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Examination of Lighting Practices at Crosswalks

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FINAL REPORT

Western Michigan University

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Disclaimer

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16. Abstract
Following a review of the lighting literature and new lighting products, this study examined the lighting level at the location of night fatal and incapacitating (K&A) pedestrian crashes over a 5-year period in SW & SE Michigan. Not surprisingly, the results revealed that almost all the night pedestrian crashes coded on police reports as occurring under dark unlighted conditions occurred under very low lighting conditions (under 5 lux). However, at least 64% of those reported to have occurred under dark lighted conditions also had light reading under 5 lux. These results suggest lighting may be a more important determinant of night pedestrian crashes than previously suspected. An examination of newer LED lighting found that 8 ft. long LED light bars mounted under signal mast arms were able to adequately illuminate entire crosswalks including entry points. A field study found that the use of LED lighting activated along with an RRFB increased driver yielding rate and was associated with a large speed reduction in vehicles driven by drivers who did not yield to the pedestrian at locations with poor street lighting. Such smart lighting may be of benefit in reducing nighttime crashes at marked crosswalks with an RRFB.

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EXECUTIVE SUMMARY

According to NHTSA, on average about 72% of pedestrian fatalities recorded between 2011 and 2020 occurred after dark nationally, and 77% occurred at night in 2021 (Petraglia, & Macek, 2023); in Michigan, the estimate is 73%. Most of the fatalities in 2022 occurred under dark conditions (79%) when overall all exposure was relatively lower (NHTSA National Center for Statistics and Analysis, 2024). The analysis of FARS data shows that most of the additional crashes occurred at night on urban arterials and collector roads (Tefft, et al (2021); Hu, & Cicchino, (2018). These data support an increasing trend in night pedestrian fatal crashes.

Lighting and visibility are important components of a safety strategy for pedestrians. Several recent studies show that fatal and serious injury night pedestrian crashes occur at locations with poor lighting with additional factors such as speeding vehicles, and rain (Ammar, et al, 2022; Hossain et al, 2023). Thus, improved lighting may be one way to decrease pedestrian crashes at night. LED lighting has many advantages over traditional lighting systems because it produces the best color rendering and can be easily aimed to critical areas to make pedestrians more visible.

Night crashes are categorized in police crash reports as occurring either at dark unlighted or lighted locations. Because police do not have access to light meters to measure the light level at the precise crash locations, they typically categorize the crash based on whether street lighting was absent or present on the roadway where the crash occurred. In the first field study, lighting was precisely measured with a light level meter at fatal and incapacitating (K&A) crash locations for at all dark unlighted and dark-lighted night crashes in a number of cities in South East and South West Michigan that occurred during a 5-year period. In each case the pedestrian was struck attempting to cross the street. All the crashes involved pedestrians attempting to cross the roadway, with approximately 31% of them crossing at intersection crosswalks and 1% at midblock crosswalks. The remaining 68% of these KA nighttime crashes occurred at midblock locations. Not surprisingly, the study found that 99% of crashes that occurred under dark unlighted conditions had low lighting conditions (less than 5 lux). However, 64% of serious injury pedestrian crashes reported to have occurred under dark lighted conditions because street lighting was present along the road had low lighting levels (below 5 lux) at the location where the pedestrian was struck. Previous research shows that at least 20 lux is recommended for detecting pedestrians at adequate response distances (Edwards & Gibbons, 2008). However, a more recent study recommended that an average vertical illuminance value of at least 10 lux be maintained in the crosswalk in the direction of the approaching vehicle when a LED lighting source is used (Gibbon et al., 2023).

The next section of the report describes several studies carried out to evaluate several new crosswalk lighting strategies designed to reduce nighttime pedestrian crashes using improved lighting. In the second study, a precision light meter was used to measure lighting levels at all departure points and the middle of each lane before and after eight-foot-long light bars were installed on the four-mast arms of two signalized intersections. The data showed that lighting was poor during baseline with street lighting alone. After the light bars were added lighting improved to recommended levels at all curbside departure points and the middle of each lane at both intersections. This study showed that low-cost light bars can produce a large change in lighting at signalized intersections with mast arms.

In the third study, RRFBs equipped with a smart lighting device were installed at three crosswalks. Each device was purchased from a different manufacturer that sold RRFBs that include an on-demand smart lighting system. Measures included: the light level during baseline under street lighting conditions, and the light levels when the smart lighting was activated; yielding without the RRFB, when the RRFB was activated alone; and when the RRFB was activated with the smart lighting; and speed reductions of vehicles driven by drivers who did not yield to pedestrians during baseline, when the RRFB was activated alone, and when the RRFB was activated with the smart lighting.

The smart lighting produced large increases in lighting at all departure points and the middle of all lanes at two of the RRFB locations and less robust increases at the third location which had better street lighting. The introduction of the RRFB alone increased the percentage of drivers yielding to pedestrians from 1% to 25% at the first location. The introduction of smart lighting further increased yielding 61%. At the second site, the introduction of the RRFB alone increased the percentage of driver yielding to pedestrians from 9% to 42%. The introduction of smart lighting increased yielding further to 67%. At the third site with better street lighting the introduction of the RRFB increased driver yielding from 10% to 20%. The introduction of smart lighting further increased yielding to 26%.

Data for slowing of drivers who did not yield to the pedestrian produced mixed results. At the first site, drivers slowed 0.2 mph during baseline, 2.6 mph when the RRFB was activated, and 6.9 mph when the RRFB was activated along with the smart lighting. At the second site, drivers slowed an average of 0.4 mph during baseline, 2.6 mph when the RRFB was activated, and 9.3 mph when the RRFB was activated along with smart lighting. At the third site with better street lighting drivers slowed 3.1 mph during baseline 9.3 mph when the RRFB was activated alone and 7.6 mph when the RRFB was activated with smart lighting. This study showed smart lighting had the best effect on driver slowing at sites with poor street lighting.

The final study examined the addition of smart lighting at a crosswalk without an RRFB and at a signalized intersection with pedestrian push button activated crosswalk lighting. At the marked crosswalks, no drivers yielded during baseline and drivers very rarely yielded when the light was activated, although the smart lighting produced a marked increase in the lighting level when it was activated. The smart lighting was only associated with a 2 mph decrease in the speed of non-yielding drivers.

At the signalized intersection, the replacement of traditional luminaires streetlights which produced poor crosswalk lighting during baseline with LED luminaires activated on demand produced a large increase in overall lighting levels but it did not produce the overwhelming change at all curb side departure points and lane lighting similar to that produced by the light bars in the first study. Many measurement positions still had lower lighting than the recommended standard. Because each crosswalk was illuminated by one luminaire mounted on each of four light poles, this situation could be remedied by mounting two arms on each pole for a total of 8 luminaries. This would greatly improve lighting levels at all locations. On-demand lighting had another advantage at these sites. Since the lights were only on when pedestrians cross rather than continuously throughout the night, there would be substantial energy savings. Activated lights would also reduce glare for pedestrians crossing outside crosswalk since the lights would not be activated.

1 INTRODUCTION

Over the period from 2009 to 2022, pedestrian fatalities increased from 4,109 to 7,522 an 83 percent increase (National Center for Statistics and Analysis, 2023; Schneider, 2020; Webb, 2019). Over this same period, the percentage of total traffic fatalities that involved pedestrians increased from 12 to 18 percent an increase of 50%. According to NHTSA, on average about 72% of pedestrian fatalities recorded between 2011 and 2020 occurred after dark nationally, and 77% occurred at night in 2021 (Petraglia, & Macek, 2023); in Michigan, the estimate is 73%.

Most of the fatalities in 2022 occurred under dark conditions (79%) when overall driver and pedestrian exposure was relatively lower (NHTSA National Center for Statistics and Analysis, 2024). Also, 51% of pedal cyclist fatalities occurred at night nationally; in Michigan, the estimate is 56%. These statistics are even more stark when one considers that only about 25% of all traffic volumes occur after dark. Thus, during the nighttime, when the least number of vehicles are on the road, the greatest number of pedestrians and bicyclists are killed in crashes. The analysis of FARS data shows that most of these increases occurred at night on urban arterials and collector roads (Tefft, et al (2021); Hu, & Cicchino, (2018). These data support an increasing trend in night pedestrian fatal crashes. This shows a heightened need to add or improve safety measures to protect areas of roadway traffic with high pedestrian and bicyclist volume, especially after dark.

This trend of more pedestrian fatalities at night highlights the critical issue of reduced visibility at night, a major factor in fatal pedestrian crashes. It was observed that poor visibility associated with inadequate lighting is a significant contributor to these crashes (Owens, et al, 1993). Similarly, Spainhour et al., (2006) found that insufficient lighting accounts for about 60% of fatal pedestrian crashes in Florida. The purpose of this study was to examine lighting issues and to provide and evaluate potential new countermeasures.

2 LITERATURE REVIEW

2.1 Impact of Lighting and Visibility on Pedestrian Safety

Lighting and visibility are important components of a safety strategy for pedestrians. Several recent studies show that fatal and serious night pedestrian crashes occur at locations with poor lighting with additional factors such as speeding vehicles, and rain (Ammar, et al, 2022; Hossain et al, 2023). Thus, improved lighting may be one way to decrease pedestrian and bicyclist crashes at night. An MDOT study of nighttime pedestrian crashes further supports this hypothesis (Van Houten, et al, 2023). This study examined crashes on higher-speed (45+ mph) corridors in Michigan and identified lighting as a potential major contributing factor for nighttime pedestrian and bicycle fatal (K) and serious injury (A) crashes. They also found that even at crosswalk locations with lighting, the crashes tended to occur in the poorest lit (lighting intensity readings below recommended standards) portion of the crosswalk.

Lighting issues include lighting levels and type at crosswalk locations, general roadway lighting, and vehicle headlights. Evidence from comparisons of pedestrian fatalities before and after transitions with daylight savings time have consistently shown that holding all other factors constant, brighter lighting conditions are associated with fewer pedestrian deaths (Sarma, 2017). Jang et al. (2013) found that severe injury pedestrian crashes are more likely to happen at night and on weekends because of low visibility and high pedestrian activities, respectively. Fitzpatrick et al. (2014) indicated that 82% of the crashes in Texas from 2007 to 2011 occurred in dark conditions, with almost half of them occurring at locations with no lighting. The increase in pedestrian fatalities in recent years primarily consists of nighttime crashes which account for 87% of the increase. The distribution of lighting has also emerged as an important factor because rather than providing a "blanket" of light along the roadway surface it is necessary to provide vertical illumination along sidewalks, crosswalks, and bikeways to ensure that pedestrians can be seen by approaching drivers. Considerable research has examined how to optimize lighting for pedestrians at intersections and crosswalks, but much of this research was conducted with lighting sources that do not render color that are more difficult to aim than light emitting diodes (LED) lighting (Cai, Jinlin, et al., 2014). Adding to the complexity of this issue is that crash reports provide information on whether lighting is present, but not the type of lighting nor the level of lighting measured by an accurate light measurement instrument.

Several variables contribute to the issue of whether lighting levels are adequate or optimal. First, most lighting standards are formulated to determine whether the lighting levels are adequate for drivers. Therefore, "street lighting" might not meet the needs required to discriminate the presence of pedestrians or cyclists. Another variable is that lighting standards are fragmented across levels of government including the Federal Highway Administration's (FHWA) *Lighting Handbook*, state roadway design manuals, and the large number of local ordinances and downtown improvement district requirements. Adding to this complexity, practitioners can also use guidance provided by the Illuminating Engineering Society (IES), published in a variety of documents. Some of these documents provide standards for lighting sidewalks, pedestrian walkways, and bikeways as well as street lighting.

IES design guidance specifies how crossings should be lighted, suggesting vertical illuminances of 10 lx and 20 lx for areas of high and medium pedestrian conflict. Other research suggests different lighting levels (Gibbons, et.al, 2008) and it has been shown that overhead lighting is not always the most beneficial approach for pedestrian safety (Bullough et.al, 2009). This variation in recommendations demonstrates a lack of consensus on what represents good lighting for pedestrians. A first step in resolving this lack of consensus is understanding what impact ambient light conditions have on the risk of a collision involving a pedestrian.

Although considerable research has examined how to optimize lighting for pedestrians at intersections and crosswalks, most of this research studied legacy lighting. Pedestrian detection under various street lighting conditions is influenced by several factors such as road surface luminance, lamp color, glare, and driver age. Human color vision is best under white lighting; however, most legacy street lighting does not provide white lighting. Four types of legacy lamps have been regularly employed for street lighting: Mercury vapor (MV), low-pressure sodium (LPS), high-pressure sodium (HPS), and metal halide (MH). HPS, which has a pinkish-orange light, is the most widely used lamp type in street lighting systems, because of its efficacy (lumens per watt), long life, and comparatively better color rendering compared to other legacy lights. LPS lamps have a high efficacy but they have a monochromatic yellow light and, accordingly, their color rendering is poor. MV and MH lamps have a bluish-white light and objects seen under these sources thus appear normally colored. White light appears more uniform than sodium light to the human eye. However, the efficacy of MV and MH lamps are lower than that of sodium lamps.

Bhagavathula et al (2018) evaluated street lighting comparing three intersection lighting designs (Lighted Approach, Lighted Box, and Lighted Approach and Box) using the objective measure of detection distance for targets located at the entrances, exits, and middle of pedestrian crosswalks at intersections. The results indicate that the design illuminating the intersection box offered better visual performance and had fewer missed target detections, with visual performance plateauing between 7 and 10 lux average intersection illuminance. However, this study did not examine light bars that can illuminate an entire crosswalk including curb side entry points.

