shown to impact soybean crops, bird behavior, and even fish migration. This requires that a lighting design must balance the need to light the road and pedestrian areas while minimizing light trespass. The criteria might become more stringent in the areas of environmental sensitivity. The Lighting Environmental Zone provided in IESNA RP-8 2018 can be used as guidance.

Design and Verification Approach

For the calculation and the verification of the lighting in the pedestrian sidewalks and areas, the calculation grid should be spaced between the luminaires and centered in the design area with a maximum spacing of 2 meters (6.6 ft) between grid points in each direction. This grid layout is shown in Figure 1

Verification of lighting levels should be made at the same location as in the calculation grid.

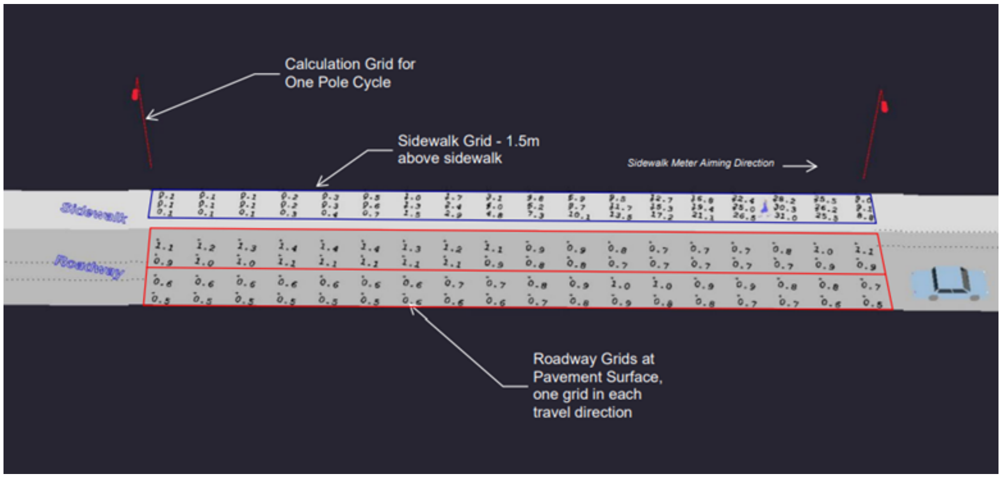

Figure 16. Calculation and Verification Grid Layout.

CONCLUSION

The objective of this research was to combine results of the three experiments to determine recommendations for lighting that benefit drivers and pedestrians. The following conclusions can be drawn from this research effort:

- A learning effect was determined for the driving experiment, leading researchers to add a weighted emphasis to the results of initial trials. Initial trials indicate that lighting level has an impact on visibility. Detection distance increased as light level increased in scenarios when the object being presented was unfamiliar. After the initial trials, detection distances plateaued regardless of the independent variables. The recommendations resulting from this effort focus on the detections recorded for each participant prior to when a learning effect was observed.
- It was determined that the optimal semi-cylindrical illuminance was 9 lux. Lighting levels below approximately 9 lux yielded shorter detection distances and beyond 9 lux there was limited benefit of the additional lighting.
- The results indicated that the 2200 K LED light type does not produce the same level of visibility for drivers detecting child-sized pedestrians offset from the roadway as the 4000 K LED or the 5000 K LED, which could be related to light distribution. SRTS interventions that incorporate lighting should consider the use of LEDs of at least 3000K.
- Urban versus rural environments warrant two different lighting designs to enhance the visibility of pedestrians. The results indicated that increased luminance levels (2 cd/m^2) may be necessary in environments with visual clutter in a typical in an urban environment. Optimal visibility could be maintained in a rural environment with an average luminance of 1 cd/m^2. These luminance levels combined with the established minimum vertical illuminance of 9 to 10 lux form a recommended guideline for illuminating pedestrian areas.
- Neither light level nor light scale influenced the responses of children and adults with regard to the extent they would no longer attempt to cross a roadway; however, it was determined that the presence of roadway lighting may inform an adult pedestrian's perception of depth more accurately.
- The results offer a consideration for future SRTS interventions by indicating that children underestimate the acceptable crossing period compared to adults. Adults were more conservative than children by an average of 30 meters (100 feet) or a range of 2 to 3 seconds with vehicle speeds of 35 and 25 mph (56 and 40 km/h), respectively. The provision of lighting seemed to provide greater depth perception which modified decision making of adults. Expectedly, the responses provided by children reinforced the need to focus on safety considerations with their decision-making and well-being as pedestrians.
- The results of the walking experiment indicated that participants of each age group could detect the presence of trip hazards from at least 50 meters across all variables. Therefore, the resulting recommendations of this document are not expected to compromise visibility of trip hazards of 0.5-inch thickness on a forward walking path.

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APPENDICES

Appendix A: Lighting Design Metrics

Illuminance

Illuminance, the amount of luminous flux per unit area, in other words, a measure of incident light illuminating a surface. For roadway lighting it is measured primarily by three approaches: horizontally, vertically, and semi-cylindrically (shown in Figure 17).

Horizontal Illuminance

Illuminance on a surface is defined as the luminous intensity on the plane normal to the direction of propagation of light divided by square of the distance between the source and the surface (the inverse square law). Illuminance is measured on a road surface horizontally; an increase in vertical illuminance improves the accuracy and speed that information can be ascertained from the roadway environment. This method is supported by previous research (Boyce, 1973; Eloholma et al., 2006; Rea, 2000; Terry & Gibbons, 2015). Night crashes at intersections have also been mitigated by increasing horizontal illuminance level (Bhagavathula et al., 2015; Minoshima et al., 2006; Oya, Ando, & Kanoshima, 2002).

Vertical Illuminance

For pedestrian visibility, studies have shown that a vertical illuminance level of 20 lux at height of 1.5 m (5 ft) from the road surface resulted in good driver visual performance at nighttime (Edwards & Gibbons, 2008). Vertical illuminance measurements are typically recorded at eye level of an observer oriented to their path of travel, whether driver or pedestrian. Generally, a height of 1.5 m (5 ft) from the ground is used for standards regarding a standing pedestrian.

Semi-cylindrical Illuminance

Semi-cylindrical illuminance, which has shown links to visual performance (Rombauts, Vandewyngaerde, & Maggetto, 1989), has gained interest as a metric since earlier crosswalk-related works. Semi-cylindrical illuminance is a measure that considers the light falling on a semi-cylinder rather than on a flat surface. Because pedestrians are not flat, this metric may more accurately represent performance and allow for the three-dimensional aspect of the object (Figure 17).

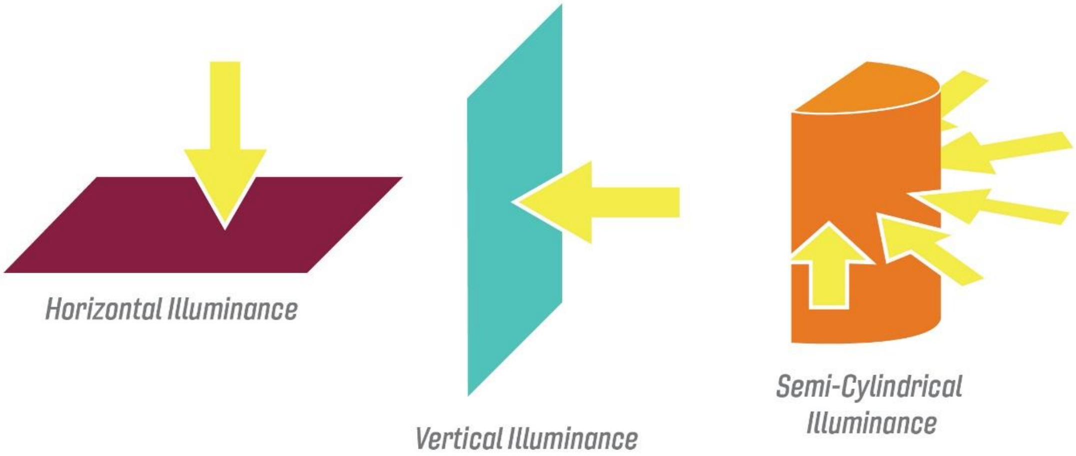

Figure 17. Illuminance measurement diagram

Semi-cylindrical illuminance is measured in the same way as vertical illuminance but is done so using a type of equipment designed to incorporate lighting from 180-degrees to better represent human vision by incorporating the peripheral vision.

It is notable that the semi-cylindrical illuminance provides an illuminance level that more closely represents actual lighting experience and gathers light from all directions within its 180-degree operational field. This metric seems to average measured illuminance, meaning that when an object is close to a luminaire, it receives light on its side face but when it is far away, it receives light on its front vertical face. This implies that while vertical illuminance varies widely, the semi-cylindrical does not.

As facial recognition is critical for the perception of safety and comfort for pedestrians (Castelli, Glowacki, Barcelona, Calvert, & Hwang, 2015; National Center for Statistics and Analysis, 2020), semi-cylindrical illuminance may be a better metric for the pedestrian lighting requirements.

Luminance

Luminance is the amount of light emitted from a surface in a specific direction per unit area. A luminance measure describes the amount of “brightness” of an object when viewed from a given direction. Research has shown that increasing the luminance of the roadway surface makes the objects on the roadway easier to detect (Economopoulos, 1978). At night, drivers can detect objects sooner as the average luminance of the roadway increases (Cuvalci & Ertas, 2000; Gibbons et al., 2015; He et al., 1997; Lewis, 1999).

Design criteria and recommended practices are guided by basic measures of luminance: such as average, minimum, and average-to-minimum ratios. ANSI/IES RP-8-18, a roadway lighting recommended practice guide, provide specifications for average luminance and average uniformity ratios for certain road classes. A street classified as major with a high pedestrian conflict should have an average luminance of 1.2 cd/m^2 (candela per square meter) and an average uniformity ratio of 3.0 L_{avg}/L_{min}. A roadway classified as local with high pedestrian conflict is required to possess an average luminance of 0.6 cd/m^2 and an average uniformity ratio of 6.0 L_{avg}/L_{min}. The difference between the two scenarios is the road class, which often involves differences in speed, lane width, and identifiable markings. The type of lighting system, mounting height of luminaires, or the color temperature of the lighting do not impact luminance metrics or recommendations for road classes and pedestrian zones (Illuminating Engineering Society, 2014).

Contrast

Contrast is the measurable visible difference between a target and the target's background. There are two types of contrast: color and luminance. Color contrast is the measurable difference between two colors. Luminance contrast is the measurable monochromatic difference between a lighted target and its background.

Contrast sensitivity is a measure of a person's ability to discern between different levels of luminance in a static environment. To test the contrast sensitivity of an individual, a visual target is placed in front of a uniform background. The contrast of the target to its background determines how visibly distinguishable it is. If the luminance of the background is changed, in either direction, it may make the target more difficult or easier to see. The ability of an individual to distinguish the background from the foreground is the standard deviation of pixels in an image. This method is commonly used to define the contrast of a single image so that two different images can be directly compared (Peli 1990).

Weber Contrast is the most commonly used metric and most applicable to night driving research. Weber Contrast incorporates the concept of absolute contrast or contrast polarity. This means both negative and positive contrasts are accounted for in the equation. In night driving, headlamps present a unique construct in that most objects within the span of headlamps contrast positively to their background even if that background is also lit by infrastructure lighting. This degree of positivity is affected by angle and distance.

$$Weber\ Contrast = \frac{L_{max} - L_{min}}{L_{background}}$$

Weber contrast is the difference in the highest and lowest luminance in each scene divided by the average luminance of its background. This value may result in a positive or negative number. With positive contrast, the target appears brighter than its background; with negative contrast, the target appears darker than its background (Figure 18) (Peli 1990, Gibbons, Edwards et al. 2008, Pelli and Bex 2013).

Figure 18. Negative and positive and contrast (Gibbons, Edwards et al. 2008)

The environment, notably glare, plays an important role in visual acuity and contrast sensitivity.

Appendix B: Independent Variables

Driver Experiment Independent Variables

Several variables were controlled for or manipulated during the study. The approximately 90-minute duration of each experimental session experienced by participants, necessitated by the need to control for numerous independent variables, had the potential to introduce confounding effects of learning, which were investigated during analysis.

Spectral Power Distribution of the Light.

In the absence of an established metric to distinguish the SPDs of luminaires, correlated color temperature (CCT) was used to evaluate the effect of SPDs on visual performance. The 2200 K and 5000 K CCT LED luminaires represent the minimum and the maximum CCTs currently available on the market. The 4000 K LED is widely used in roadway lighting. Figure 19 shows the visual differences between the three different light sources used in the driver experiment.