One problem with recognition distances studies is the variability of different headlights. Human Factors research should not include telling the participants they are looking for a pedestrian because this improves their ability to detect the pedestrian and in real life driving the person is not normally alerted to the presence of a pedestrian. The detection of pedestrians at crosswalks depends not only on the light level but also on the design of the crosswalk. They also found that lane narrowing at the crosswalk had a beneficial effect on the recognition of pedestrians in the crosswalk, while intense illumination in the absence of lane narrowing deteriorated the detection of pedestrians that cross the street outside of the crosswalk. When intense illumination was combined with lane narrowing, the visibility of pedestrians was improved, both for pedestrians at and behind the crosswalk.

Glare is another factor that needs to be considered in evaluating lighting. Glare is experienced when a light source in the visual field is brighter than the luminance level that the eye is adapted to. Glare can produce discomfort or impairment of vision. This means that crosswalk lighting strategies need to consider the visual background from the perspective of the on-coming motorist. Bright roadways or bright off-road installations (gas stations, etc.) increase background luminance and either reduce contrast or create negative contrast on the pedestrian making them more difficult for motorists to see. Oncoming vehicles are also a common source of glare. Unshielded non-directional lights often cause glare. The effects of glare are worse when crosswalk lighting levels are low.

2.2 Street Light versus Spot Lighting on Pedestrian Crossings Facilities

Much of the research that examines street lighting and spot lighting at pedestrian treatment sites has been conducted using legacy lighting. Adding lighting to roadways has been shown to be an effective countermeasure against all crashes at night. A study measuring lighting levels (illuminance vs. luminance) at rural intersections in Iowa concluded that it was difficult to quantify the effect of lighting on intersection safety. However, the authors noted that the presence of fixed overhead lighting made intersections safer than unlighted ones. More recently, lighting data collected from 100 rural intersections in Virginia showed that for a 1-unit increase in illuminance, the number of night crashes decreased by 7%. For the lighted intersections, the same increase in average horizontal illuminance decreased the number of night crashes by 9%. The largest decrease in the number of night crashes was for unlighted intersections, where for a 1-unit increase in the average horizontal illuminance the night crashes decreased by 21%. These relationships between illuminance and night crashes may only be valid, however, for the tested illuminance ranges (0.28 to 31.6 lux). A previous study collected illuminance data from 63 intersections in Minnesota and reported that an increase in 1-lux of average intersection illuminance resulted in a 9% reduction in nighttime crash rates. The study also reported that an increase in 1-lux in average illuminance at lighted intersections was associated with a reduction in nighttime crashes by 20%. Again, these changes were not specific to pedestrian crashes but crashes of all types.

A study by Polus and Katz (1978) treated 99 crosswalks with lighting and a sign in Israel. This treatment produced a significant decrease in car pedestrian crashes at night but did not have a significant effect on crashes during the day, indicating that the addition of lighting was the primary factor influencing the crash reduction. They also examined night and day crashes at a group of unlighted crosswalks each of which adjoined the treated crosswalks. Crashes also did not show as significant reduction at these sites. An analysis of vehicle and pedestrian exposure and other factors such as weather confirmed the crash reductions were caused by the addition of lighting. It would be a good idea to replicate this study at a US site with newer LED lighting.

Street lighting may not meet the needs of pedestrians because lighting standards are primarily formulated to meet the needs of the driver's navigational needs, and may not meet the requirements necessary for detecting pedestrians particularly at crosswalks at marked and unmarked intersections or locations where spot treatments such as crosswalks, RRFB, Hybrid Beacons or other specific crosswalk treatments are installed. At these locations, a sound argument can be made that specific lighting designed to light these treatments do not fall under general street lighting. When considering the design of roadways and pedestrian safety, it is important to understand that street lighting does not equate to pedestrian lighting. Several studies on visibility at crosswalks have been reported in recent years.

Edwards and Gibbons studied the visibility of pedestrians under different lighting conditions. Two legacy lamp types, HPS and MH, with vertical illuminance levels of 6, 10, 20, and 30 lux placed to produce positive contrast were compared. In all cases, the vertical illuminance was measured 5 feet from the ground across the entire roadway. The detection distance was the greatest at 30 lux for the HPS and 20 lux for the MH light. A more recent study reported by Bhagavathula and Gibbons (2023) tested LED lamps and determined that illuminating crosswalks with a vertical illuminance of 10 lux were optimal with this type of lighting. The need for less lighting when using LED is likely related in part to better color rendering. It is interesting to note that the detection distance did not necessarily increase with increasing luminance in these studies.

2.3 Role of LED Technology in Enhancing Pedestrian Visibility

Crash reports provide information on whether lighting is present, but not the details, such as the placement, type of lighting, and whether lighting was adequate or optimal based on lighting research. The ongoing revolution in solid-state lighting technology provides opportunities for new approaches to pedestrian/cyclist lighting that can reduce the number and proportion of pedestrian and cyclist fatalities on the road. LED lighting has generated a low-cost way for traffic engineers to light specific areas. This type of lighting provides excellent color rendering and better capability for aiming the light source. Newly available light bars further increase the capability to spotlight an entire crosswalk. This approach allows for spotlighting crosswalks at crosswalk locations with an RRFB, or a Hybrid Beacon treatment.

The major advantage of LED lighting is that allows drivers to use day vision also known as photopic vision. Photopic vision employs cones in the retina responsible for color vision. Photopic vision has a major advantage over night vision also known as scotopic vision. Scotopic vision employs rods on the outer portion of the retina. Rods are more sensitive than cones and provide black-and-white vision. One major disadvantage of scotopic vision is it takes considerable time for night vision to adapt to dark conditions and a flash of bright light drastically reduces night vision. It can take up to 15 minutes for scotopic vision to fully recover after exposure to a bright light. The recovery of scotopic vision typically shows a logarithmic recovery. Thus, light levels on the side of the road near a location with a crosswalk facility or oncoming headlights can greatly degrade scotopic vision at crosswalks with legacy lighting. Uniformity in illuminating a crosswalk also becomes more critical when legacy lighting is employed but is not a major factor with LED lighting.

2.3.1 Advantages of LED Lighting

<u>Energy Efficiency</u>

LED lights are more efficient and can greatly reduce the electricity cost over legacy lighting systems saving 50% in power costs (Huang et al., 2012). Because of the lower Power Requirement LED lights can be practically powered by solar arrays.

<u>Longevity.</u>

LED lights have a longer lifespan, contributing to lower maintenance costs. For example, an LED bulb has a lifespan of 100,000 hours, which is superior to that of a HID light source, which has a light span of 20,000 hours or less (Rofaie et al., 2022). LED lights are also more resistant to shock and vibration damage.

Reduced light pollution

Because LED lighting can be aimed and the brightness can be controlled, it is easier to put the amount of light you want in the location you want it because it is aimed down with less light dispersed into the sky.

Brighter Light and Better Visibility

LED lights offer near-daylight illumination quality and has a color-rendering index (CRI) ranging between 70 to 85 for improved visibility and comfort. Moreover, this creates a more natural rendering of colors for better visible inspection and safety (Schratz et al., 2016).

LEDs are more Uniform.

Light uniformity is important for both positive contrast and adequate vertical illuminance, particularly with legacy lighting. Light uniformity is the ratio of maximum to minimum levels. An overall goal would be to obtain a 1:1 ratio or an even spread of light across the crosswalk. The poor uniform ratio would be an average to a maximum ratio of 6:1, which would indicate that the brightest parts of the crosswalk are six times brighter than the darkest parts of the crosswalk. Most agencies recommend a maximum contrast of 4:1. The IES recommends nothing greater than a 3:1 ratio. LED Street lighting lamps produce more uniform light than HPS lamps (Jiang et al., 2018; Lee, et al., 2013).

However, uniformity is not as critical with LED lighting that can illuminate an entire crosswalk (such as light bars). With lighting sources providing poor color rendering that depends on rod cells used for scotopic, or night vision, uniformity is critically important, because exposure to a bright light source can cause night blindness to an object lighted at a lower level. For example, when legacy lighting with poor color rendering is used and one portion of the crosswalk has 300 lux illuminations while another portion has only 20 lux, looking at the portion at 300 lux will cause night blindness to anyone lit by the 20-lux light source. With lighting providing good color rendering someone in either area will be visible because photopic vision which depends on cone cells does not show this effect.

Although all the LED systems tested produced superior uniformity than HPS lights there was considerable variability between LED systems. One advantage of LED systems is that they achieve light uniformity through multiple, discrete sources, rather than from one fixed point, which can provide better uniformity measures. A key design principle for both light uniformity and area lighting at crosswalks is the placement of overhead lights. Agencies have traditionally positioned crosswalk lighting directly over the crosswalk. New guidelines recommend placing lighting fixtures ahead of the crosswalk, from the perspective of oncoming traffic. However, this variable may also be less critical with lights that provide good color rendering (LED). It is also critical to light curb side entry points to the crosswalk as well. LED lighting achieves uniformity because it consists of many small light sources that can be aimed using micro lens arrays. This same principle extends to the use of light bars which can focus light over an entire crosswalk including entry locations.

Rapid onset and offset.

When LED lights are turned on, there is no noticeable delay between onset and the presence of light at its full intensity. Similarly, when LED lighting is turned off there is no noticeable delay between offset and the absence of light. This makes LED lighting ideal for smart lighting applications where the lighting is switched on when a pedestrian is detected or activates a push button.

Aimability

LED lighting has many small light sources and faceted reflectors which can be used to aim the luminous flux of LED lighting to form uniform illumination on a specific target area (Cai, Jinlin, et al., 2014). In addition, LED light bars can extend the coverage of the illuminated area.

Excellent Color Rendering

Because LED is a white light source it allows one to use color vision which is not attenuated after brief exposure to bright light. Unlike HID lights, LED street lighting can provide a more uniform light distribution that improves visibility and recognition of pedestrians (Schratz et al., 2016).

Can be Operated by Solar Arrays

This feature makes them useful for RRFB installations as well as midblock crosswalks without a lighting source.

2.3.2 Installation Considerations

The preferred type can be either solar power or connected with electricity. Solar power has an advantage when electricity is not easily available. Solar Power is practical for many RRFB installations and for other crossings that do not have electric power nearby. Most intersection lighting at marked crosswalks and unmarked crosswalks can easily be directly connected to the available wiring. The preferred configuration is primarily dependent on how many lights should be installed on each pole, and identifying whether it is possible to install a light bar on a mast arm or an available pole. In some cases, there might be a need for an overhead light to be mounted over the crosswalk and another that illuminates the entry point.

2.4 Smart Lighting

One approach that has not been systematically examined is increasing the lighting level when a pedestrian enters a crosswalk. Not only does this approach decrease light pollution, but it also can alert the driver that a pedestrian is initiating crossing or crossing the street. Such on-demand use of illumination also requires a lower power use, which allows the use of a solar array, increasing the number of locations that could be economically treated. If this approach proves effective it could be a low-cost way to increase the visibility of pedestrians crossing at night while the stimulus onset of the light would also alert drivers to pay attention to the area with increased illumination. In the case of a dark intersection, it could "turn on the lights" when the pedestrian approaches the crosswalk, and in the case of a lighted crosswalk, it could intensify the lighting when the pedestrian enters the crosswalk. If this method proves effective, it could also be used in a smart city to alert drivers of pedestrians detected entering the road at midblock locations. However, for drivers to learn that the light onset is associated with the presence of a pedestrian or a cyclist, these systems would need to be in general use.

One simulator study examined the use of two in-road red lines that illuminated at the crosswalk when someone was crossing the street on the behavior of drivers who were distracted while driving the simulator in a night scenario. The results indicated that the system led to faster reaction times. However, in roadway systems have problems when road work is required and the use of red would require changes to MUTCD. Patella (2020) examined an LED lighting system that illuminated the crosswalk from below when the system was activated by a pedestrian who was crossing. This system led to a significant reduction in driver speed both when the system was activated and when the system was continuously lit.

Van Houten conducted a study funded by the Insurance Institute for Highway Safety (IIHS) that examined the effect of continuous increased lighting at crosswalks alone versus increased lighting that was activated when a pedestrian entered a crosswalk (Hu, et.al). This preliminary study used a portable lighting device that could be installed at a variety of crosswalks. It is possible that there will be interactions between smart lighting and other pedestrian countermeasures such as the Hybrid Beacon and in-street signs. This approach could be applied to unmarked crosswalks where pedestrians enter the roadway related to pedestrian generators. Previous studies on Smart Lighting only examined smart lighting during twilight conditions and did not compare smart lighting to a continuous lighting condition with the same device (Nambisan et al., 2009). A more recent study examined direct lighting from panels below the crosswalk when a pedestrian was present. This condition was compared with the crosswalk lighting system being continuously on. Both conditions produced a reduction in speed (Patella et al., 2020). This study found a speed reduction even when pedestrians were not present, but the authors cautioned that as drivers become more familiar with this device, they will be less likely over time to slow down if a pedestrian is not present. This finding suggests that a long-term study should be conducted to determine the effects of these systems on driver behavior.

Another similar study examined the TAPCO Safewalk LED crosswalk illuminator used as part of their RRFB product (but which can be ordered alone) and the Salex flood light LED crosswalk illuminator. This simulator study only examined recognition distance and did not measure driver behavior such as yielding or slowing. In all cases, the driver was told they were to report when they first saw a pedestrian, so they were primed to engage in pedestrian search behavior (Bhagavathula et al., 2021). Several studies have demonstrated that recognition distance is greatly enhanced when the subjects are primed to detect a specific target. One limitation of the study conducted by the IIHS (Yu, in press) is that all conditions were conducted each night including crossing onset and a constantly present condition. Thus, the device was not installed long enough at each site to evaluate whether drivers were able to learn that the device was consistently correlated with the presence of a pedestrian crossing the street.

A number of companies are producing smart crosswalk lighting systems that are activated when a pedestrian enters a crosswalk at night. These systems are typically powered by a solar array but can be wired into the power grid. These systems can be installed as a stand alone system or along with an RRFB or Hybrid Beacon. Below are some of the systems currently available.

- Tapco Safewalk Crosswalk Illuminator System – This solar-powered system can be either with or without an RRFB.
- Western Systems Crosswalk Lighting
- Carmanah Overhead lighting system. This system is sold with an RRFB
- JSF Crosswalk Illuminator System – This system is sold with an RRFB.
- Bercman Technologies Smart Pedestrian Crosswalk
- Step Crosswalk Visibility System
- Coral Sales Co. Lumiwalk Crosswalk Lighting System
- ISS Intelligent Lighting System – AI-driven system

It would also be helpful to determine the value of LED light bars to illuminate crosswalks more uniformly at crosswalks at traffic signals and crosswalks at uncontrolled midblock and intersection locations. Light bars consist of a long array of LED light sources with a series of aimed faceted reflectors to further increase the capability to spotlight an entire crosswalk. This approach allows for spot treatment as part of an engineering treatment such as a high visibility crosswalk. Currently there are LED light bars available that can be installed under mast arms, which more uniformly illuminate crosswalks at traffic signals. These could be evaluated by measuring whether they provide better crosswalk lighting at a lower installation cost. Although these devices currently are only available for mounting under a mast arm, it may be possible to design mounting arms that could be attached to standard light posts. The major advantage of installing them at sites where light posts are available is that they can illuminate a crosswalk over a longer distance than a conventional LED luminaire.

3 EXAMINING LIGHT LEVEL ON KA PEDESTRIAN NIGHTTIME CRASHES

The lighting condition variable in crash data is used by police officers at the crash scene to classify crashes into either daytime, dark-lighted, dark-unlighted, dawn, or dusk. Typically crashes that occur under dark-lighted and dark-unlighted conditions are referred to as nighttime or dark crashes. Police officers classify a crash as a dark-lighted crash if it occurs in an area with street lighting, while a dark-unlighted crash occurs in an area lacking street lighting. However, this classification can be inaccurate and inconsistent. This is because a streetlight might not be close to the crash site, and/or it might not fully illuminate the entire area if not properly aimed. Therefore, this section illustrates the light readings measured in lux taken at crash sites of both labeled dark-lighted and dark-unlighted pedestrian crash locations between 2018 and 2022. This will demonstrate the actual role of lighting intensity in pedestrian nighttime crashes.

3.1 KA Pedestrian Night time Crashes Light Readings

To understand the impact of lighting levels on serious pedestrian nighttime crashes, the study examined light readings at pedestrian fatal or incapacitating injury (KA) nighttime crashes between 2018 and 2022. This study focused only on severe crashes that are fatal or cause incapacitating injuries, aligning with the Vision Zero approach that aims to eradicate all traffic-related fatalities and serious injuries. The findings aim to demonstrate that inadequate lighting levels play a significant role in these severe incidents and therefore, cost-effective solutions can be suggested to prevent further pedestrian fatalities.

Light readings were taken after sunset using a Konica Minolta T-10A Illuminance Meter, positioned 5 feet above the road surface to measure vertical illuminance. Vertical illuminance is most often used at a height of 5 ft above the roadway or sidewalk (the approximate height of a pedestrian's face). Since vertical illuminance can represent the amount of light illuminating pedestrians, it is considered important in terms of visibility and detection of pedestrians in crosswalks (Gibbons et al., 2008). Police reported crash narratives and diagrams were referenced to identify the exact crash locations and the light level was measured at the point where the crash occurred.

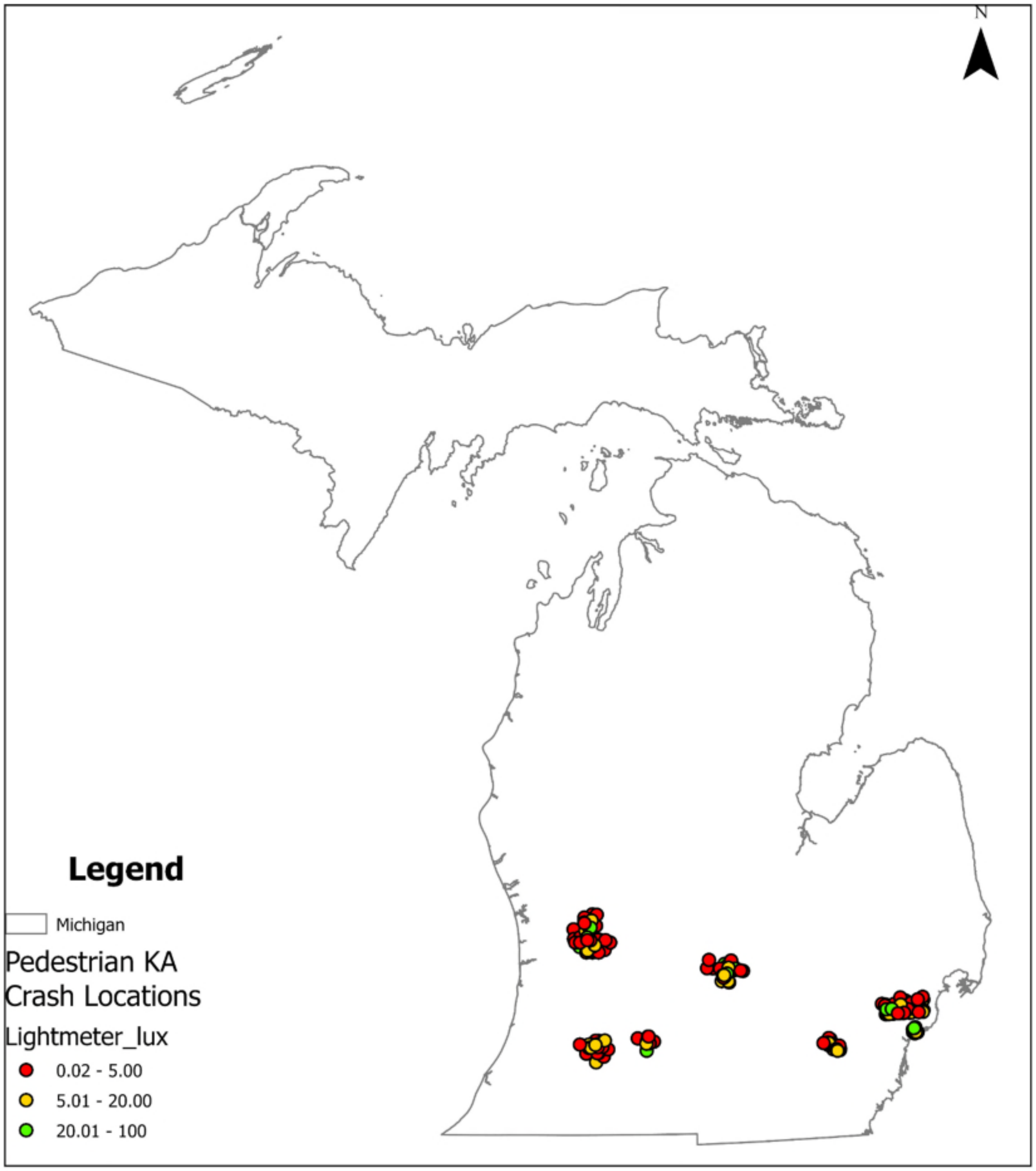

Figure 3-1. Study locations

Together with light measurements, other observable information such as the presence of LED lighting at the crash site was also recorded. Since taking light measurements is an extensive process, light measurements were taken on severe crash locations in some cities and neighborhoods in Michigan based on the geographical area and conduciveness of these locations. These cities include Lansing, Grand Rapids, Kalamazoo, Ann Arbor, Wyoming, Kentwood, Southfield, Warren, Downtown Detroit, Center Line, Madison Heights, Berkley, Huntington Woods, Oak Park, Hazel Park, Ferndale, Royal Oak, and neighboring cities as shown in Figure 3-1. Afterward, to ensure that the light level corresponded to the time of the crash, the team verified with the respective light owners to cross-check whether any improvements had been made at the surrounding streetlights since the crash occurrence to ensure that our analysis was valid.

3.2 Analysis of the Observed Light Readings

3.2.1 LED versus Traditional Lights

The presence or absence of LED lights was documented when collecting light meter readings at crash sites. This was done to compare the light intensity at locations with LED to those without. Table 3.1 shows the descriptive statistics of the light measurements comparing LED locations to traditional light locations. Similarly, Figure 3-2 shows the box plot comparing light levels at LED versus non-LED. Crossings that have LED lights have higher light intensity than those without.

The median value and the interquartile range (the box) are elevated in the LED lights, indicating higher lux achieved by LED lights compared to traditional lights. Previous studies have demonstrated that LED lighting achieves higher illuminance levels while consuming less electricity (Peña-García et al., 2015). LED lighting has excellent color rendering and precise directional capabilities, which enhances overall visibility and pedestrian safety through uniform lighting (Van Houten et al., 2023). Moreover, previous research has analyzed LED lighting on pedestrian safety (Carries et al., 2023; Patella et al., 2020). It was determined that LED lighting effectively improves the visibility of pedestrians at night with drivers slowing down on crosswalks in both the presence and absence of pedestrians.

Table 3-1. LED light readings versus traditional lights

Variable	**Obs.**	**Mean**	**Std. Dev**	**Min**	**Max**
No LED Lights	195	3.54	6.09	0.02	47.8
LED Lights	158	22.29	17.40	1.12	98.0
Total	353	11.93	15.58	0.02	98.0

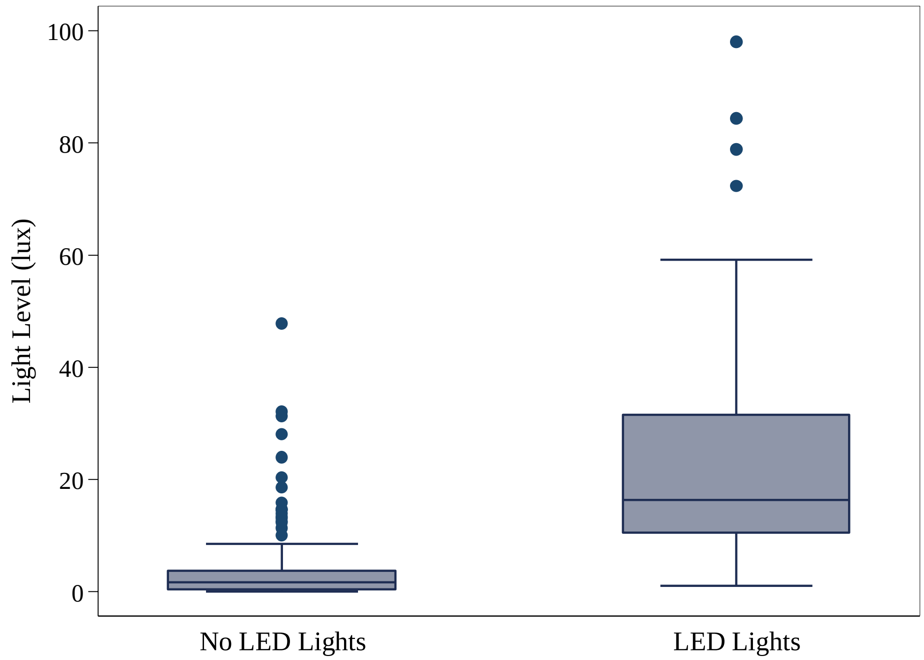

Figure 3-2. Box plot Comparing Light Levels on LED versus non-LED

3.2.2 Police-Reported Lighting Condition vs Actual Lighting

Figure 3-3 shows the number of severe pedestrian nighttime crashes in LED and no LED lighting conditions measured in lux in the current conditions. Although some of these light readings might not reflect the actual light conditions present at the time of the crash, this Figure shows the light intensity of crash locations from up to five years ago (2018 -2022) at this time. It can be said that most locations where severe pedestrian crashes occurred at night are still not well-lit (light level less than 5 lux). Due to the possibility that these readings might not reflect the conditions during the crash, there is a need to verify which readings correspond to the actual crash occurrences.

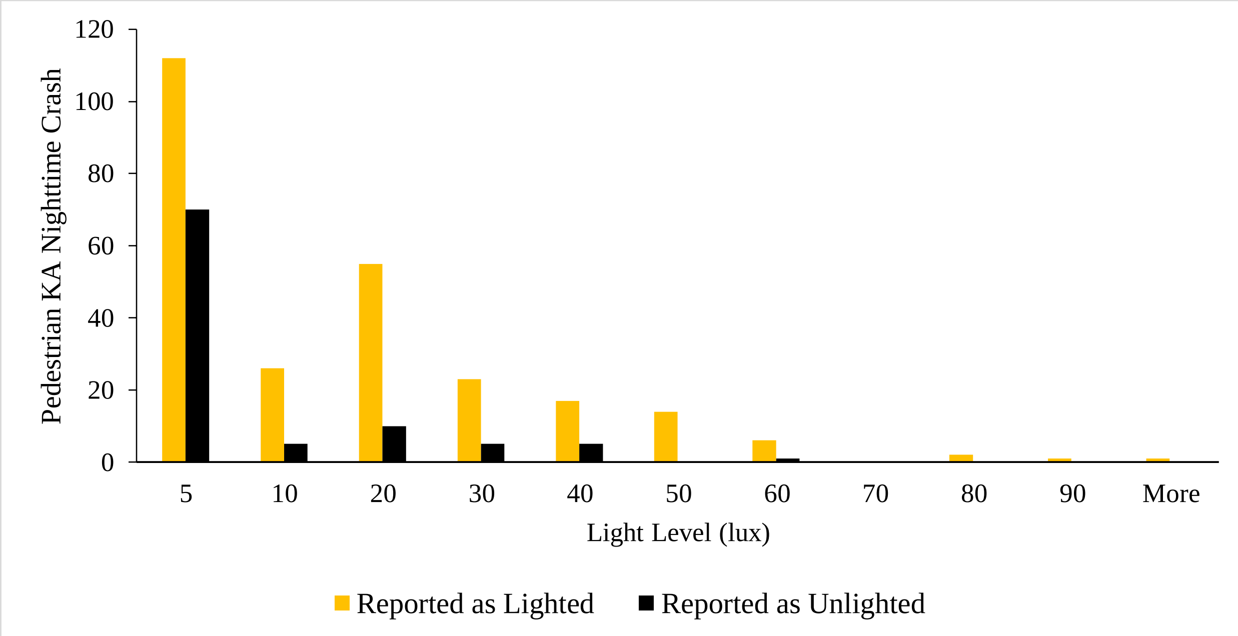

Figure 3-3. Current Light Readings at All Crash Sites

<u>Accuracy of Reported Crash Lighted Conditions</u>

To ensure our analysis was valid the team verified with the respective light owners whether any improvements had been made to the surrounding streetlights since the crash occurred. Sites that were verified to have had no improvements since the crash occurred were used to evaluate whether police-reported lighting conditions in crashes are reliable using 250 unchanged sites suitable for this analysis. Figure 3-4 shows the percentage light level at reported lighted KA pedestrian nighttime crashes.