Figure 19. View of child-sized mannequin under each SPD

The Smart Road dimming system balances luminance on the roadway between each of the luminaire configurations. The SPDs of the luminaires is shown in Figure 20.

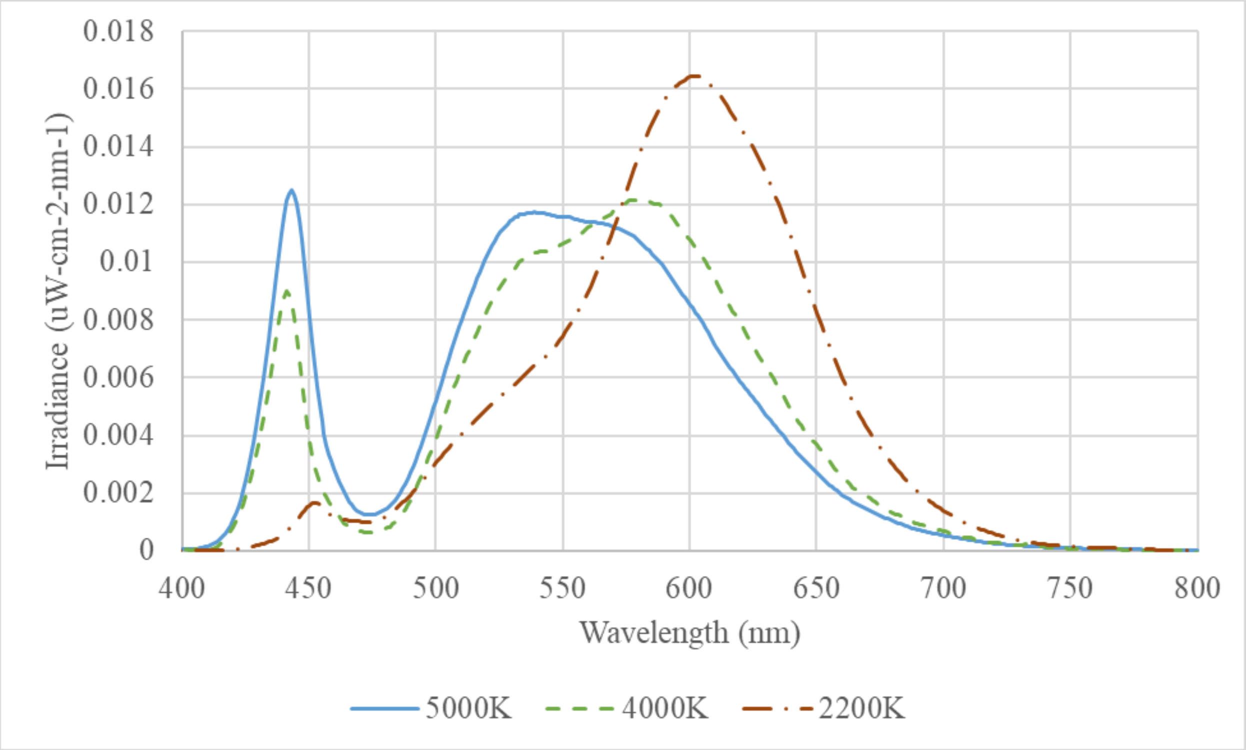

Figure 20. Spectral Power Distribution of luminaires; relative irradiance spectral content normalized for 6.27 lux

For the walker and gap acceptance experiments, 4000 K luminaires were mounted at two heights on poles within the Surface Street expansion. The two luminaire types chosen for the study were to represent a roadway lighting system and an urban/suburban lighting system, which are distinguished by mounting height. The first luminaire, pole-mounted at a height of 30 ft (9.1 m), was an overhead road-scale luminaire. The second, mounted at height of 15 ft (4.5 m) was post-top luminaire.

Road Luminance and Vertical Illuminance.

Researchers examined the effect of three roadway luminance levels (2 cd/m^2, 1 cd/m^2, and 0.5 cd/m^2) on the effect of visual performance of objects in that surrounding area. These levels were achieved by adjusting the output of the lighting systems. The lighted test area was designed to achieve the specific roadway luminance using AGI-32 software and verified upon installation manually using a handheld LS-110 luminance meter.

Positions along the test track that were used for placement of the child-sized mannequins were selected on the basis of vertical illuminance to control the amount of illuminance on the visual target and to ensure that variations of illuminance were evaluated across each variable combination of light type and luminance level.

Age

While younger drivers have better visual acuity, older drivers have more driving experience. Thus, by including age as an independent measure, a wide range of physiological capabilities and driving experiences were considered. To examine how these physiological changes in the eyes affect the visual performances of drivers and pedestrians, the driver experiment included 36 participants divided between two age groups: younger (25-45 years) and older (65 and older).

Environment

Only one location on the route provided an environment simulating an urban setting. The urban environment included a sidewalk, light pole, bicycle, work zone sign, and trash can. A golf cart simulated a bus stop or structure behind the mannequin's location (Figure 21). The mannequin was placed on the sidewalk during experimental trials. The precise location along the sidewalk was determined by vertical illuminance and light type. The remaining four locations on the route were rural settings with only a guardrail in the background of the mannequin.

Figure 21. Urban environment for driver experiment (mannequin highlighted with green outline)

Light Source Scale

The three experiments compared the impact of different mounting heights. Road-scale lighting was mounted 30 ft (9.1 m) high, as is typical for most roadway lighting installments. The second mounting height, 18 ft (5.4 m), is considered street lighting or pedestrian-scale lighting, as it is designed for the benefit of pedestrians and is mounted lower than road scale lighting. This lighting design is typically found in urban environments where pedestrian traffic is greater in favor of the higher-mounted streetlights (Figure 22). The third lighting design, not shown here, is highway-scale luminaires mounted (50-ft [15.2m]) high.

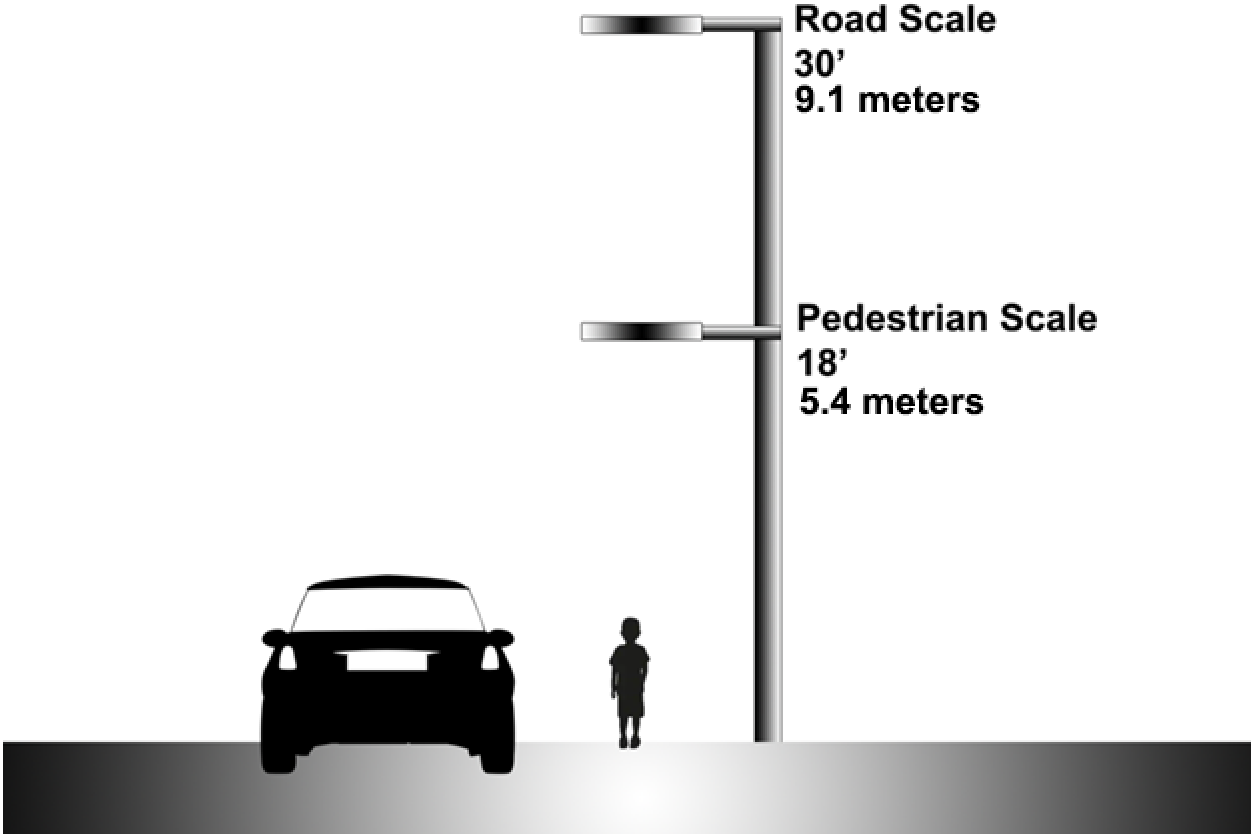

Figure 22. Comparison of pedestrian- and road-scale mounting heights

Walker Experiment Independent Variables

Many of the variables for the walker experiment were the same as those for the driver experiment. The SPD, luminance, and light types remained largely the same.

The key differences include the illuminance on the tripping hazard. The illuminances were measured vertically, rather than semi-cylindrically. These measurements were taken at the ground (oriented vertically) facing the direction of the observer. Ped- and road-scale vertical illuminance levels were different because they required different levels of output for each to achieve the luminance levels. Due the luminaire's shorter distance to the roadway and the angle of the light, the ped scale illuminance levels at the road's surface were slightly higher than that of the road scale for each luminance.

In addition to the two adult age groups used for the driver experiment, this experiment added a child age group of age 8 to 12. This age range was chosen due to their ability to follow instructions and the amount of walking required for the protocol, so younger ages were excluded. There were 36 total participants: 18 children, 9 younger adult (25-45 years) and 9 older adults (65 years and older).

Trip Hazards

The objects depicted in Figure 23 were 30.4 x 30.4 cm (1 x 1 ft) plywood squares that were painted black and covered with gray shingle to disguise themselves to the roadway. Two different thicknesses were used to compare variations in trip hazards. Targets were 1.2-cm (0.5-inch) and 2.5-cm (1-inch) thick (Figure 23).

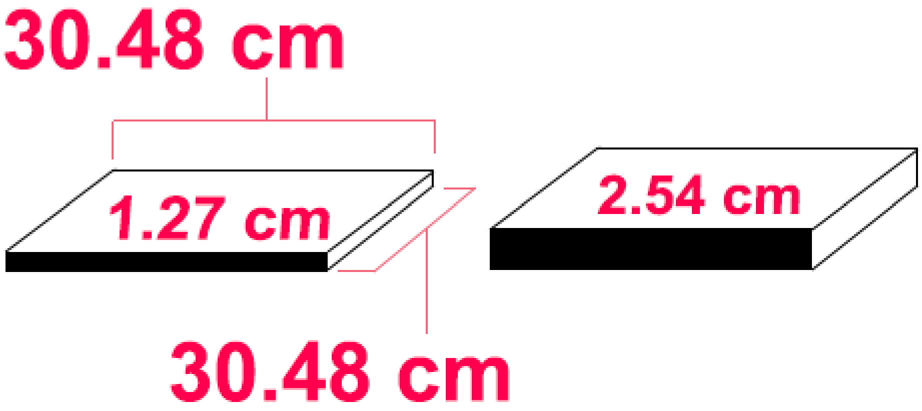

Figure 23. Tripping hazards

Lanes

Two targets were positioned in each lane. One position was 40 ft (12.2 m) further away than the other. Figure 24 diagrams the different lanes used and the position of the targets. On the left, the separation of lanes A and B are shown, and an individual is pictured walking toward the lighted intersection. On the right, the four circles represent the approximate location of the luminaires. Each square represents an area where a target could be positioned for each trial.