Generally, it can be observed that most pedestrians are killed or sustain an incapacitating injury at low light conditions (less than 5 lux). About 64 percent (111 KA pedestrian crashes) of all reported lighted pedestrian crashes occurred in locations that had streetlights along the road, but the pedestrian was hit on a spot that was not well-lighted. These locations had an illuminance level of less than 5 lux. Previous research shows that at least 20 lux is recommended for detecting pedestrians at adequate response distances (Edwards & Gibbons, 2008). The Federal Highway Administration (FHWA) lighting handbook recommends an average vertical illuminance value of at least

10 lux to be maintained in the crosswalk in the direction of the approaching vehicle (Gibbon et al., 2023).

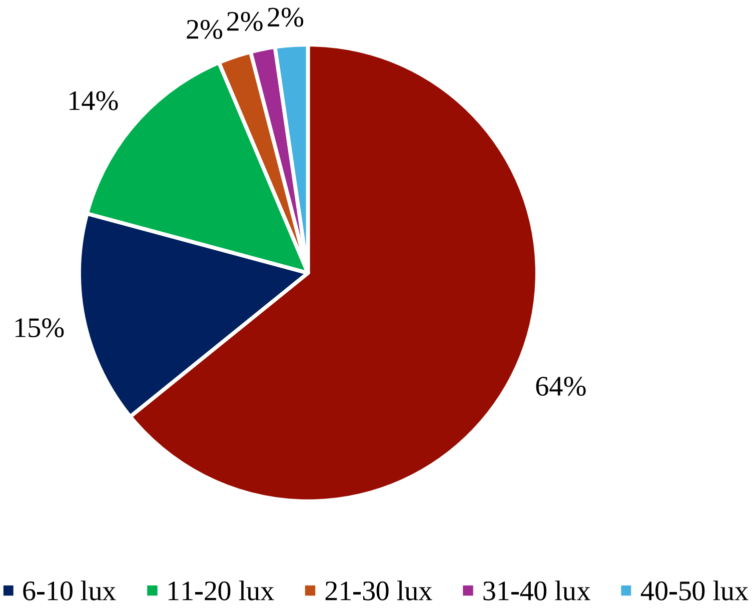

Figure 3-4. Percentage of Light Levels for Reported Lighted Pedestrian KA Nighttime Crashes

Variation in Light Levels on Reported Lighted Conditions

Figure 3-5 shows that a broad variance in illumination existed among crash sites reported as lighted and that most serious injury pedestrian crashes occurred at locations with low lighting. For instance, 68 crashes occurred at sites designated to have lighting sources present but had measured lighting levels at the site of the crash of less than 5 lux. Data show that 99 percent of crashes in dark-unlighted conditions happen in areas with less than 5 lux. This highlights the need for an objective measure of lighting when reporting crash conditions. Most crashes occurred at locations with less than 5 lux yet law enforcement officers categorized these locations as lighted due to the presence of ambient lighting fixtures not related to the location where the crash occurred. This suggests that the impact of lighting on pedestrian nighttime crashes is underestimated or inaccurately estimated when relying solely on current light conditions rating methods used by law enforcement officers.

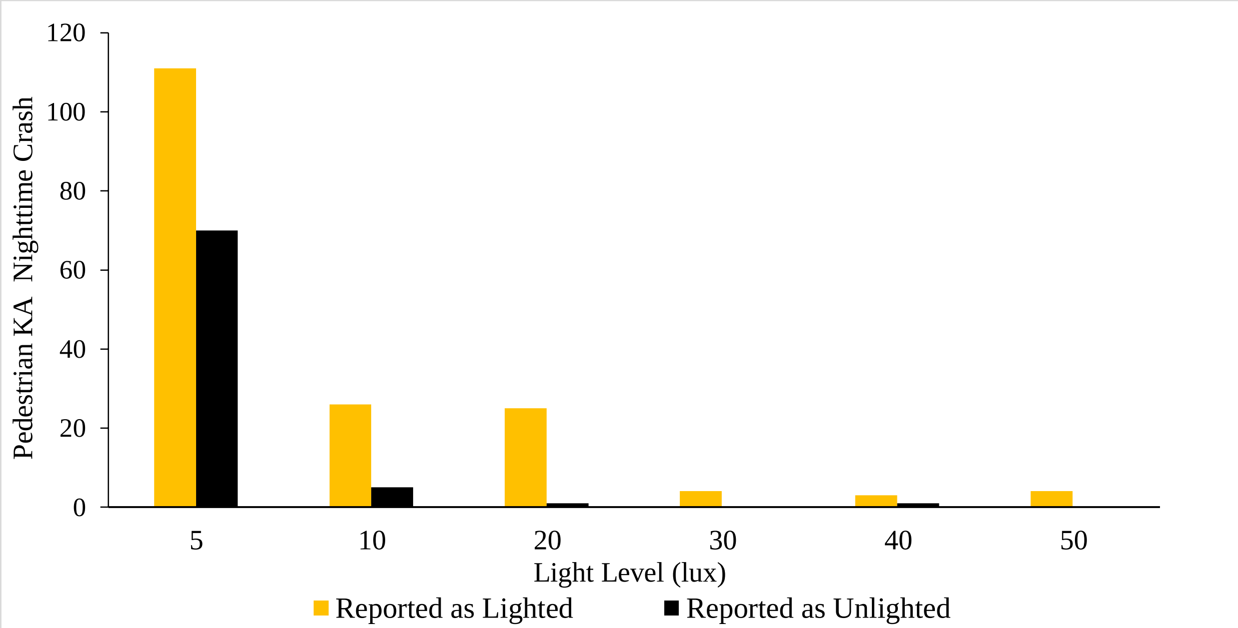

Figure 3-5. Light Readings Verified to be Similar to when Crash Occurred

3.2.3 Influence of Lighting on Pedestrian Crash Frequency

A comparative analysis was conducted across four cities to determine a relationship between the rate of pedestrian nighttime KA crashes and lighting levels. Total pedestrian KA nighttime crashes were aggregated at a city level and normalized using the city's 2022 population obtained from the U.S. Census Bureau for the Michigan cities in 2020 (U.S. Census Bureau, 2020) to enable a fair comparison. The percentage of well-lit locations was estimated for each city based on the sample of collected data, whereby well-lit locations were considered to have 20 or more lux where there is conventional legacy lighting (Edwards & Gibbons, 2008) and 10 lux or more where there is LED lighting (Bhagavathula & Gibbons, 2023). Figure 3-6 illustrates the relationship between the percentage of locations with good lighting and the rate of nighttime pedestrian crashes resulting in fatalities or serious injuries for 11 cities. Only cities with at least 9 light readings were maintained for analysis to eliminate bias from having a lower sample. Similarly, Figure 3-7 illustrates the relationship between the average light level in lux and the rate of nighttime pedestrian crashes resulting in fatalities or serious injuries the cities.

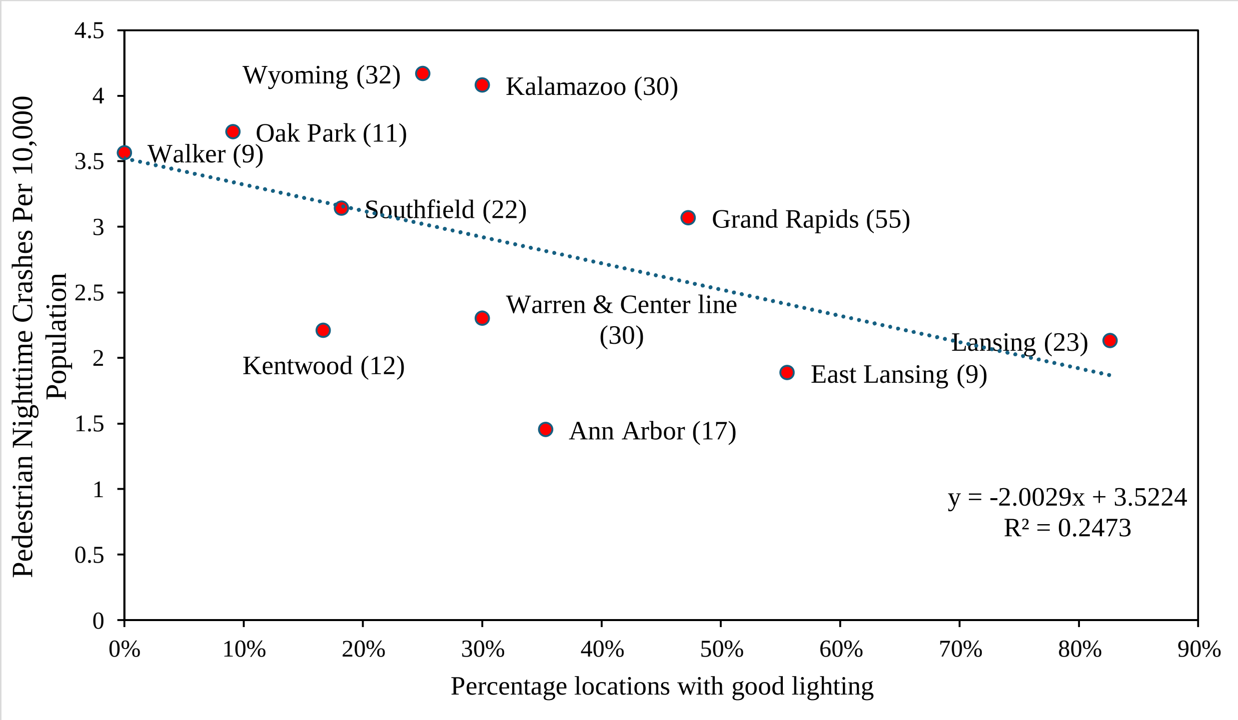

Figure 3-6. Relationship between Crashes and Percentage of well-lit locations

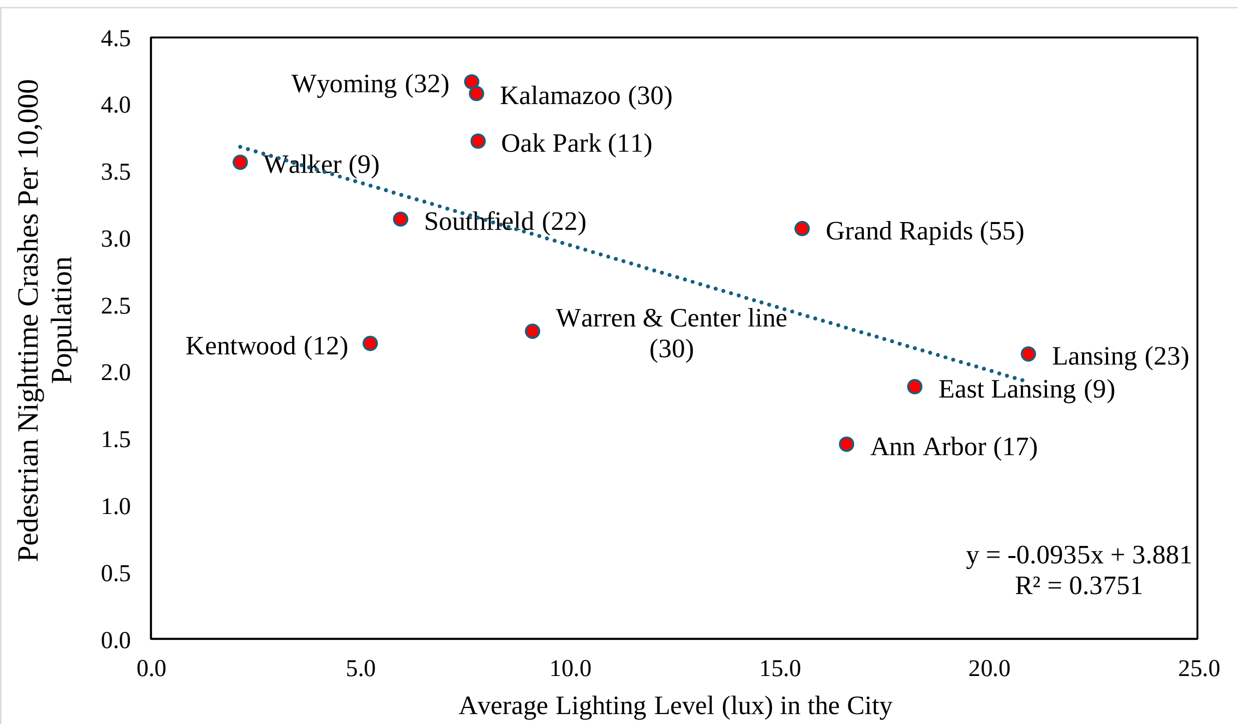

Figure 3-7. Relationship between Crashes and Average Lighting locations

The figures show a negative correlation between the percentage of well-lit locations or average good lighting in a city and the rate of pedestrian nighttime KA crashes. There is a clear trend of a decrease in pedestrian nighttime crashes with improved lighting conditions in the city. This suggests that communities with better lighting conditions overall tend to have lower rates of serious nighttime pedestrian crashes. The results emphasize the need to prioritize improving lighting in pedestrian facilities in communities as an effective measure to enhance pedestrian safety at night.