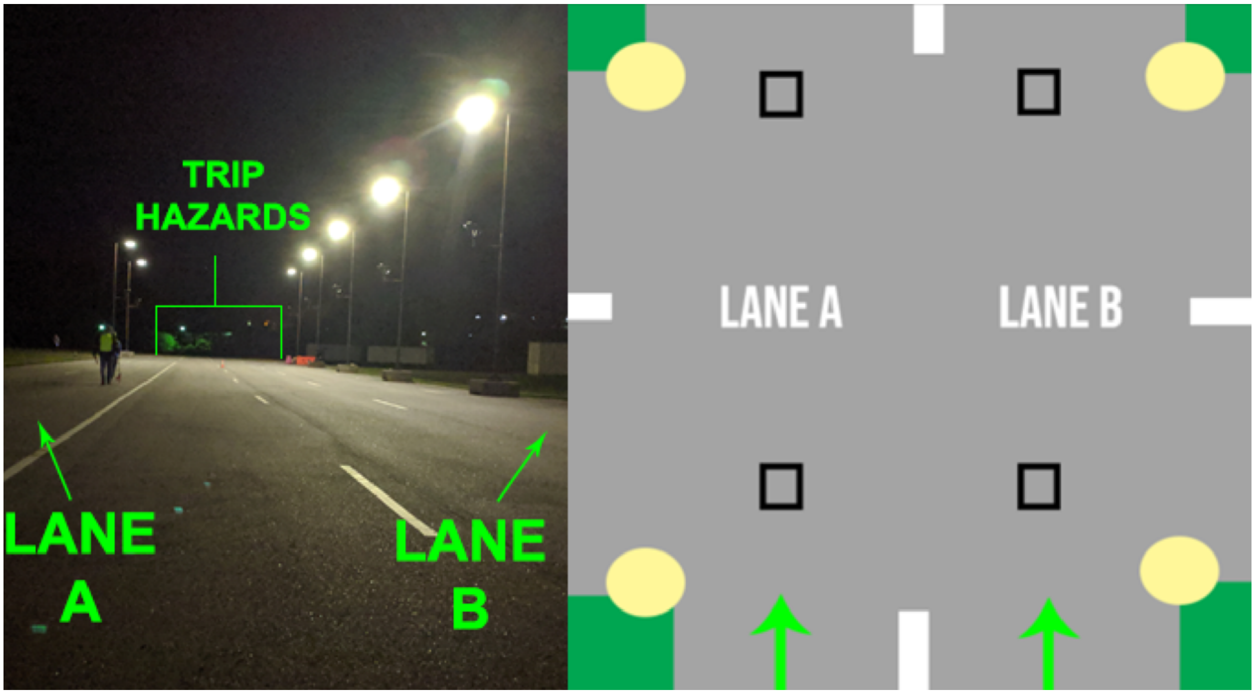

Figure 24. Diagram of Walker Experiment lanes and target positions

Gap Acceptance Independent Variables

The lanes were chosen for safety and due to time limitations of study length. To incorporate all four lanes of travel, or even three, would increase the number of trials and extend the study an amount of time that would make recruiting small children to participate more difficult. The nearest lane that could be chosen was the second lane (one lane separated from the jersey barriers for safety considerations). The furthest lane (lane four) was selected to observe a greater contrast in observations than the next lane (lane 3) would be expected to show.

The speeds of 25 mi/h (40 km/h) and 35 mph (56 km/h) were selected as typical speeds where crosswalks are common.

Appendix C: Vehicles and Experimental Area

Vehicles

For the driver experiment, the test vehicles driven by participants were two identical 2017 Ford Explorers. Each vehicle was equipped with a data acquisition system that captured four camera views inside and outside the vehicle, GPS data, and vehicle network data. In-vehicle experimenters denoted when a participant detected a mannequin with a button press. The press and recorded in-vehicle audio were used to determine when an experimental object was seen.

For the gap experiment, the same two vehicles traversed through the intersection.

Experimental Area

This project was conducted on the Virginia Smart Roads, a suite of testing facilities that includes 2.5 m (4 km) of controlled-access roadway (Figure 25). The Smart Roads are equipped with a configurable roadway lighting system that includes 75 poles, each of which supports three luminaires. The lighting system can be configured to spacings of 40, 60, 80, and 120 m (131, 197, 262, and 394 ft) between lights. With the remotely controlled lighting system, researchers can change luminaires, spacing, or luminance levels as needed. A speck of 80 m (262 ft) was used for the driver experiment.

The Surface Street Facility allows a reconfigurable visual environment in a controlled environment. This area allowed for the pedestrian and road scale luminaires to be implemented. Due to the flexibility of the testing area, the design of these lights could be tailored specifically to the experimental area and were movable via forklift.

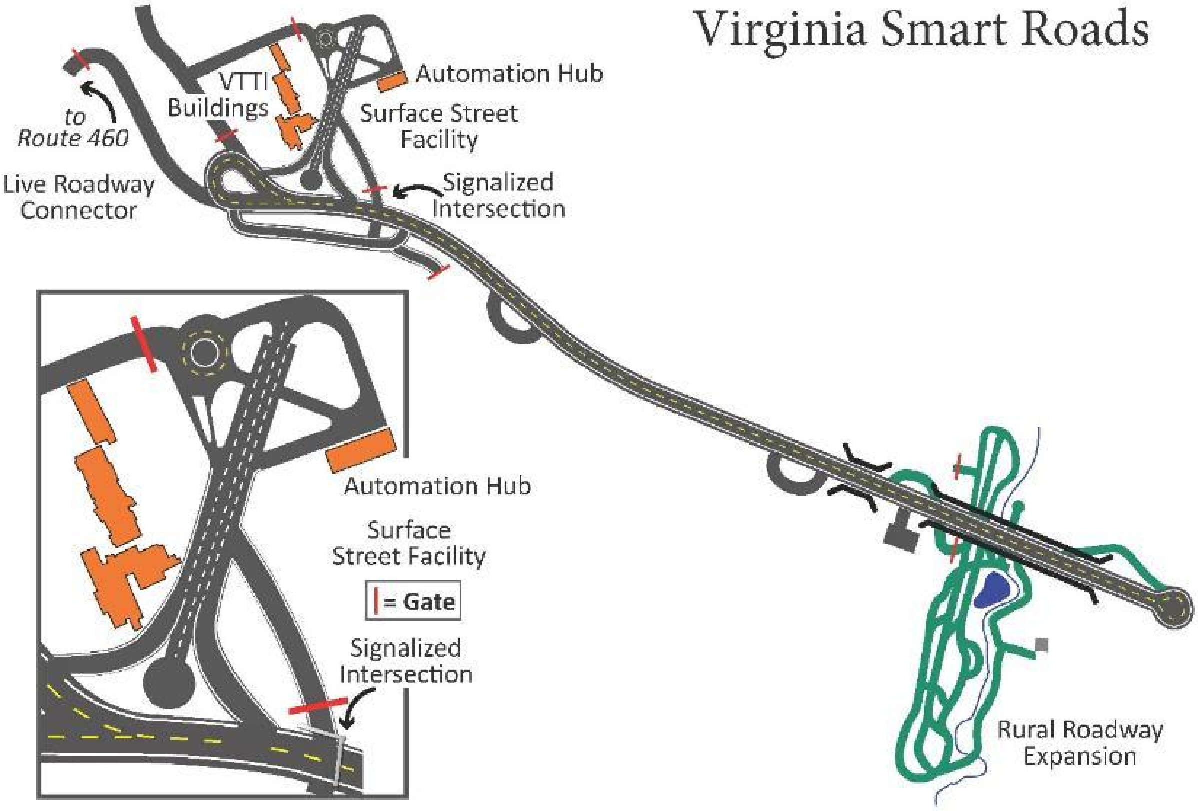

Figure 25. Smart Road test area.

Appendix D: Analysis and Discussion of Experimental Results

This section will highlight the significant main effects, interactions, and relationships between the variables tested across the three experiments conducted for this research. Linear Mixed Modeling (LMM), ideal for repeated measures designs (NCSS Statistical Software, 2019) was used to examine the fixed effects of luminance, vertical illuminance, and light spectral power distribution on the detection distances. Post hoc analyses were performed on significant interactions using a difference of least squared means procedure adjusting for multiple comparisons. The significance level (α) was set at 0.05 for all statistical tests.

Semi-cylindrical versus Vertical Illuminance

A secondary objective of this research was to compare different methods of measuring illuminance:

1. using an Everfine Photo-2000EZ semi-cylindrical illuminance meter and
2. using a vertical Konica Minolta T-10 illuminance meter.

The illuminance at locations used for the visual targets in the driving study was recorded using both methods and plotted in Figure 26. All vertical illuminance measurements were taken at the height of the child mannequin’s face (approximately 1.2 m (4 ft) from the ground) facing the direction participants would be observing them. The result is a linear relationship ($R^2=0.9142$). As expected, the semi-cylindrical instrument resulted in higher illuminance values because it is designed to receive light from a wider angle.

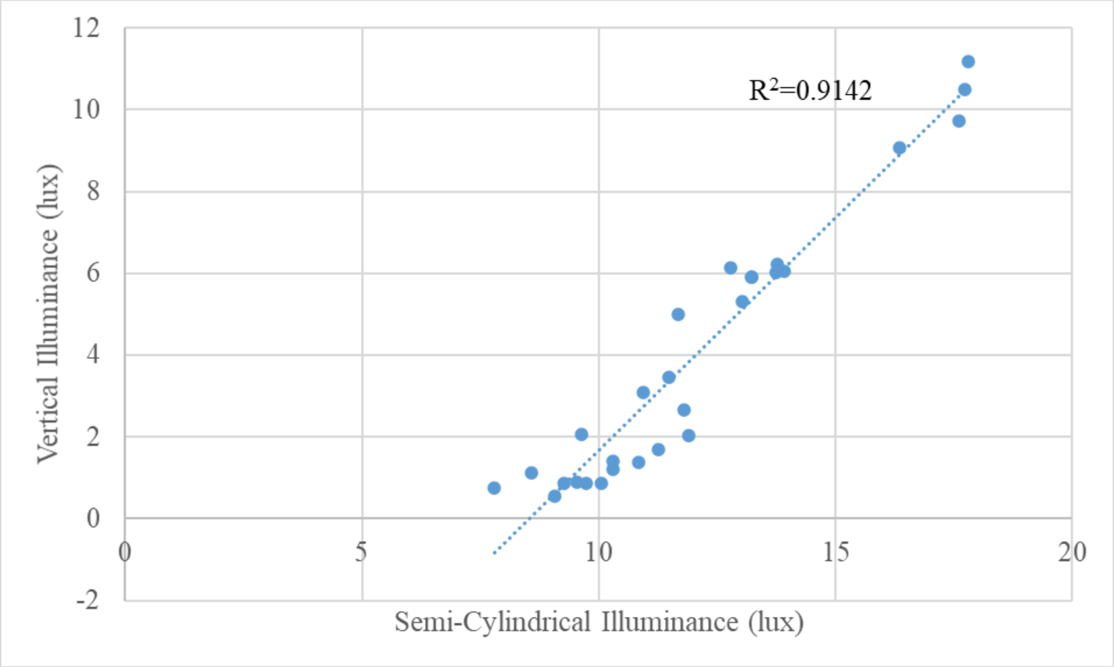

Figure 26. Comparison of illuminance methods (Konica Minolta T-10 versus Everfine Photo-2000EZ Semi-Cylindrical).

Figure 27 shows the illuminance measured by detection distance via both the semi-cylindrical and vertical methods. The results of this experiment indicate that neither metric is a better predictor for visibility; however, semi-cylindrical was chosen to represent the measurements taken in this document due to its accounting for multiple angles of light similar in characteristic to a human face would.

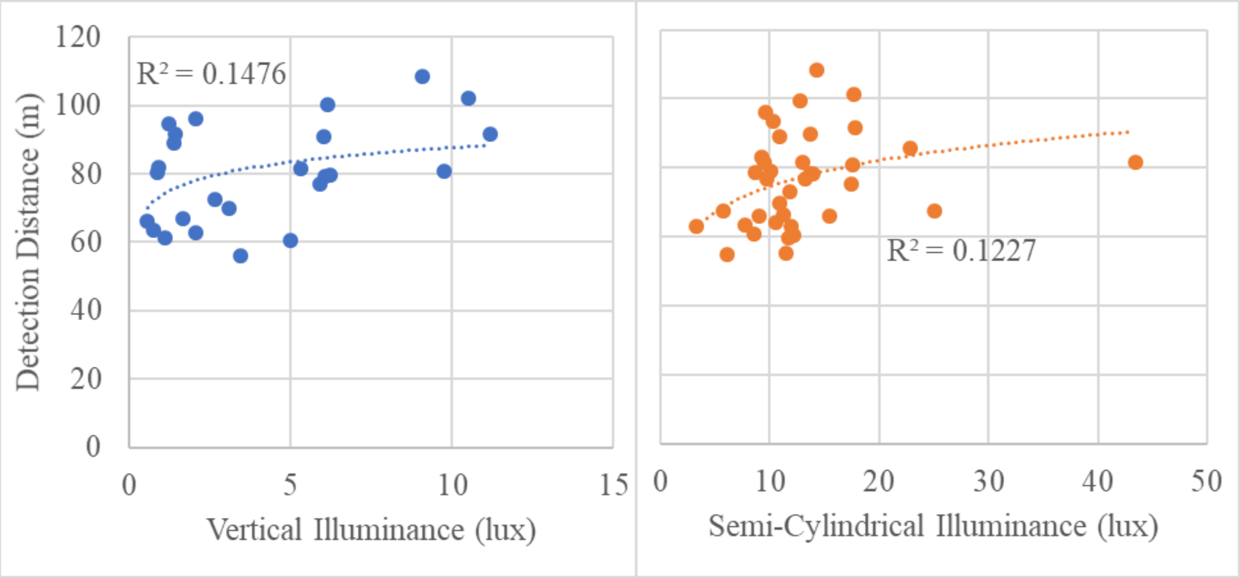

Figure 27. Detection distance by illuminance per measurement method

To further compare semi-cylindrical and vertical illuminance measurement methods, the research team plotted out a 25 x 4 grid marked at 5-ft (1.5-m) intervals with two parking lot luminaires spaced 105 ft (32 m) apart inside the grid (leaving a 1 x 4 end grid second behind the luminaries) Using both methods, the team measured illuminance at every intersection of the grid at 5-foot (1.5-m) intervals, including in the end grids beyond the poles. Each measurement instrument was mounted on a 5-ft tripod oriented orthogonally toward the direction of the second luminaire. Figure 28 illustrates the lighting profile created by the two measurement types.

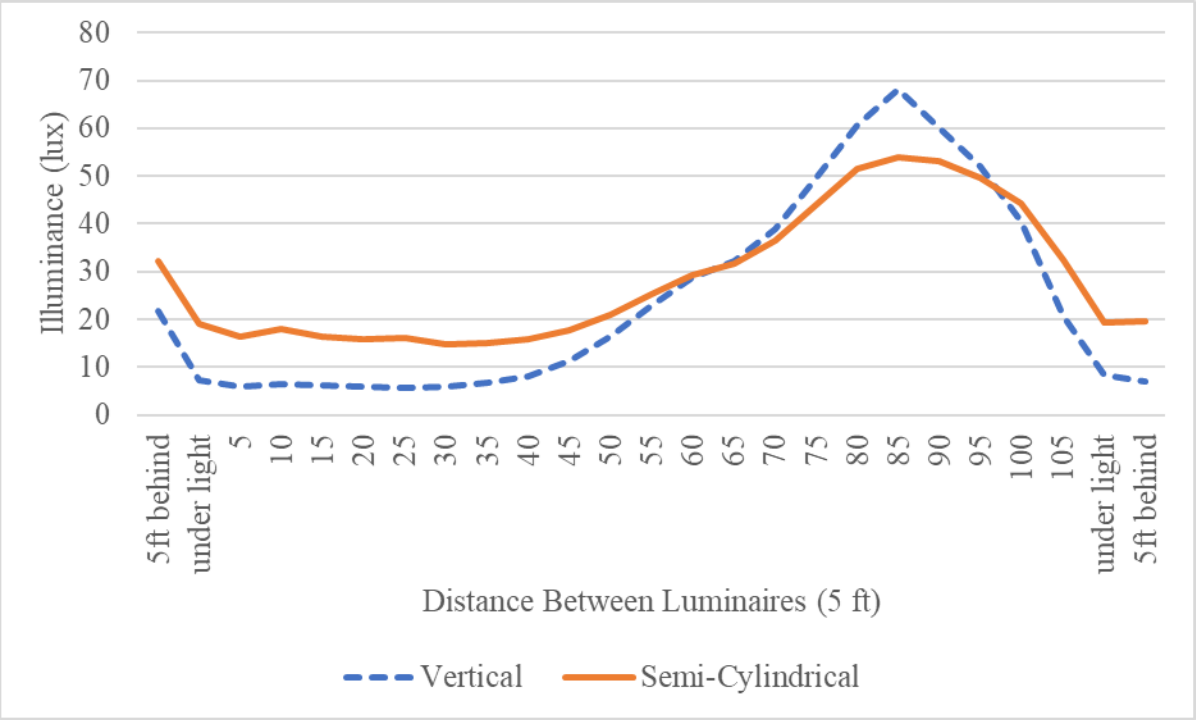

Figure 28. Spatial comparison of illuminance methods (vertical illuminance versus semi-cylindrical illuminance)

In this comparison, the semi-cylindrical measurements are higher under the luminaire than the vertical because the side of the meter detects the light, whereas the vertical is higher farther from the light where the luminaire throws light towards the measurement point.

Driver Experiment Results

Figure 29 shows the relationship between vertical illuminance measured with the semi-cylindrical illuminance meter and detection distance. In general, detections of mannequins under the 2200 K LED were lower than those of 4000 K and 5000 K LEDs. Additionally, no strong relationship is found between the amount of illumination at the face of the child-sized mannequin and the distance at which they could be detected for any light source.

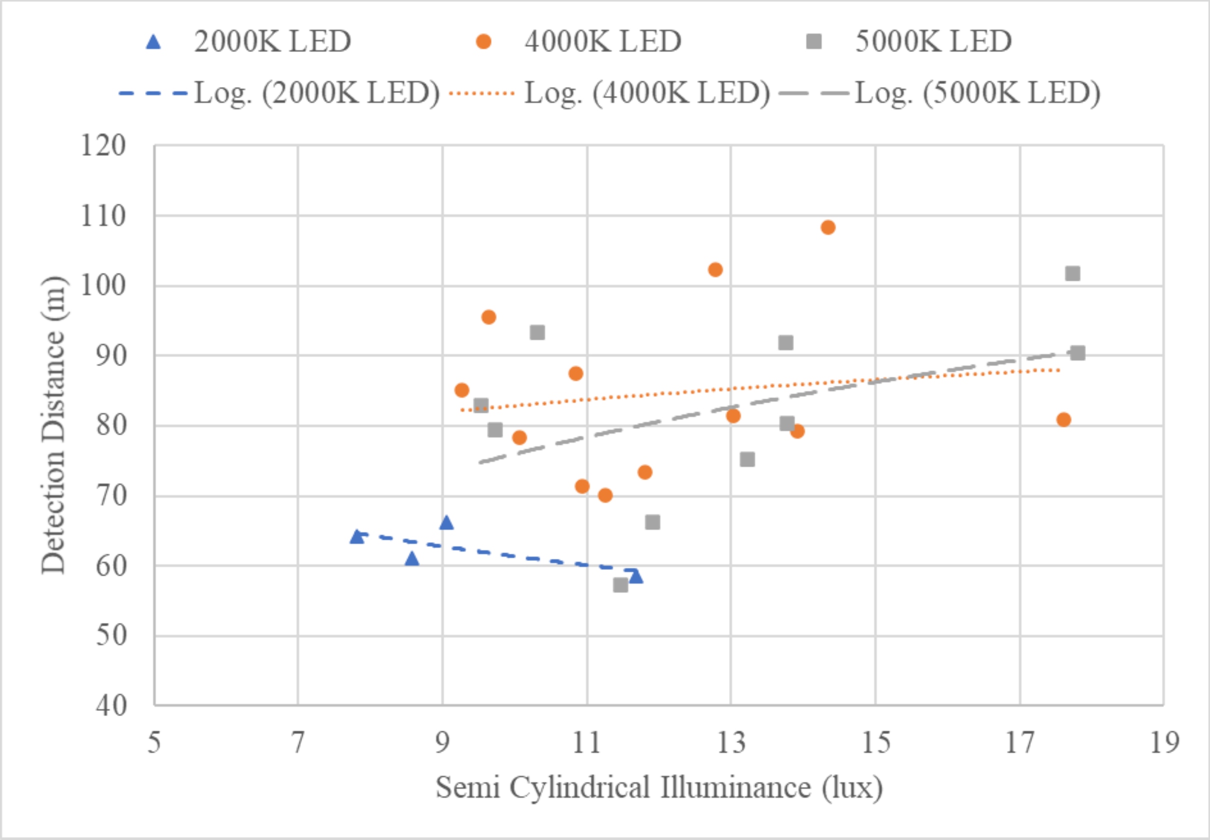

Figure 29. Detection distance by semi-cylindrical illuminance for each light type (2200 K, 4000 K, 5000 K LEDs)

Figure 30 isolates the detection distances of the first two laps when presentations of the mannequin were less expected by the participants. The first lap indicates the impact of luminance as detection distances stair-step upward by approximately 10 m (3.3 ft) for each luminance level. On lap 2, when participants have learned what to expect from the experiment, the 0.5 cd/m^2 luminance level outperforms all luminance levels from the first lap. There is little difference between luminance levels on lap 2, indicating that the learning effect can supersede the luminance required for vision, and that design guides should put a weighted emphasis on unexpected scenarios, such as the results of lap 1.

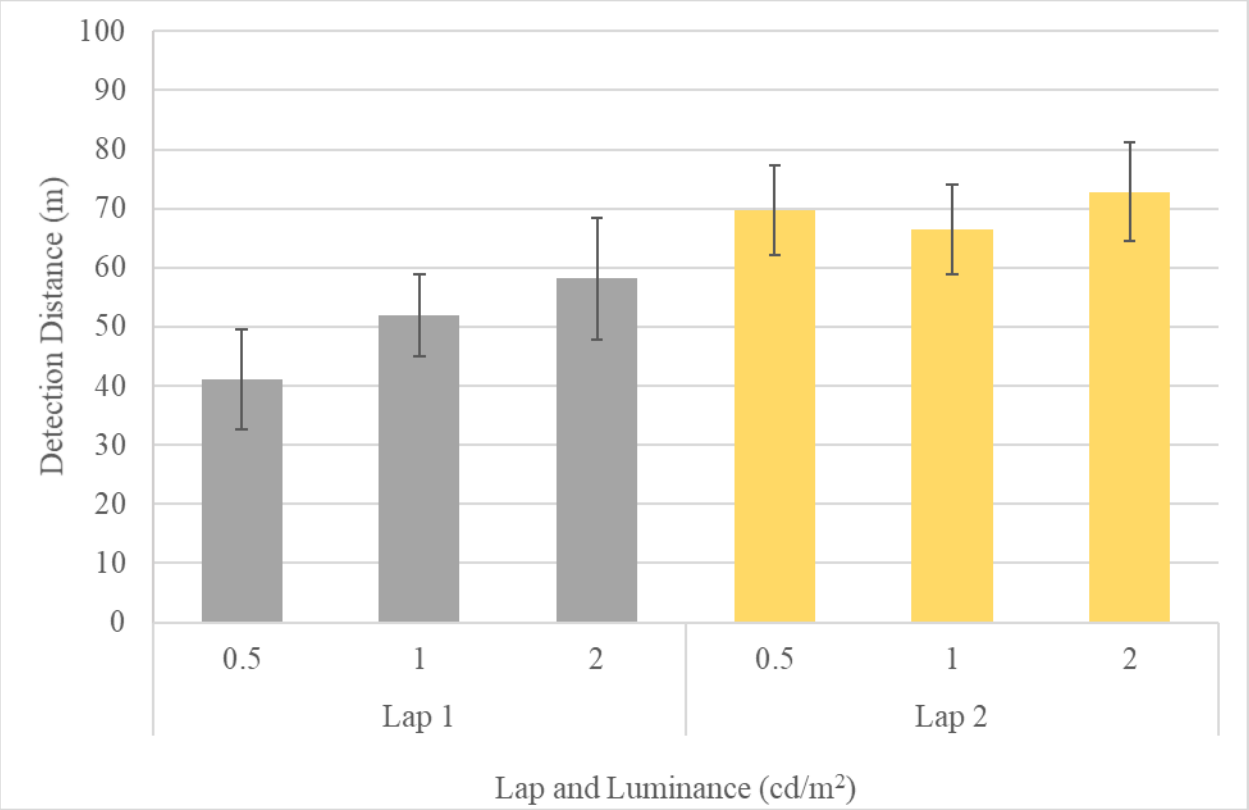

Figure 30. Detection distance by luminance (cd/m2) per lap for first two laps of the driver experiment

Detection distance by semi-cylindrical illuminance for laps one and two are shown in Figure 31. The low R-square value indicates that, unlike luminance, semi-cylindrical illuminance was not a factor in the visibility of the mannequins. However, it can be deduced that illuminances of approximately 9 semi-cylindrical lux and greater were able to produce longer detection distances than those less than 9 semi-cylindrical lux, perhaps indicating a minimum semi-cylindrical level for design considerations.