4 EVALUATING THE EFFECTIVENESS OF LIGHTING IMPROVEMENTS

4.1 Light Bars

It would be helpful to determine the value of greater adequacy of light throughout the crosswalk using light bars at traffic signals and crosswalks at uncontrolled midblock and intersection locations. Currently, there are LED light bars available that can be installed under mast arms, which can uniformly illuminate crosswalks at traffic signals. These were evaluated by measuring lighting levels before and after the light bars were installed. The WMU team used a sensitive light level meter to determine the brightness and uniformity of lighting levels before and after light bars were installed. This study explored the optimum placement of light bars to produce a uniform level of lighting in the crosswalk. Several studies conducted by Gibbons recommend illuminating crosswalks with a vertical illuminance of 20 lux from above with luminaires placed to produce positive contrast. A more recent study recommends 10 lux for LED lighting at midblock crosswalks.

In this study, light bars were installed at two signalized intersection locations in Kalamazoo. The research team obtained light measurements at these crosswalks before and after light bars were installed on the bottom of the signal mast arms. A Konica Minolta T-10A illuminance meter was used to measure light levels. Both sites were located at four-way intersections (East Paterson St. and North Burdick St, and East Paterson St. and North Rose St.) Light bars were installed by the Kalamazoo traffic engineer at both sites. The light bars were 8 ft long and cost $150 each and were strapped to the bottom of the Mast Arms and wired to the controller.

4.1.1 Light-Level Data Collection

The measurement team consisted of two persons wearing safety vests taking the lighting measurements with one person taking the readings in the roadway and the other person serving as the spotter. The spotter continuously repeated the words “clear” when no drivers were approaching the crosswalks. When a driver approached the crosswalk measurement area, the spotter said “Out of the road”. All data were collected beginning one hour after sunset under clear and dry conditions.

4.1.2 Light-Level Measurement Method

Measurements were taken at all eight departure points for each of the four crosswalks and in the middle of each travel lane in each crosswalk. The person taking the light level readings stood in each measurement location. Vertical illuminance was measured at a height of 1.5 m (5 ft.) from the surface of the roadway using a Minolta T10A illuminance meter. Light levels were measured before and after the light bars were installed at each location.

4.1.3 Results

Tables 4.1 and 4.2 show the light levels in lux before and after the light bars were installed, and the difference in light level at each of the measurement sites at the intersection of E Patterson St. and N Rose St and E Patterson St and N Burdick St respectively. Both Tables show that with the installation of light bars, more lux is achieved, higher than that recommended by the Gibbons study hence better visibility.

Table 4-1. Light Level in Lux Street Lights Alone (SLA) and Street Lights plus Light Bars (Bars) and the difference in Lux Between the Two (Diff) at the Crosswalks of N. Patterson St. at N. Rose St.

	North			East			South			West		
Leg	SLA	Bars	Diff	SLA	Bars	Diff	SLA	Bars	Diff	SLA	Bars	Diff
Curb 1	11.11	30.48	19.37	1.96	14.83	12.87	17.88	41.80	23.92	5.41	20.74	15.33
Lane 1	9.97	21.29	11.32	2.87	56.40	53.53	16.22	123.70	107.48	5.94	121.30	115.36
Lane 2	6.62	101.60	94.98	3.46	125.30	121.84	13.78	164.50	150.72	6.31	147.60	141.29
Lane 3	3.37	66.80	63.48	5.11	65.00	59.89	10.10	45.80	35.70	8.26	101.20	92.94
Lane 4				7.83	16.94	9.11				9.19	94.60	85.41
Curb 2	2.51	28.53	26.02	8.17	14.93	6.76	19.56	23.15	3.59	10.18	70.40	60.22
Mean	6.72	49.74	43.03	4.9	48.9	44	15.51	79.79	64.28	7.55	92.64	85.09

Table 4-2. Light Level in Lux Street Lights Alone (SLA) and Street Lights plus Light Bars (Bars) and the difference in Lux Between the Two (Diff) at the Crosswalks of N. Patterson St. at N. Burdick St.

	North			East			South			West		
Leg	SLA	Bars	Diff	SLA	Bars	Diff	SLA	Bars	Diff	SLA	Bars	Diff
Curb 1	1.75	28.33	26.58	9.43	78.40	68.97	23.12	40.30	17.18	18.09	41.90	23.81
Lane 1	2.14	94.00	91.86	9.87	126.20	116.33	23.74	78.30	54.56	16.74	28.30	11.56
Lane 2	4.23	190.30	186.07	10.32	182.40	172.08	24.03	203.50	179.47	14.46	99.40	84.94
Lane 3	5.38	101.50	96.12	11.58	105.50	93.92	24.55	67.70	43.15	11.19	200.50	189.31
Lane 4				12.66	31.40	18.74				6.69	91.81	91.81
Curb 2	6.72	51.9	45.18	13.69	23.56	9.87	24.67	42.40	17.73	2.59	24.44	21.85
Mean	4.04	93.21	89.16	11.26	91.24	79.99	24.02	86.44	62.42	11.63	81.06	70.55

Figure 4-1 shows the light readings for E Patterson St. and N. Rose St for the baseline condition and lightbar conditions. Figure 4-2 shows photographs of a pedestrian standing at the entry point at the crosswalk at E. Paterson St. at N. Rose St. The left frame shows the person crossing under legacy street lighting while the right frame shows a picture of the person crossing with the street lighting plus the light bars. Figure 4-3 shows the light levels before and after the light bars were installed at E. Paterson St. and Rose St. The differences are readily apparent for all locations.

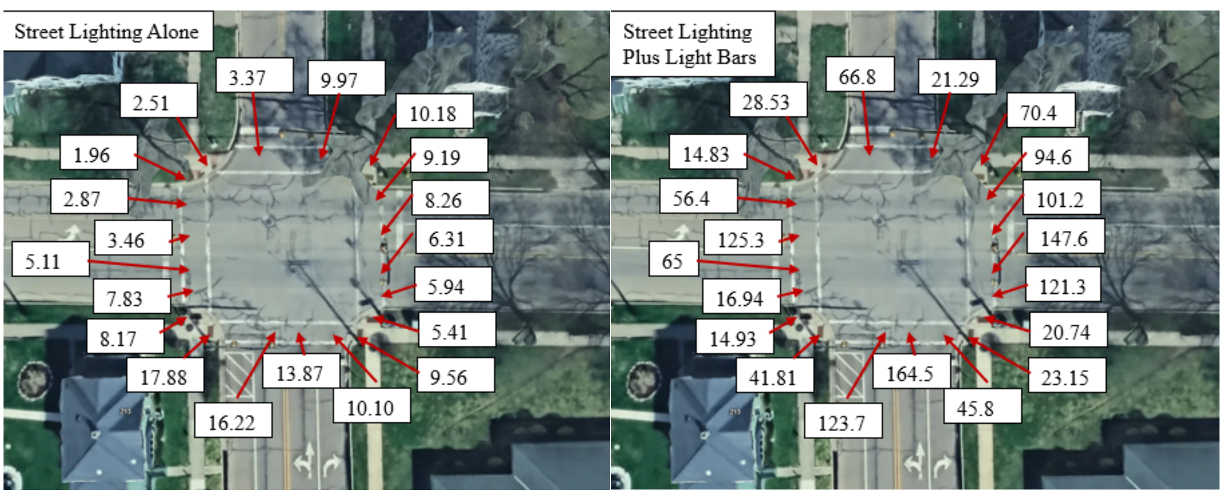

Figure 4-1. Light readings for baseline and lightbar lighting levels superimposed over a map of the location E Patterson St. and N. Rose St.

Figure 4-2. Picture showing how drivers see a pedestrian on traditional lights versus light bars

These data show that 8 ft. long light bars can light an entire crosswalk including both entry points. These light bars can be economically installed at on mast arms provided the mast arm is located above or nearly above the crosswalks. Finding other economical ways to use light bars at locations without mast arms should be a priority in future research.

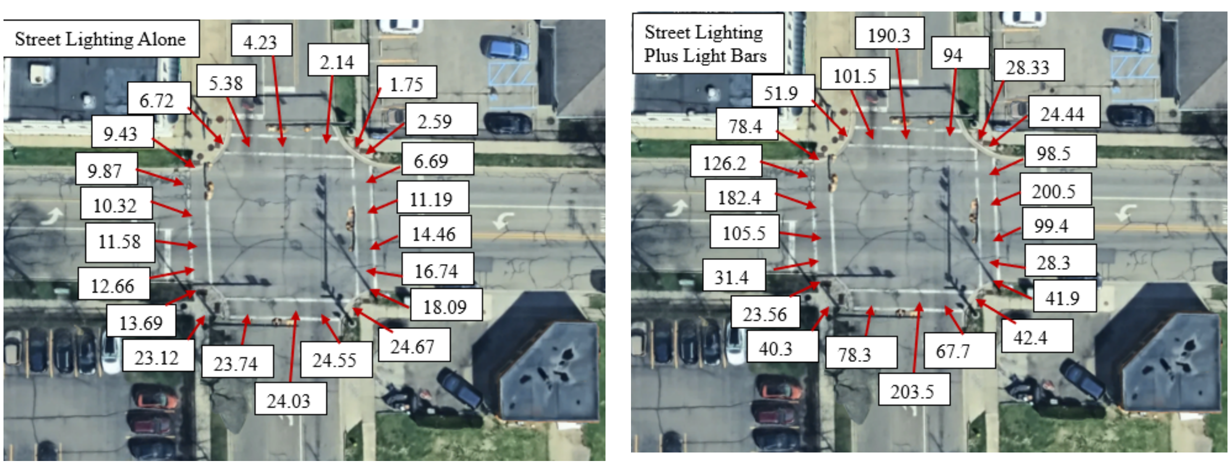

Figure 4-3. Light readings for baseline condition and lightbar conditions for E Patterson St. and N. Burdick St.

4.2 Smart Lighting and RRFB

Lighting and visibility are important components of a safety strategy for pedestrians. For example, comparisons of pedestrian fatalities before and after transitions with daylight savings time have shown consistently that holding all other factors constant, brighter lighting conditions are associated with fewer pedestrian deaths. The distribution of lighting is also emerging as an important factor, because rather than providing a "blanket" of light along the roadway surface, only lighting the area where the pedestrian is crossing attracts the driver's attention to the pedestrian in the crosswalk. Treatments in place at midblock crosswalks include high visibility crosswalk markings, the Hybrid beacon, the Rectangularly Rapid Flashing Beacon, Refuge Islands, and Advance Stop Lines. Because most serious pedestrian crashes occur at night it is critical to include these safety countermeasures with lighting.

Rajaram and Gibbons (2023) examined the efficacy of five midblock lighting designs with two crosswalk treatments: an RRFB and a flashing pedestrian sign. The LED luminaires had a lateral width of 25 degrees and were installed on the edge of the roadway on the crosswalk line either on the approach side of the crosswalk (positive contrast) or the exit side of the crosswalk (negative contrast). They also varied the amount of illumination. The dependent measure was recognition distance. One important finding was that recognition distance increased with increased brightness but attained high levels with a lighting level of 10 lux and only marginally improved at 20 lux with LED lighting. These data suggest that 10 lux may be an adequate level with LED lighting. However, with excess lighting on the side of the road and approaching headlights, the performance of lights that produce 20 lux is likely to be superior to lighting at 10 lux.

One approach that has not been systematically examined is increasing the lighting level when a pedestrian enters a crosswalk. Not only does this approach decrease light pollution, but it also can alert the driver that a pedestrian is initiating a crossing. If this approach proves effective it could be a low-cost way to increase the visibility of pedestrians crossing at night while the stimulus onset of the light would also alert drivers to pay attention to the area with increased illumination. Another advantage of this approach is that requiring less power, it can be operated with a battery charged by a solar array. This study tests this countermeasure at crosswalks at night at dark intersections and at lighted intersections. In the case of the dark intersections, it would “turn on the lights” when the pedestrian enters the crosswalk, and in the latter case it would intensify the lighting when the pedestrian enters the crosswalk. If this approach proves effective, it could also be used in a smart city to alert drivers of pedestrians detected entering the road at both midblock and intersection crosswalk locations. However, for drivers to learn that the onset of increased crosswalk lighting is associated with the presence of a pedestrian crossing the street, such a system (or systems) would need to be installed at crosswalks over an extended period. The purpose of this study is to test a system that is now commercially available and being installed at several locations in Kalamazoo using products from different vendors to determine its efficacy.

4.2.1 Light-Level Data Collection

Data was collected at three midblock crosswalks, one on a road with one travel lane in each direction and a refuge island in the turn lane (Parkview Avenue at Barnard Avenue); one on a four-lane road with two travel lanes in each direction, and a refuge island in the middle of the road (Howard Street at Waite Avenue); and at a third site with three lanes in each direction and a refuge island in the middle (West Michigan Avenue at Academy Street) shown on Figure 4-4. At all three sites, there were Rectangular Rapid-Flashing Beacons (RRFBs) and smart lighting (lights aimed at the crosswalk that light up when the pedestrian crosses). Each RRFB was purchased from a different manufacturer that sold RRFBs that included a different on-demand smart lighting system. The Howard Street site also had advanced stop lines and signs. The light levels were measured using a Minolta T10A light level meter. The speed limit on Parkview Avenue was 30 mph, the speed limit on Howard Street was 40 mph, and the speed limit on West Michigan Ave was 35 mph.