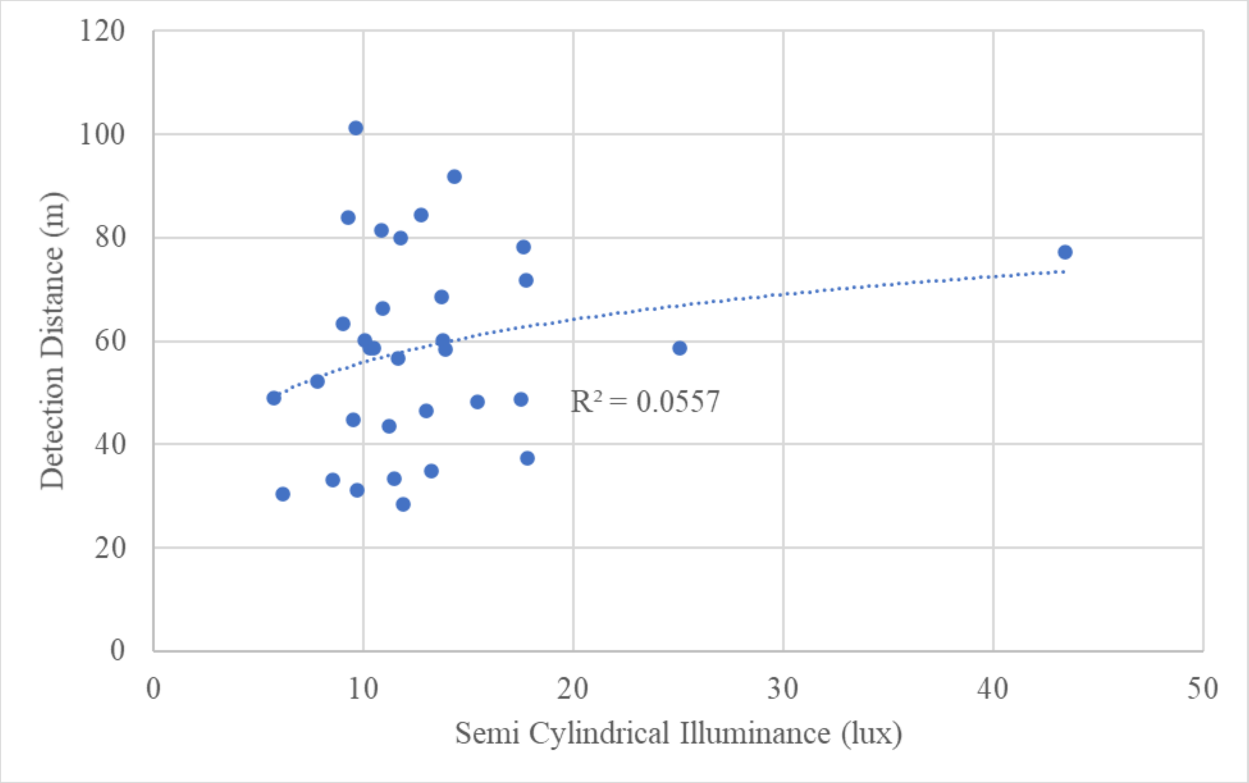

Figure 31. Detection distance by illuminance per measurement method for laps 1 and 2

For the mannequin placed in the urban environment, where the ped scale and road scale luminaires were positioned, luminance appears to have an impact on visibility. There was a significant difference found between within the ped scale-light type between 2 cd/m^2 and 0.5 cd/m^2 *(*adjusted p = 0.0101*)*. For the road-scale light type, statistically significant differences were found between 2 cd/m^2 and each other luminance: 1 cd/m^2 *(*adjusted p-value=0.0037*)* and 0.5 cd/m^2 (adjusted p-value=0.0087*)* (Figure 32).

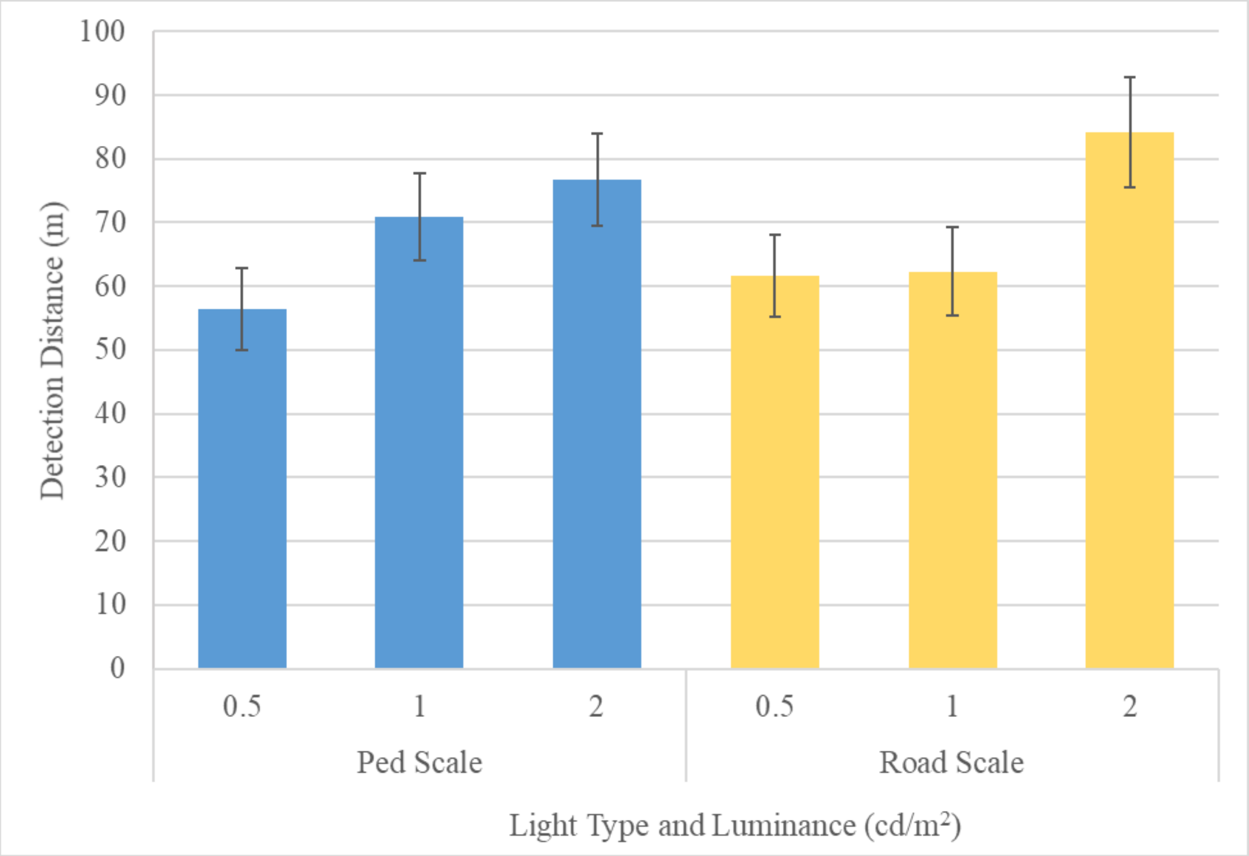

Figure 32. Detection distance for urban environment by light type and luminance

Walker Experiment Results

Figure 33 shows the relationship between horizontal and vertical illuminance of the trip hazard target (at the ground) for each luminance level. The right vertical axis corresponds to the average detection distance under each light level. Increase in the light level (both horizontal and vertical) resulted in longer detection distances.

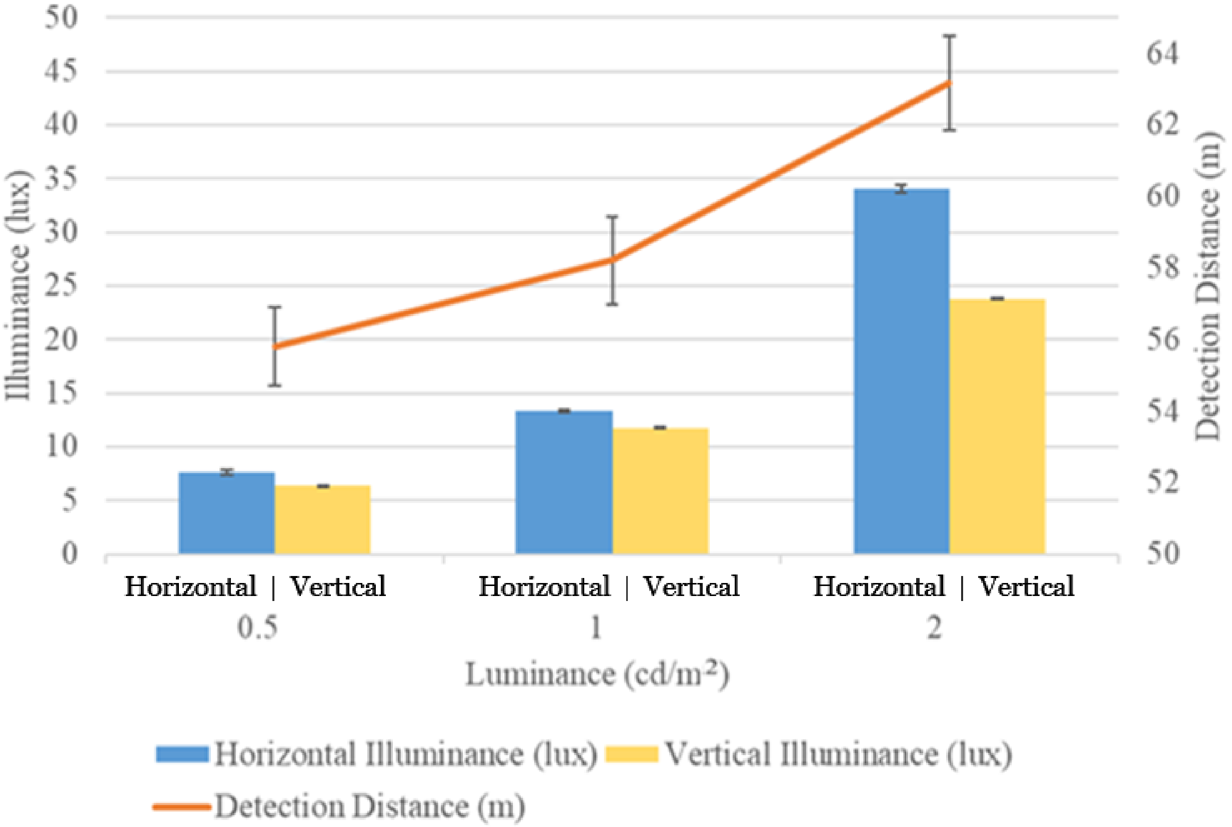

Figure 33. Horizontal and vertical illuminance (lux) and detection distance (m) by luminance level (cd\m2)

Results indicate there is no significant effect between any two light combinations (ped scale or road scale) and their lighting levels among child participants. There was only a significant difference between light type within an age group as ped scale-2 cd/m^2 and ped scale-0.5 cd/m^2 (adjusted p-value = 0.0134) resulted significantly different distances among older adults. One noteworthy result is that older adults identified the presence of trip hazards approximately 6 m (20 ft) further under road scale 0.5 cd/m^2 compared to road scale 1 cd/m^2.

From a practical detection standpoint, every light combination used in the experiment allowed pedestrians to visualize trip hazards as small as 12.7 cm (0.5 in) from at least approximately 40 m (131 ft). This distance is more than ample for the detection of a potential trip hazard. It is important to note that this experiment was conducted on a closed road course and participants were instructed to look for an object in an intersection; therefore, the task required no saccades and attention was focused on trip hazard detection. Though not statistically significant, the mean detection distances shown in (Figure 34) indicate that the detection distances are affected by light level, as expected. There is a noticeable difference between ped scale and road scale distances for each light type within each age group of approximately 6 to 10 m (20 to 32 ft), but this difference was not determined to be statistically significant.

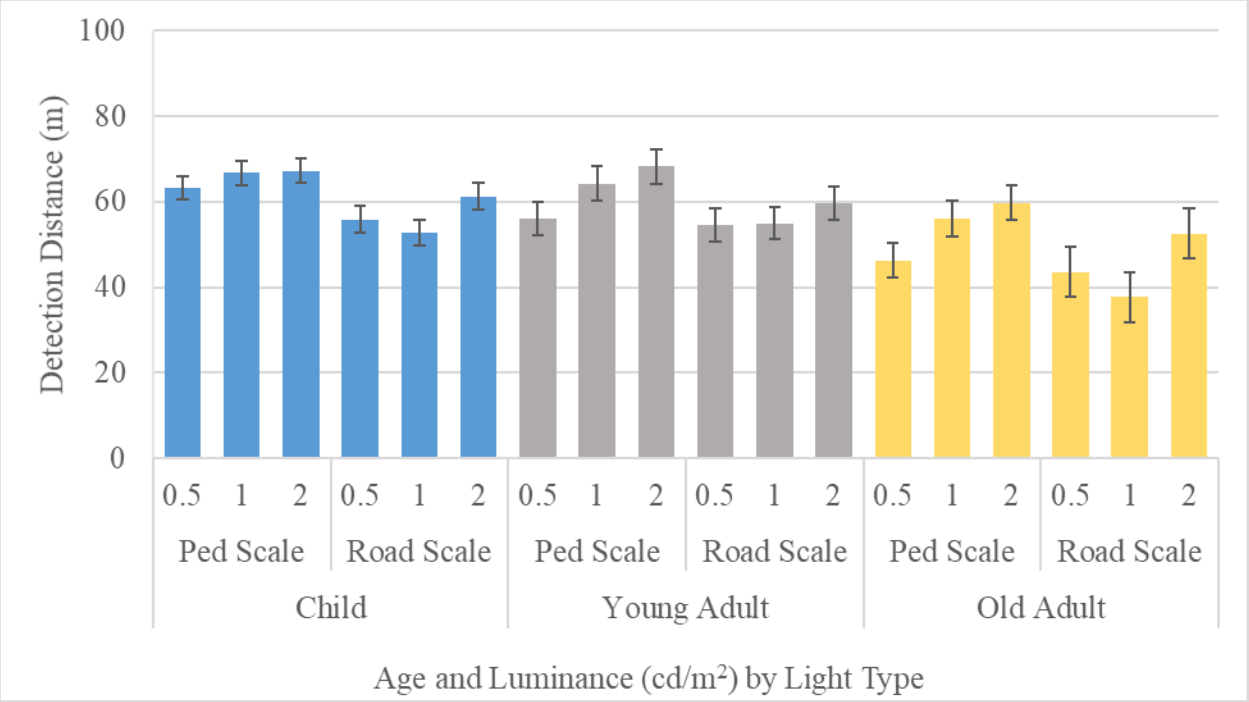

Figure 34. Detection distance for age by light type and luminance (cd/m2)

Statistical significance was found in the model comparing ped-scale lighting to road-scale lighting (Figure 35). The average detection distances for ped scale were estimated to 61.9 m (203 ft); those for road scale were estimated at 54 m (178 ft) (adjusted p-value = 0.0001).

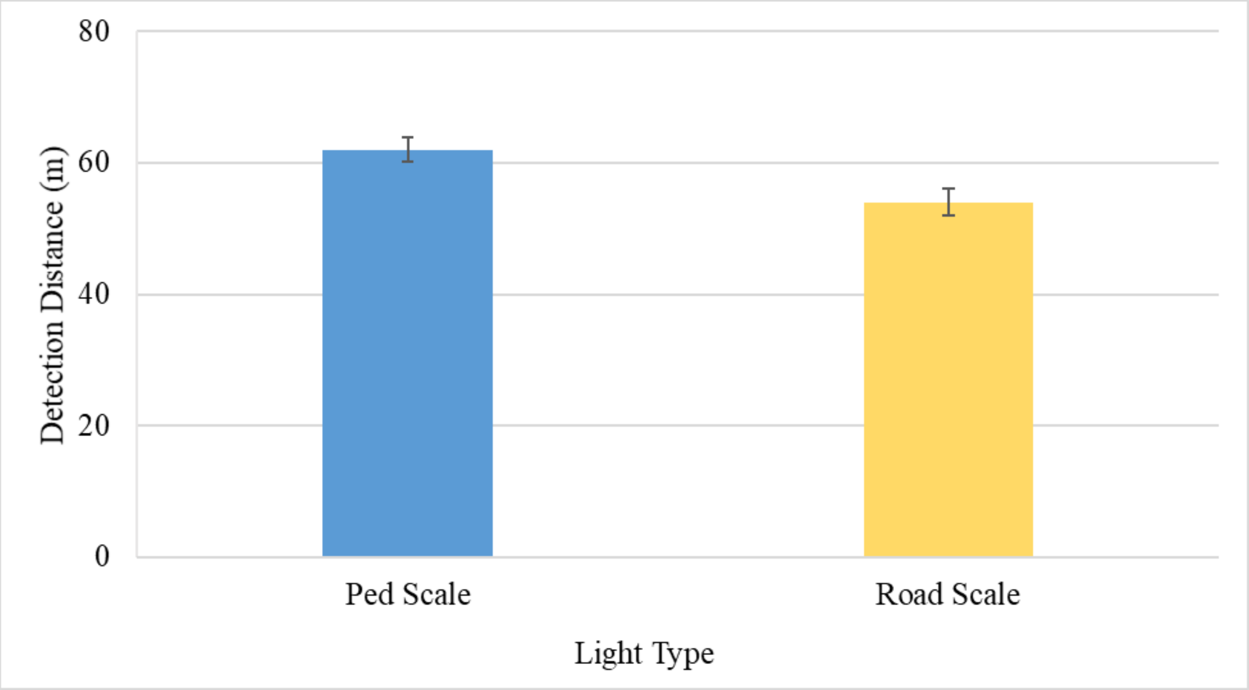

Figure 35. Detection distance by light type

Comparing the luminance levels produced by ped- and road-scale light types, participants identified trip hazards significantly further away under 2 cd/m^2 luminance compared to 1 cd/m^2 (adjusted p-value = 0.0004*)* and 0.5 cd/m^2 (adjusted p-value = <0.0001*)* levels (Figure 36).

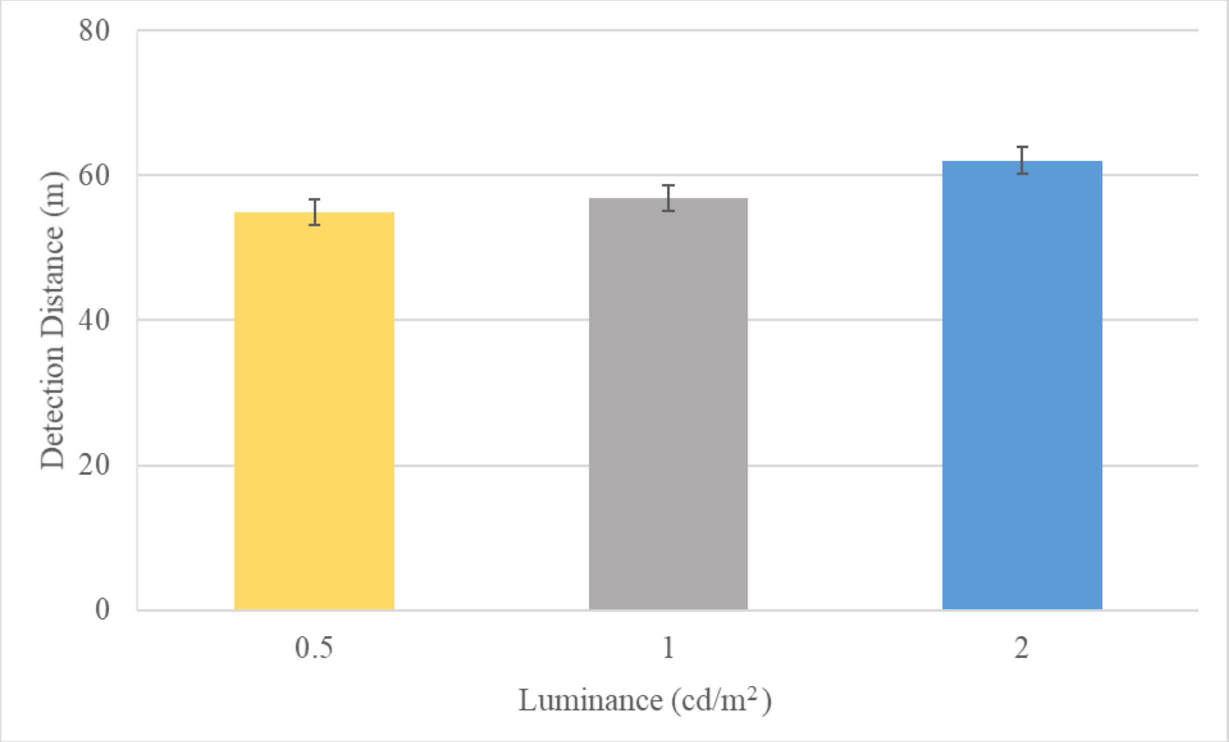

Figure 36. Detection distance by luminance

As in the driver experiment, the walker experiment saw the impact of a learning effect with age groups. Figure 37 shows the number of trials broken into three groups of five. During the experiment, the lighting condition changed every five laps, providing a natural break for this data. The children and young adults improved between the first and second five trials and then plateaued, indicating a subtle learning effect. Older adults improved between the first and second five trials, indicating a learning effect, but regressed for the third group of trials, perhaps indicating fatigue.

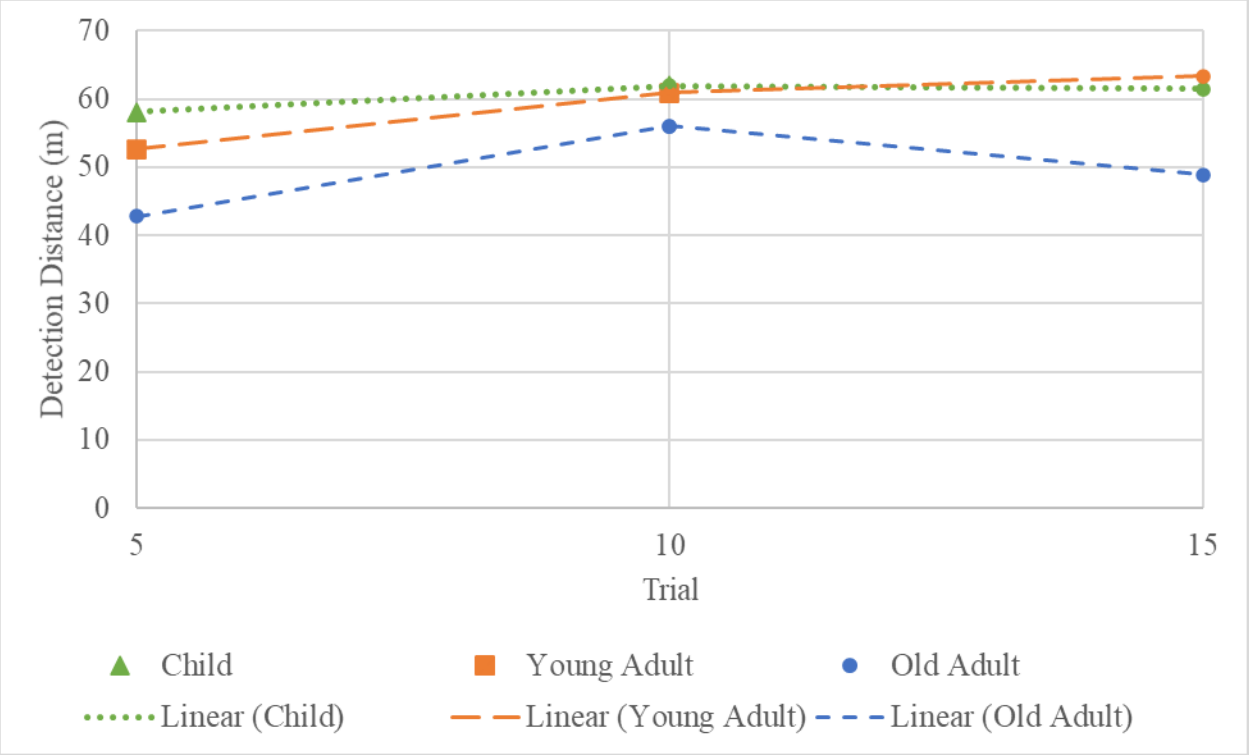

Figure 37. Detection distance by number of trials for each age group 9

Gap Experiment Results

The research team was interested in how the responses of children would differ from adults. Overall, adults were more conservative and indicated they were uncomfortable crossing much sooner than children by approximately 30 m (100 ft), a statistically significant difference (adjusted p-value = 0.0499) (Figure 38).