(a) Parkview Avenue at Barnard Avenue (b) Howard Street at Waite Avenue

(c) West Michigan Avenue at Academy Street

Figure 4-4. Three sites where Smart Lighting and RRFB were Evaluated

4.2.2 Light-Level Measurement Method

The person taking the light level readings stood in each measurement location and measured the vertical illuminance at a height of 1.5 m (5 ft.) from the roadway's surface. Light levels were established at each location when the smart light was off and when the smart light was on. The light levels for each condition were measured at each departure point and in the center of each lane. The light readings at each of the three crosswalks during each condition at each crossing location during the smart light “off” condition and the smart light “on” condition and the difference between the two readings in Lux are summarized in tables.

4.2.3 Drivers' Speed Data Collection

All data were collected beginning one hour after sunset under clear and dry conditions. Staged crossings always followed a specific safe crossing protocol. First, the pedestrian placed one foot in the crosswalk when an approaching vehicle was just beyond the dilemma zone. Second, a spotter repeatedly called out to the crosser through a walkie-talkie earpiece the words "STAY" and only switched to "CLEAR" once it was confirmed the vehicle was stopping. If the vehicle did not attempt to stop, the staged pedestrian did not proceed to cross the street, and the vehicle was scored as not yielding. If the vehicle began to yield and the next lane was free, the staged pedestrian began crossing. The staged pedestrian was always prompted to stop at the lane line and make sure the next lane was clear and that the spotter again stated "clear" before completing the crossing. If a large gap appeared the staged pedestrian also finished the crossing. This is the protocol followed by police officers when they conduct pedestrian crossing enforcement sting operations. This protocol ensures the safety of the staged pedestrians. Actual pedestrians using the crossing being observed were only scored if they initiated the crossing in the same manner as the staged pedestrian by placing at least one foot in the crosswalk.

Research Design. A multiple baseline across crosswalks design was employed in this study. In a multiple baseline design data are independently collected at two or more locations. After sufficient stable data are collected the treatment is introduced at the first site while the second site remains in the baseline condition. Once the effect of the treatment has been determined at the first site, the treatment is introduced at the second site. Introducing the treatment at different points in time controls for other variables that may have been responsible for the change if all sites were treated at the same time.

Staged pedestrians begin to cross as a driver approaches the distance marking at the dilemma zone. To control for the reflectance of the pedestrian's clothing, the pedestrian wore dark clothing without any reflective material. During the baseline condition data were collected under the unlighted condition without activating the RRFB or the smart lighting system. After behavior stabilized at the first crosswalk during the baseline condition the RRFB treatment was introduced at this crosswalk. After data stabilized during the RRFB condition at the first crosswalk the RRFB treatment was at introduced at the second crosswalk. Next the smart lighting was activated along with the RRFB at the first crosswalk while the second crosswalk remained in the RRFB alone condition. Once data have stabilized this under the RRFB and smart lighting condition at the first crosswalk the smart lighting treatment was added at the second crosswalk. Each data collection session consisted of 20 crossings at each site.

4.2.4 Drivers' Speed Measurement Method

Speed data were measured using the Falcon HR K-Band Doppler traffic radar operating at 24150 MHz. This device was manufactured by Kustom Signals, Inc., and it included a certificate of accuracy. The accuracy was periodically verified using a Kustom K-Band Tuning Fork SN 81695. Data were recorded for all vehicles as they crossed the dilemma zone and again as they drove over the crosswalk to calculate the speed changes of vehicles not yielding to the pedestrians at all four study sites. The measurement team consisted of a decoy pedestrian who made staged crossings, and a spotter to ensure the safety of the person making the crossing, who periodically exchanged roles during the session. A third team member measured speed with a radar device. A fourth team member recorded yielding behavior.

The following two measures were recorded for all drivers approaching the crosswalk when pedestrians were initiating a crossing.

Yielding to Pedestrians

Drivers yielding right-of-way to pedestrians in crosswalks were measured using a standard recording sheet at each marked midblock crosswalk. Yielding right of way to the pedestrian in a crosswalk was defined as the driver stopping or slowing to allow the pedestrian to cross the street. A yielding violation was defined as a driver who was able to safely yield right of way to the pedestrian, but who proceeds through the crosswalk without stopping or slowing to allow the pedestrian to cross. This behavior was scored as not yielding to the pedestrian. In the case of multiple vehicles, only the behavior of the driver in the first vehicle was scored.

Driver yielding was determined for approaching vehicles that were beyond an objective dilemma zone (a location beyond which a driver can easily yield if a pedestrian enters the crosswalk). The ITE signal timing formula used to calculate whether a driver could have safely stopped at a traffic signal, was used to determine whether a driver could have stopped for a pedestrian standing with one foot in the crosswalk. This formula considers an appropriate driver reaction time, a safe deceleration rate, the posted speed, and the grade of the road to calculate this interval for the yellow traffic light. This formula was used to determine the distance to the dilemma zone boundary by multiplying the calculated time by the posted speed limit in feet per second. To aid observers in identifying the dilemma zone, the zone was marked by using a natural feature in the environment which was readily visible at night. For example, at Howard at Waite had a clearly visible light post at the dilemma zone. We used a reflective barrel moved to the dilemma zone at W. Michigan Ave and Academy Ave.

Motorists who had not passed the outer boundary of the dilemma zone when a pedestrian entered the crosswalk were scored as yielding or not yielding because they had sufficient time and space to stop safely for the pedestrian. Motorists who entered the dilemma zone before the pedestrian placed a foot in the crosswalk could be scored as yielding, but could not be scored as failing to yield because the motorist was not legally required to yield at this distance. However, the signal timing formula employs lenient criteria hence, many vehicles that pass the dilemma zone could yield safely, particularly those traveling below the speed limit.

Driver speed changes.

Speed data were measured using the Falcon HR Microwave Radar. The radar operator sat in a chair concealed with a black sign with a 5ft bicycle passing sign placed above the black sign. Drivers of vehicles approaching the crosswalk and passing the sign could not see the radar operator who obtained the speed of retreating vehicles. The radar operator recorded vehicle speeds as the vehicle crossed the dilemma zone and again as they traversed the crosswalk. This allowed the research team to compute speed changes for all vehicles driven by drivers who did not yield to the pedestrian. Because the observer was located two feet from the roadway there was no significant cosine error. In the case of multiple vehicles, speed was recorded only for the first vehicle in the queue.

4.2.5 Results

Light Level at the Crosswalks

Tables 4.3, 4.4, and 4.5 show the light levels in Lux with street lighting alone, with the smart lighting activated, and the difference for each of the three sites. These measurements are shown graphically in Figures 4-5, 4-5 and 4-8, respectively. Figures 4-7 and 4-9 show how drivers see a pedestrian when smart lighting is on and off. At Parkview Ave at Barnard Ave and at Howard St. at Waite Ave sites light levels were consistently very low during the before or baseline (BL) condition and consistently over 10 lux during the smart lights condition. At the W. Michigan Ave at Academy St. site, the light levels during the baseline condition were consistently close to or above the 10 lux criteria for LED lighting.

Table 4-3. Light Level in Lux Street Lights Alone (SLA) and Street Lights plus Smart Lighting (Smart) and the difference in Lux Between the Two (Diff) at the Crosswalk of Parkview Ave. at Barnard Ave.

Leg	SLA	Smart	Diff
Curb 1	2.32	54.20	50.80
Lane 1	4.17	28.10	50.90
Island 1	7.00	50.90	43.90
Island 2	18.62	53.70	35.08
Lane 2	21.09	59.60	38.51
Curb 4	23.31	46.35	23.04
Mean	12.75	48.81	40.37

Figure 4-5. Lighting levels at each location in crosswalk with street light alone (left frame) and Street light plus smart lighting (right frame).

Table 4-4. Light Level in Lux Street Lights Alone (SLA) and Street Lights plus Smart Lighting (Smart) and the difference in Lux Between the Two (Diff) at the Crosswalk of Howard St. at Waite Ave.

Leg	SLA	Smart	Diff
Curb 1	1.72	104.20	102.48
Lane 1	1.64	87.20	85.56
Lane 2	1.45	52.90	51.45
Island 1	1.31	13.09	11.78
Island 2	1.12	12.78	11.66
Lane 3	1.01	29.00	27.99
Lane 4	0.82	105.50	104.68
Curb 2	0.47	84.10	83.63
Mean	1.19	61.10	59.90

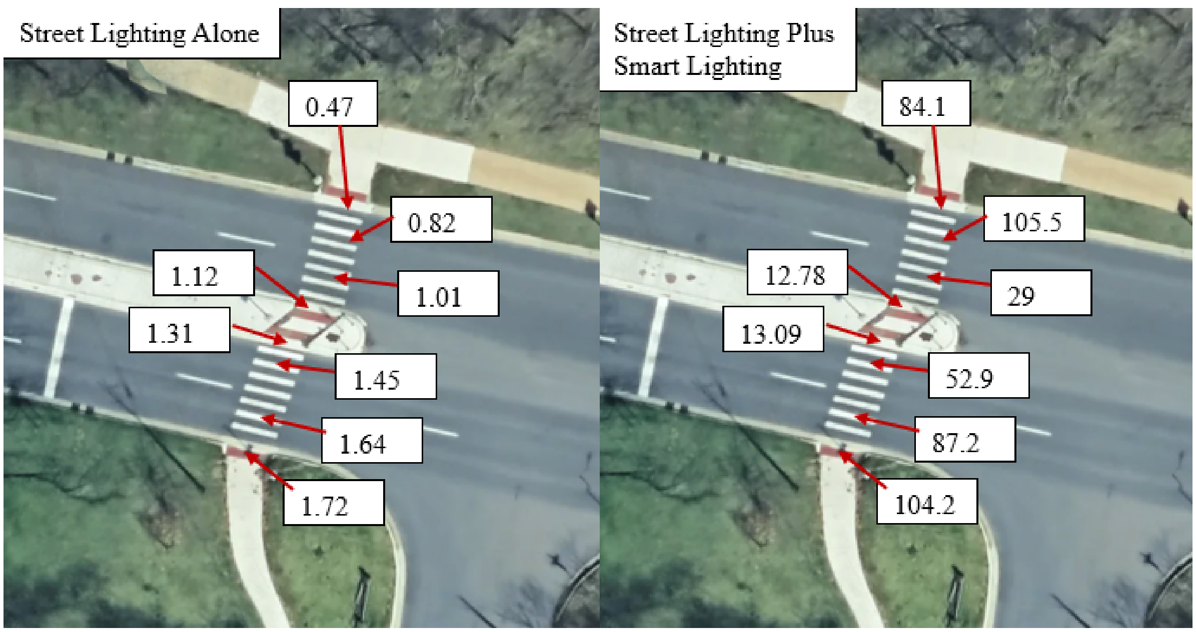

Figure 4-6. Lighting levels at each location in crosswalk with street light alone (left frame) and Street light plus smart lighting (right frame).

Figure 4-7. Picture showing how drivers see a pedestrian on at Howard St. and Waite St. when the smart lighting was off (left frame) and when the smart lighting was on (right frame).

Table 4-5. Light Level in Lux Street Lights Alone (SLA) and Street Lights plus Smart Lighting (Smart) and the difference in Lux Between the Two (Diff) at the Crosswalk of Western Michigan Ave. at Academy St.

Leg	SLA	Smart	Diff
Curb 1	7.69	133.90	126.21
Lane 1	8.15	100.40	92.25
Lane 2	11.21	27.49	16.20
Island 1	6.80	9.46	2.66
Island 2	8.45	9.65	1.20
Lane 3	8.37	19.75	11.38
Lane 4	16.77	44.60	27.83
Lane 5	30.90	102.30	71.40
Curb 2	29.70	88.10	58.40
Mean	14.23	59.52	45.28

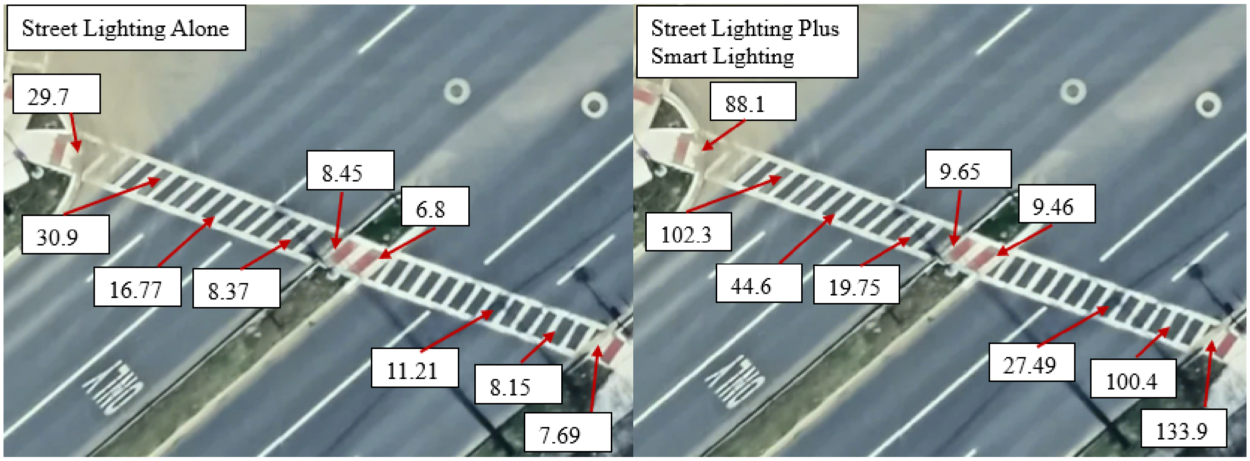

Figure 4-8. Lighting levels at each location in the crosswalk at W. Michigan Ave. and Academy St. with street light alone (left frame) and Street light plus smart lighting (right frame).

Figure 4-9. Picture showing how drivers see a pedestrian on at Howard St. and Waite St. when the smart lighting was off (left frame) and when the smart lighting was on (right frame).

Figure 4-10 shows the percentage of drivers yielding to pedestrians during each condition of the experiment. The top frame shows the percentage of drivers yielding to pedestrians at the crosswalk at Howard Street at Waite Avenue, the middle frame shows driver-yielding data for the crosswalk at Parkview Avenue and Barnard Avenue, and the bottom frame shows the driver-yielding data for the crosswalk at West Michigan Avenue Academy Street. When the RRFB was not activated, and smart lighting was absent yielding at the Howard Street at Waite Avenue site yielding averaged 1%. When the RRFB was activated alone yielding increased to an average of 25%. When the RRFB plus smart lighting was activated, driver yielding to pedestrians increased to 61%.

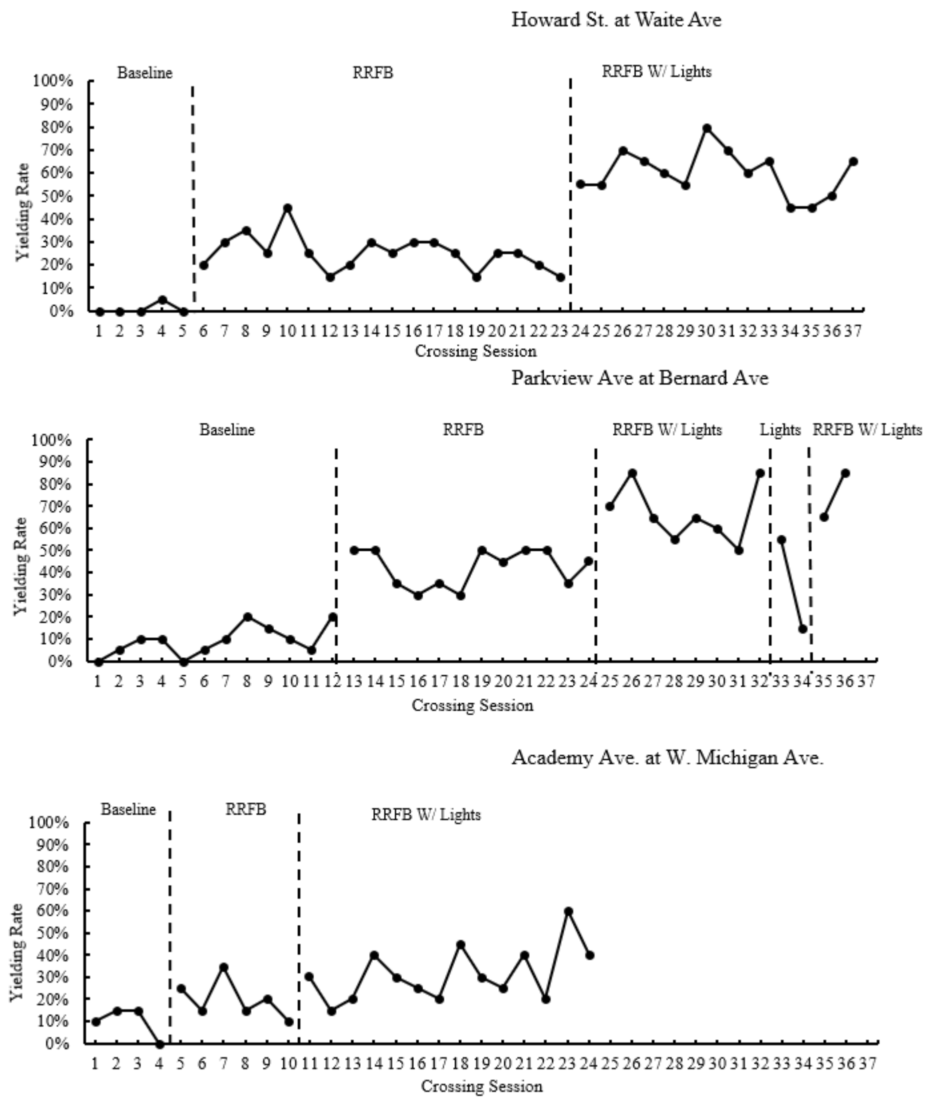

Figure 4-10. Percentage of drivers yielding to pedestrians at each of the three sites.

The middle frame shows the percentage of drivers yielding to pedestrians at the Parkview Ave at site. The percentage of drivers yielding to pedestrians averaged 9% during the baseline condition when the RRFB and the smart lighting was not activated. During the RRFB alone condition yielding increased to an average of 42%. When the RRFB and smart lighting were activated together yielding increased to 67%. When the smart lighting was activated alone for two sessions yielding decreased to 35%. When the RRFB and smart lighting were activated together again yielding increased to 75%. At the W. Michigan Site yielding averaged 10% during baseline, increased to 20% during the RRFB condition and 26% during the RRFB and smart light condition.

Speed Reduction

Figure 4.11 shows the average speed reduction of drivers who failed to yield to pedestrians during baseline and during sessions one or both light types activated when a pedestrian entered the crosswalk. The top frame shows the average speed reduction made by drivers who did not yield to the pedestrian in the crosswalk during the baseline and lighted condition at the crosswalks at Howard Street at Waite Avenue, the middle frame shows the average speed reduction made by drivers that failed to yield to the pedestrian during each condition at the crosswalk at Parkview Avenue and Barnard Avenue, and the bottom frame shows the average speed reduction made for the crosswalk at West Michigan Avenue Academy Street. When the RRFB was not activated, and smart lighting was absent the average speed reduction was 0.5 mph for drivers who did not yield to pedestrians When the RRFB was activated alone the average speed reduction of drivers who did not yield right of way to the pedestrians was 2.2 mph. When the RRFB plus smart lighting was activated, the average speed reduction by drivers who did not yield to pedestrians increased to 6.9 mph.

At Parkview Avenue and Barnard Avenue when the RRFB was not activated, and smart lighting was absent the average speed reduction was 0.4 mph. When the RRFB was activated alone the average speed reduction of drivers not yielding to pedestrians was 2.6 mph. When the RRFB plus smart lighting was activated, the average speed reduction by drivers who did not yield to pedestrians increased to 9.3 mph. A two day return to the baseline condition was associated with the speed reduction of 3.7 mph. A return to RRFB plus smart lighting at this site was associated with an 8.3 mph decrease in the speed of nonyielding drivers.

At the W. Michigan Ave. at Academy St. site the average reduction in speed during the baseline condition for drivers who did not yield to the pedestrian was 3.1 mph. During the RRFB alone condition the average speed reduction was 9.3 mph and during the RRFB plus smart light condition the average speed reduction was 7.6 mph.

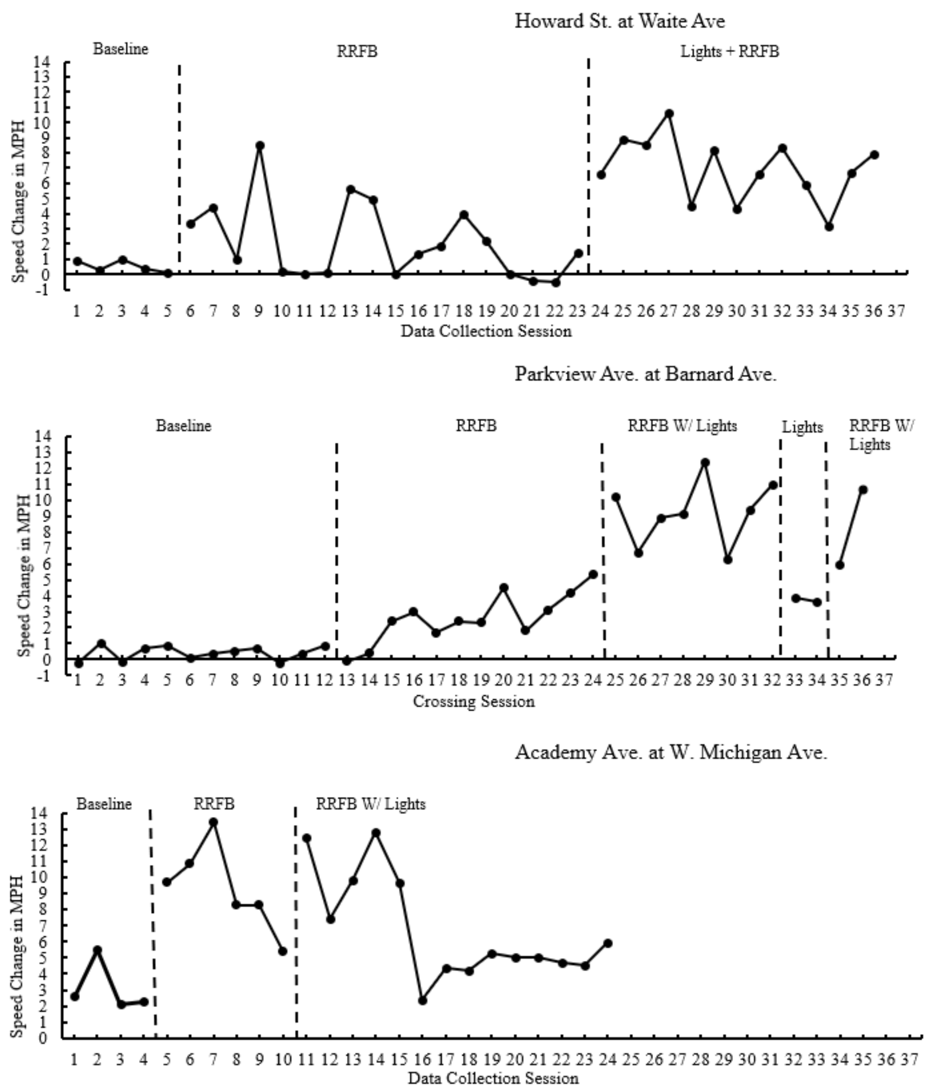

Figure 4-11. The average speed reduction during each session was made by drivers who did not yield to the pedestrian in the crosswalk.

The results of this experiment showed that products that add lighting when an RRFB is activated led to an increase in the percentage of drivers yielding to pedestrians at all three experimental sites. The result also showed that the addition of on demand or smart lighting led to a large reduction in the speed of vehicle driven by drivers who did not yield to two sites which had low ambient levels of street lighting and failed to produce a reduction at a third site with a higher ambient lighting level.

4.3 Evaluation of Smart Lighting Alone at a Unsignalized and a Signalized Crosswalk

Unsignalized Location. During this study push button smart lighting was added to an unsignalized marked crosswalk on Oakland Drive at the T intersection at Edgewood Drive. Oakland Drive had one lane in each direction and a turning lane. The measures of driver yielding rate and the slowing behavior of drivers not yielding to pedestrians was measured in the same manner as described in the study at RRFB locations. The speed limit on Oakland Drive was 35 mph. Table 4.6 shows the Light Level in Lux of Street Lights Alone (Alone) and with Smart Lights (Smart Lighting) and the difference in Lux (Diff) at the crosswalk on Oakland Drive at the T intersection with Edgewood Drive. These are shown in the intersection layout in Figure 4-12. The average light level was 2 lux in absence of the smart lighting intervention and increased to 45 lux when the lights were activated. The percentage of drivers

Table 4-6. Light Level in Lux Street Lights Alone (SLA) and Street Lights plus Smart Lighting (Smart) and the difference in Lux Between the Two (Diff) at the Northern Crosswalk of Oakland Dr. and Edgewood Dr.

Leg	SLA	Smart	Diff
Curb 1	4.64	95.90	91.26
Lane 1	1.96	80.20	78.24
Lane 2	2.38	18.11	15.73
Lane 3	0.58	21.09	20.51
Curb 2	0.34	8.61	8.27
Mean	1.98	44.78	42.80

Figure 4-12. Lighting levels at each location in crosswalk with street light alone (left frame) and Street light plus smart lighting (right frame) at Oakland Dr. and Edgewood Drive.

Yielding to pedestrians during the streetlight alone and streetlight plus smart lighting conditions are presented in the top frame of Figure 4-13. These data show that drivers do not yield right of way to pedestrians at this site and the addition of lighting only adds a small amount to the level yielding with baseline levers of yielding at 0% and yielding levels of 3% with lights when the button is pressed. Driver slowing at the crosswalk in mph is shown in the lower frame of Figure 4-13. During baseline when the crosswalk light was not illuminated driver speed change for nonyielding drivers averaged 0 mph. During the Push Button light condition drivers speed reduction for non-yielding drivers averaged 2.15 mph.

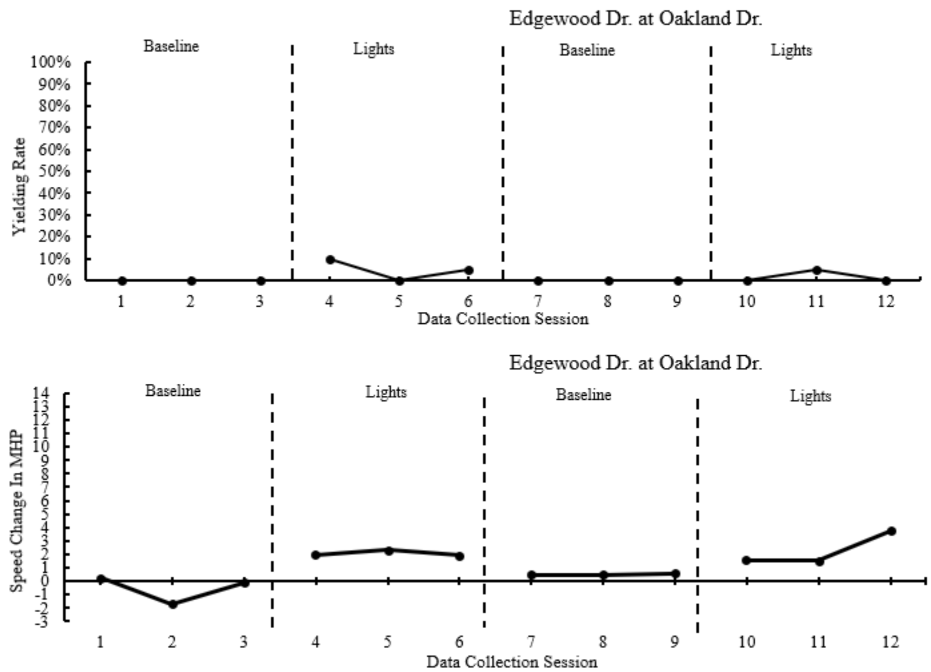

Figure 4-13. The top frame shows the percentage of drivers yielding to pedestrians during each data collection session for the baseline and lighting conditions, the bottom frame shows the speed change during each observational session during each condition

Figure 4-14. Photo of pedestrian standing at the departure point with smart light off (left frame) and smart light on (right frame) at Oakland Dr. and Edgewood Dr.