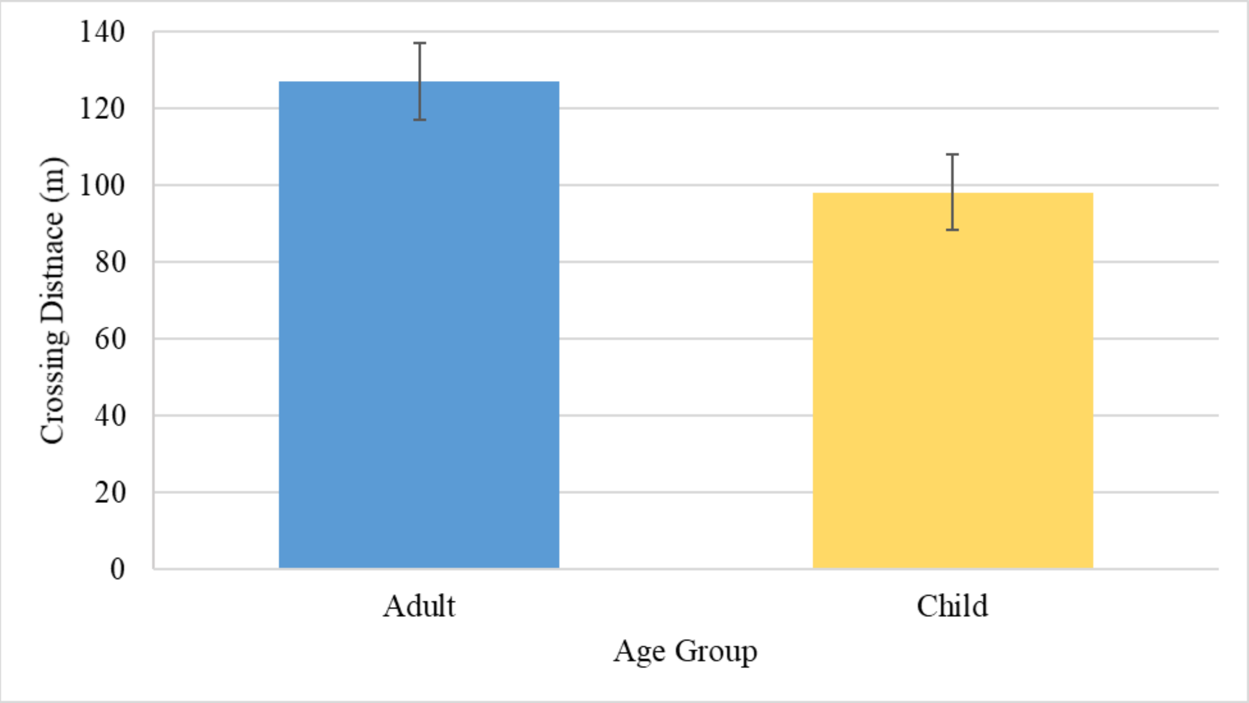

Figure 38. Crossing acceptance distance for gap experiment by age group

Appendix E: Lighting Design Examples

Design examples included below show some typical areas for the various classes of pedestrian facilities. They are focused on areas where child pedestrians are expected which typically includes school zones, recreational facilities, sports, and community facilities, etc. It is also worth noting that the dark times of day when children use these types of facilities is limited and dependent on location and time of year. Consideration should be given for the use of adaptive lighting systems on new installations meeting the recommendations of this guideline in order to meet the safety intent of the recommendations but also limit control any lighting impacts to the surrounding areas. Methods for applying adaptive lighting technologies is included in ANSI/IES RP-8-18 as well as Solid-State Roadway Lighting Design Guide: Volume 2: Research Overview (Lutkevich et al., 2019).

Example A: Low/Medium Pedestrian Volume

Design Problem:

Lighting design for the selection and placement of Luminaire for both the roadway and the adjoining pedestrian facility.

Base Condition:

- A collector type of street with a medium pedestrian volume in a suburban area.
- The peak hourly pedestrian volumes occur before and after school hours as this street is used by some students living in the neighborhoods within walking distance of the school and sports facilities.
- Volumes during peak hours on this street are approximately 50 pedestrians per hour.

Design Criteria:

Selection and placement of luminaire to provide an average vertical illuminance in the sidewalk area of 2 lux.

- No roadway light levels are recommended as part of this guideline, so levels advised by IES, AASHTO, or local criteria should be applied.
- The IES recommendations for the roadway lighting are 0.6 cd/m^2 per the table from ANSI/IES RP-8-18 for a collector roadway with medium pedestrian volumes.

Design Approach:

- As shown in Figure 39, Figure 40, and Table 8, a mounting height of 9.1 m (30 ft) was used for the LED roadway luminaires with pole located behind the sidewalk and spaced 48 meters (160 feet) apart. A vertical illuminance grid is then placed on the sidewalk area at a height of 1.5 meters. Three rows of points are used in this example.

- The light levels on the roadway meet the IES recommended levels as well as uniformity and glare and the vertical illuminance levels recommended by this guideline are exceeded at 8.8 lux, meeting the needs identified in this research.

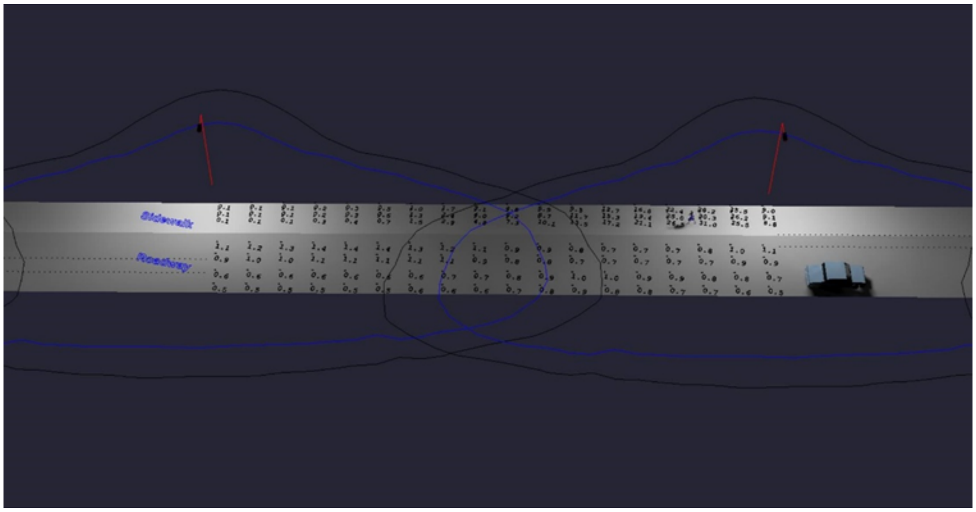

Figure 39. Simplified grid and values for Low/Medium pedestrian traffic in rural area design

Figure 40. Illustration for low pedestrian traffic design

Table 8. Values for low pedestrian traffic design.

Label	CalcType	Units	Avg	Max	Min	Avg/Min	Max/Min	LVRatio
Road East_Luminance	Luminance	Cd/Sq.m	0.68	1.0	0.5	1.36	2.00	N.A.
Road East_Veil_Lum	Veiling Luminance	Cd/Sq.m	0.06	0.2	0.0	N.A.	N.A.	0.29
Road West Luminance	Luminance	Cd/Sq.m	0.98	1.4	0.7	1.40	2.00	N.A.
Road West_Veil_Lum	Veiling Luminance	Cd/Sq.m	0.10	0.2	0.0	N.A.	N.A.	0.20
Sidewalk_Vert_Illum	Vertical Illum.	Lux	8.81	31.0	0.1	88.10	310.00	N.A.

Example B: High Pedestrian Volume / School Zone (Rural-Suburban)

Design Problem:

Lighting design for a pedestrian area on a suburban road within a school zone.

Base Condition:

- Suburban road with Crosswalk in a School Zone
- During school hours or after school activities the pedestrian volumes in the area would also be classified as high.

Design Criteria:

- The recommendations are to provide 10 lux semi-cylindrical for the pedestrian/sidewalk areas and between 1 and 2 cd/m^2 on the roadway.
- Because this roadway is considered a suburban area, a roadway lighting level of 1.5 cd/m^2 is used for the roadway light level.

Design Approach:

- This example design uses 10.6 meter (35 ft) mounting height for the LED roadway luminaires with pole located behind the sidewalk and spaced 48 meters (160 ft) apart.
- A semi-cylindrical illumnance grid is placed on the sidewalk area at a height of 1.5 meters. The rows of points in this example are in accordance with the CIE:140 methodology.
- The lighting levels on the roadway meet the 1.5 cd/m^2 roadway lighting level and 10 lux semi-cylindrical recommendations included in this guide.
- It also meets IES recommended levels for uniformity and glare (Figure 41, Figure 42, and Table 9).).

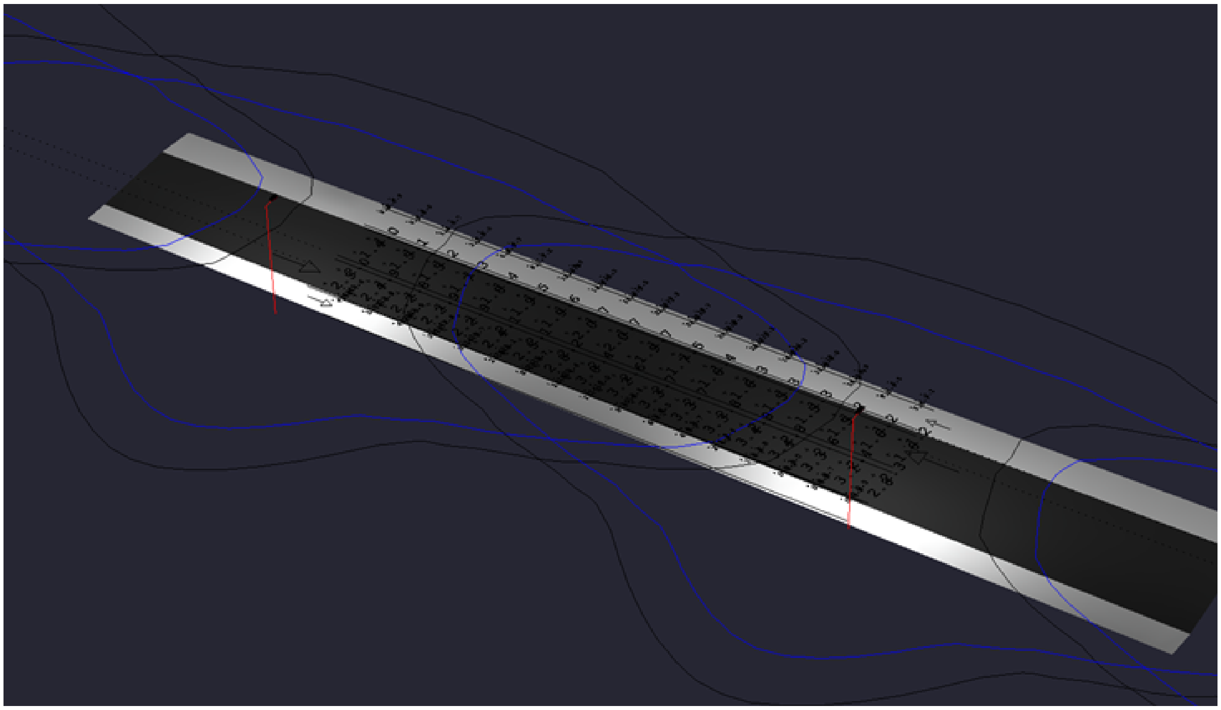

Figure 41. Simplified grid and values for School Zone in a Suburban Area

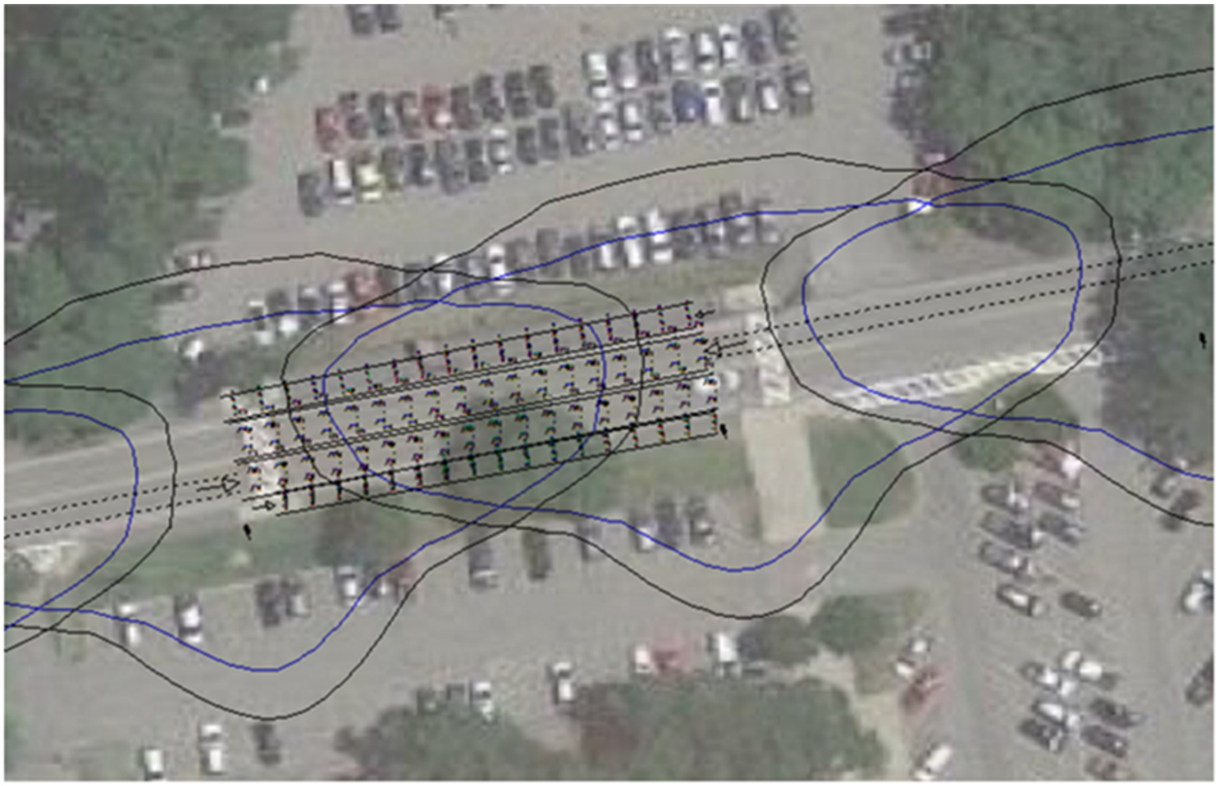

Figure 42. Illustration for high pedestrian traffic in rural or suburban area design

Table 9. Values for high pedestrian traffic in rural or suburban area design

Label	CalcType	Units	Avg	Max	Min	Avg/Min	Max/Mini	LVRatio
Road North_Luminance	Luminance	Cd/Sq.m	1.52	2.0	1.0	1.52	2.00	N.A.
Road North_Veil_Lum	Veiling Luminance	Cd/Sq.m	0.18	0.4	0.0	N.A.	N.A.	0.26
Road South Luminance	Luminance	Cd/Sq.m	2.59	3.4	1.8	1.44	1.89	N.A.
Road South_Veil_Lum	Veiling Luminance	Cd/Sq.m	0.22	0.4	0.0	N.A.	N.A.	0.15
Sidewalk North Semi Ill	Semicylindrical Illum.	Lux	10.15	20.4	3.8	2.67	5.37	N.A.
Sidewalk North_Vert_Ill	Vertical Illum.	Lux	11.43	28.4	0.5	22.86	56.80	N.A.
Sidewalk South Semi Ill	Semicylindrical Illum.	Lux	12.76	35.5	0.3	42.53	118.33	N.A.
Sidewalk South_Vert_Ill	Vertical Illum.	Lux	19.62	53.8	0.4	49.05	134.50	N.A.

Example C: High Pedestrian Volume / School Zone (Urban)

Design Problem:

This example represents a school zone in an urban environment on a major road.

Base Conditions:

- School-related pedestrian volumes for this school is considered high and medium during non-school hours.
- The roadway has parking along each side of the roadway and relatively wide sidewalk cross sections.

Design Criteria:

The recommendations are to provide 10 lux semi-cylindrical illuminance for the pedestrian/sidewalk areas and a luminance of 2 cd/m^2 on the roadway.

Design Approach:

- This example design (Figure 43, Figure 44, and Table 10) uses 9.1-m (30-ft) mounting height for the LED roadway luminaires with poles located behind the face of curb for the sidewalk and spaced 36.5 m (120 feet) apart with an opposite pole layout arrangement and lumunaires on each side to the roadway.
- A semi-cylindrical illumnance grid is placed on the sidewalk area at a height of 1.5 m (5 ft). The rows of points in this example are in accordance with the CIE:140 methodology.
- The luminance on the roadway exceeds the 2 cd/m^2 roadway light level and meet the 10 lux semi-cylindrical illuminance recommendations included in this guide.
- Lighting levels meets IES recommended levels for uniformity and glare.

Other Considerations:

- Because of the wide roadway cross section, light levels on the roadway are driven by the pedestrian lighting requirements.
- An adaptive lighting control for this installation would be beneficial.

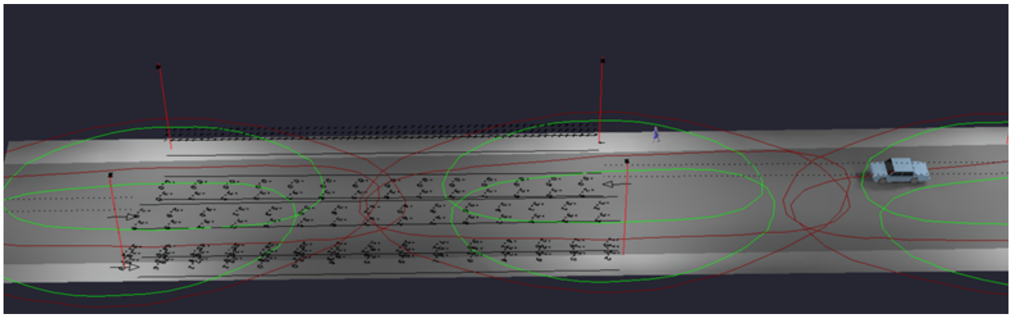

Figure 43. Simplified grid and values for High Pedestrian traffic School Zone in Urban Area Design

Figure 44. Illustration for high pedestrian traffic school zone in urban area design

Table 10. values for high pedestrian traffic school zone in urban area design

Label	CalcType	Units	Avg	Max	Min	Avg/Min	Max/Min	LVRatio
Road 1 Luminance	Luminance	Cd/Sq.m	3.45	4.2	2.8	1.23	1.50	N.A.
Road_1_Veil_Lum	Veiling Luminance	Cd/Sq.m	0.36	0.6	0.1	3.60	6.00	0.17
Road 2 Luminance	Luminance	Cd/Sq.m	3.43	4.0	2.9	1.18	1.38	N.A.
Road_2_Veil_Lum	Veiling Luminance	Cd/Sq.m	0.35	0.6	0.1	3.50	6.00	0.17
Sidewalk 1 Semu Illum	Semicylindrical Illum.	Lux	11.30	32.7	2.5	4.52	13.08	N.A.
Sidewalk_1_Vert_Illum	Vertical Illum.	Lux	15.93	49.4	1.2	13.28	41.17	N.A.
Sidewalk Semi Illum	Semicylindrical Illum.	Lux	10.10	30.4	2.7	3.74	11.26	N.A.
Sidewalk_Vert_Illum	Vertical Illum.	Lux	13.64	45.4	1.2	11.37	37.83	N.A.

Example D: Urban Roadway

Design Problem:

This is a roadway in an urban area with significant pedestrian volume, wide sidewalks, and residential buildings on each side of the roadway.

Base Conditions:

- The road is 5 lanes wide with a center turn lanes and parking on both sides of the roadway.

- The sidewalks are 10 feet wide and separated from the roadway with an 8-foot paved median.

- Trees are located on each side of the roadway in front of mid level residential buildings

- There are high pedestrian volumes due to the residences and proximity to public transport.

Design Criteria:

The recommendations are to provide 10 lux semi-cylindrical illuminance for the pedestrian/sidewalk areas and a luminance of 2 cd/m^2 on the roadway.

Design Approach:

- The layout of the calculation grids is shown in Figure 45.

- This example design (Figure 45, Figure 46, and Table 11) uses 9.1-m (30-ft) mounting height for the LED roadway luminaires with poles located behind the face of curb for the sidewalk and spaced 21.3 m (70 feet) apart with an opposite pole layout arrangement and lumunaires on each side to the roadway.

- A semi-cylindrical illumnance grid is placed on the sidewalk area at a height of 1.5 m (5 ft). The rows of points in this example are in accordance with the CIE:140 methodology.

- The luminance on the roadway exceeds the 2 cd/m^2 roadway light level and meet the 10 lux semi-cylindrical illuminance recommendations included in this guide.

- Lighting levels meets IES recommended levels for uniformity and glare.

Other Considerations:

An adaptive lighting control for this installation would be beneficial for times of low pedestrian volumes and during times when the residents in the adjacent apartment buildings are sleeping.

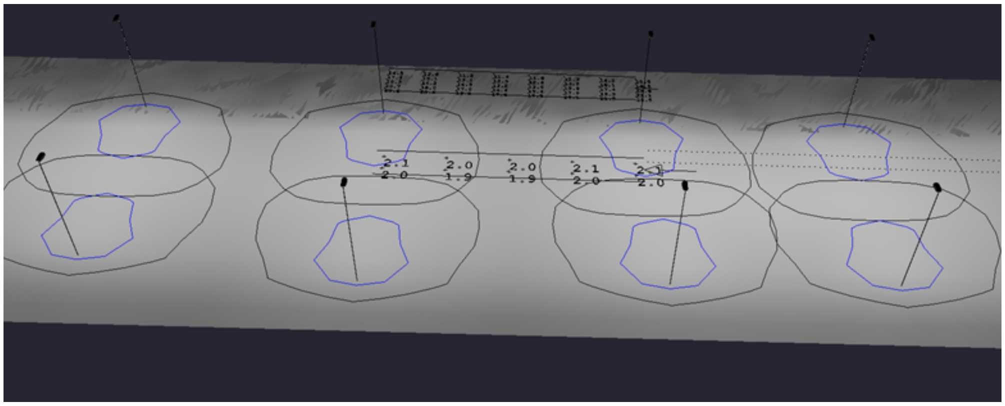

Figure 45. Simplified grid and values for high pedestrian traffic in urban area design

Figure 46. Illustration for high pedestrian traffic in urban area design

Table 11. Values for high pedestrian traffic in urban area design

Label	CalcType	Units	Avg	Max	Min	Avg/Min	Max/Min
Road_1_Illum	Illuminance	Lux	35.53	39.5	32.0	1.11	1.23
Road_1_Luminance	Luminance	Cd/Sq.m	2.01	2.1	1.9	1.06	1.11
Road_1_Veil_Lum	Veiling Luminance	Cd/Sq.m	0.18	0.3	0.1	1.80	3.00
Road_1_Vis_Level	Visibility Level	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
Road_1_Vis_Level_Bkgd_Lu	Background Luminance	Cd/Sq.m	1.98	2.1	1.9	1.04	1.11
Road_1_Vis_Level_Target_	Target Luminance	Lux	3.59	4.3	2.7	1.33	1.59
Sidewalk_Illum	Illuminance	Lux	16.58	25.5	11.4	1.45	2.24
Sidewalk_Semi_Illum	Semicylindrical Illum.	Lux	10.52	15.1	7.3	1.44	2.07
Sidewalk_Surr_Illum_Off-	Surround Illum.	Lux	27.90	38.9	20.7	1.35	1.88
Sidewalk_Surr_Illum_Off-	Surround Illum.	Lux	11.35	14.9	9.3	1.22	1.60
Sidewalk_Surr_Illum_On-L	Surround Illum.	Lux	18.85	25.8	13.6	1.39	1.90
Sidewalk_Surr_Illum_On-R	Surround Illum.	Lux	14.29	19.0	11.3	1.26	1.68
Sidewalk_Vert_Illum	Vertical Illum.	Lux	10.12	17.2	4.8	2.11	3.58

Appendix F: Figure Source List

Figure Number	Description	Page	Figure Source
Cover – Left	Lighted Virginia Smart Road with Pedestrians	C	Ronald Gibbons, VTTI
Cover - Upper Right	Example Pedestrian crossing in Massachusetts	C	Paul Lutkevich, WSP
Cover - Lower Right	Sidewalk Lighting in Cambridge Ma	C	Paul Lutkevich, WSP
Figure 1.	Example of a SRTS traffic improvement project as reported by Commission Internationale de l'Éclairage (2010)	16	Commission Internationale de I'Eclairage (2010)
Figure 2.	Top six occupational injuries in the United States in 2017 (National Safety Council, 2017)	19	National Safety Council (2017)
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