The results of this study showed that drivers did not yield at the marked crosswalk at an unsignalized intersection and the lighting activated when a pedestrian was crossing had little effect on the percentage of drivers yielding to pedestrians but was associated with a small 2 mph decrease in the speed of vehicles driven by drivers who did not yield to the pedestrian.

Signalized Location. During this study push button smart lighting was added to a signalized intersection of Oakland Drive and Parkview Avenue. Oakland Dr. has one through lane and right turn and left turn lane in each direction. Parkview Ave has one through lane in each direction and one left turn lane in each direction. Driver yielding behavior and speeds were not measured in this study. The measures of driver yielding behavior and the slowing behavior of drivers not yielding to pedestrians was measured in the same manner as described in the study at RRFB locations. The speed limit on Oakland Drive and Parkview Drive at this location was 30 mph. Table 4.7 shows the Light Level in Lux of Street Lights Alone (Alone) and with Smart Lights (Lighting) and the difference in Lux (Diff) at the signalized crosswalk on Oakland Drive at the intersection of Parkview Drive. At this site, additional lighting was added when the pedestrian pushed the call button for the leg they selected to cross. Lighting was provided by standard LED crosswalk lights.

Table 4-7. Light Level in Lux Street Lights Alone (SLA) and Street Lights plus Smart Lighting (Smart) and the difference in Lux Between the Two (Diff) at the Crosswalk of Parkview Ave. and Oakland Drive.

	North			East			South			West		
Leg	SLA	Smart	Diff	SLA	Smart	Diff	SLA	Smart	Diff	SLA	Smart	Diff
Curb 1	8.90	8.04	0.76	1.76	3.73	1.96	6.80	113.50	106.70	1.57	63.20	61.63
Lane 1	2.23	44.80	42.57	1.69	24.12	22.43	2.89	50.50	47.61	1.72	35.30	33.58
Lane 2	2.61	13.90	11.29	1.29	10.09	8.80	1.42	14.91	13.49	1.66	11.67	10.01
Lane 3	1.88	5.85	3.97	1.25	4.86	3.61	1.33	5.96	4.63	3.10	7.36	6.03
Lane 4	1.94	3.30	1.36				1.40	2.19	0.79			
Curb 2	1.60	1.72	0.12	1.33	2.39	1.06	1.59	1.64	0.05	7.21	10.95	3.74
Mean	3.19	12.94	10.01	1.46	9.04	7.57	2.57	31.45	28.88	3.05	25.7	23.00

Figure 4-15. Lighting levels at each location in crosswalk with street light alone (left frame) and Street light plus smart lighting (right frame) at Oakland Dr. at Parkview Ave.

At the signalized intersection the replacement of traditional luminaires streetlights which produced poor crosswalk lighting during baseline with LED luminaires activated on demand produced large increase in overall lighting levels but it did not produce the overwhelming change at all curb side and lane lighting similar to that produced by the light bars in the first study. Many measurement positions still had lower lighting than the recommended standard. Because each crosswalk was illuminated by one luminaire mounted on each of four light poles this situation could be remedied by mounting two arms on each pole for a total of 8 luminaries. This would greatly improve lighting levels at all locations. On-demand lighting has another advantage at these sites. Since the lights were only on when pedestrians cross rather than continuously throughout the night, there would be substantial energy savings. If manufactures could determine a way to install lightbars on standard lighting posts it could produce a better quality of lighting for pedestrians. Alternatively, manufacturers could install two luminaires on each post which should lead to more consistent lighting.

4.4 Statistical Analysis

The t-test was used to analyze differences in the average speed of drivers at the dilemma point and the crosswalk under different lighting conditions for those who did not yield to pedestrians. Table 4.8 summarizes the results. The findings indicate that during dark conditions, drivers did not slow down for pedestrians at the crosswalk on Howard St and Waite Ave, and Parkview Ave and Barnard Ave. However, when pedestrians activated the RRFB, drivers at these locations reduced their speed by approximately 2 mph. With the combination of smart lighting and RRFB, drivers significantly reduced their speed at the crosswalk by approximately 6 mph or more.

Table 4-8. T-Test results on speed difference for different conditions

Site	Dark				RRFB				Lighted			
	DP	**CW**	**Diff**	**p**	**DP**	**CW**	**Diff**	**p**	**DP**	**CW**	**Diff**	**p**
Howard St. & Waite Ave	38.7	39.2	0.5	0.25	37.9	36.0	-1.9	0.00	38.5	32.2	-6.4	0.00
Parkview Ave & Barnard Ave	34.4	34.0	-0.4	0.15	35.0	32.3	-2.6	0.00	34.8	27.4	-7.4	0.00
Academy St. W. Michigan Ave	31.5	28.4	-3.1	0.00	33.0	29.1	-3.9	0.00	32.4	28.2	-4.2	0.00
Edgewood Dr. & Oakland Dr.	33.2	33.2	0.0	0.50	-	-	-	-	33.6	31.4	-2.2	0.00

At the crosswalk on Academy St and W Michigan Ave, there was a significant speed reduction under all three conditions, although a slightly greater reduction (4.2 mph) was observed during lighted conditions. This crosswalk likely benefited from ambient lighting from nearby sources, meaning the baseline condition was not entirely dark, which may have influenced the results. Lastly, at the crosswalk on Edgewood Dr and Oakland Dr, where only smart lighting was implemented and evaluated, a speed reduction of 2.2 mph was observed. These results highlight the effects of lighting and driver behavior toward pedestrians across different conditions. Locations that received improved lighting compared to the baseline condition, such as Howard St & Waite Ave and Parkview Ave & Barnard Ave, showed significant speed reductions among drivers.

5 COST-BENEFIT ANALYSIS

5.1 Introduction

This chapter summarizes the cost-benefit analysis that has been conducted in an attempt to explore the cost-benefit of examined improvements to lighting for pedestrian crosswalks. As documented in Chapter 4, enhanced lighting significantly improves light levels at crosswalks during nighttime. This leads to better drivers' yielding behavior and reduced vehicle speeds, ultimately enhancing pedestrian safety. The chapter covers various data used, cost-benefit analysis, and results. The benefits were calculated based on crash reductions, while the costs accounted for fixtures or units, installation, and ongoing operation and maintenance expenses.

5.2 Data Used

5.2.1 Lighting Improvements Costs

The cost of lighting improvements was based on agencies that installed respective systems at the sites where the lights were evaluated as described in Chapter 4. Table 5.1 summarizes the average costs of these improvements and service years. It is important to note that these costs may vary depending on specific site conditions. For instance, both installation and operational costs may vary depending on the contractor, the proximity of electric poles from the site, and the electricity providers servicing the area.

Table 5-1. Lighting treatment costs and service life

Treatment	Fixture/Unit ($)	Installation Cost ($)	Total Cost per Site ($)	Yearly Operation /Maintenance Cost ($)	Service Life (Years)
Light bars	170 - 800	2,000	2,680 - 5,200	200	15
Smart lighting alone	500 - 1,000	2,500	3,000-3,500	200	15
Smart lighting with RRFB	8,000 - 24,000	3,600 - 6,000	11,600-30,000	200	15

5.2.2 Crash Costs

The Societal Costs of Traffic Crashes and Crime in Michigan (2023 update) was used to estimate the cost of crashes (St Louis et al., 2023). The average cost of a crash was estimated to be $65,180 as shown in Table 5.2.

Table 5-2. Crash cost in Michigan in 2023 (St Louis et al., 2023)

Severity	**Traffic Crash Casualties**	**Percentage out of the total crashes**	**Unit Cost ($)**
Fatal	1,170	0.3	10,394,583
Serious Injury	6,413	1.4	935,744
Moderate Injury	21,316	4.6	194,433
Minor Injury	45,575	9.8	100,690
PDO	391,988	84.0	8,949
Average		**$65,180**	

However, since this study focuses on nighttime crashes specifically for pedestrians, these costs were recalculated using the proportion of nighttime crashes in Michigan for 2023 to estimate the average cost of nighttime crashes. This is because the initial costs were based on total crashes, where a high proportion of the crashes are PDOs. This proportion distribution is not similar for pedestrian nighttime crashes. The results for the recalculated costs are summarized in Table 5.3.

Table 5-3. Estimated crash cost for nighttime conditions

Severity		**Nighttime Crashes**	**Pedestrian Nighttime**
Yearly crashes (2023)		89,585	917
% by severity	Fatal	0.5	13.8
	Serious Injury	1.8	22.0
	Moderate Injury	5.1	28.2
	Minor Injury	8.8	25.6
	PDO	83.7	10.3
Average crash cost		**$96,344**	**$1,727,365**

5.2.3 Crash Reduction

Crash Modification Factors (CMFs) from the CMF Clearinghouse were reviewed to identify the most suitable CMF for estimating crash reduction. The CMF clearinghouse provides only three CMFs developed for pedestrian crash reduction by improved lighting. One of the earliest studies, conducted by Elvik & Vaa (2004), evaluated the impact of intersection illumination on pedestrian nighttime crashes. They estimated a CMF of 0.22 for fatal crashes and 0.41 for injury crashes, based on multiple studies where actual light readings were not measured.

Also, a CMF of 0.56 was estimated by Ye et al., (2009) for pedestrian-vehicle crashes for all severity where intersection illumination is improved. This study's lighting condition was based on the presence or absence of lighting in the intersection. The third study evaluated the effects of roadway lighting and estimated a CMF of 0.3 for pedestrian-vehicle crashes at night (Wanvik, 2009). Interestingly, this study's lighting condition was based on crash reports, and as shown in Chapter 3, most of the reported lighted conditions are not well-lit when checking the actual light levels.

There are a number of studies that estimated CMF for crashes using the exact light levels however, they were based on all nighttime crashes. In this study, the crash modification function by Wang et al., (2017) was used since it took into account the average illuminance in lux of a location. This function is given by

$$CMF = X^{-0.0773} \qquad \text{Equation 1}$$

Where X represents the average horizontal illuminance which was estimated to be more than 20 lux for our sites after implementing the LED lighting. This resulted in a CMF of 0.80, which was used in this study on lighting improvements. For locations where the lighting was paired with RRFB, the respective CMFs were multiplied to derive a combined CMF (0.8 x 0.31 = 0.25).

In summary, due to the limited availability of CMFs, this study applies a 20% reduction in nighttime crashes with light bars and smart lighting, and a 75% reduction when smart lighting paired is paired with RRFBs. While various factors can influence CMFs, it is not feasible to account for these variables in this study due to the lack of sufficient data and established practices.

5.3 Analysis and Results

Due to the scarcity of nighttime pedestrian crashes, this study assumes that lighting is improved at locations with one nighttime pedestrian crash over the past 10 years, which is equivalent to 0.1 nighttime pedestrian crashes per year. For locations with one nighttime pedestrian crash, it is estimated that there would be approximately 54 total nighttime crashes and 0.08 fatal pedestrian nighttime crashes, based on crash data proportions. Therefore, this study analyzes two types of benefits. The first case considers benefits only from the reduction in nighttime pedestrian crashes, while the second case includes benefits from the reduction in all nighttime crashes, as the lighting improves both pedestrian and vehicle safety (for example, rear-end vehicle crashes associated with sudden braking when a pedestrian was not visible to the driver of the leading vehicle).

Table 5.4 summarizes the expected Benefit-Cost Ratio (BCR) for installing light bars at intersections, smart lighting alone, or with RRFB at the midblock crosswalk. The results indicate that in a location experiencing at least one pedestrian night time crash in 10 years (equivalent to 0.1 pedestrian night-time crashes annually), the installation of light bars is expected to yield a BCR of 54.4 over their service life, assuming a CRF of 20 percent applies to pedestrian crashes. Moreover, the benefits significantly increase when accounting for all night time crash reduction including vehicle crashes, with the BCR nearly tripling for locations experiencing 5.4 total night time crashes annually.

Moreover, installing smart lighting at a midblock crosswalk with 0.1 pedestrian night time crashes annually results in a BCR of 70.1. At a similar location, combining smart lighting with RRFB achieves a BCR of 47.9 within the service life of the system. In general, locations with at least 0.002 pedestrian night time crashes per year yield a BCR of 1.0, indicating that all locations with even 1 pedestrian night time crash warrant lighting improvements to enhance safety.

Table 5-4. Cost-Benefit Analysis (For Locations with One Night time Pedestrian Crash in 10 Years)

Treatment	CRF (%)	BCR		Yearly number of crashes to achieve a BCR of 1.0	
		Pedestrian Nighttime[1)]	Total Nighttime[2)]	Pedestrian Nighttime[1)]	Total Nighttime[2)]
Light bars	20	54.4	163.7	0.002	0.04
Smart lighting alone	20	70.1	210.9	0.002	0.03
Smart lighting with RRFB	75	47.9	333.9	0.003	0.02

Note: 1) Include benefits only from the reduction in nighttime pedestrian crashes
2) Include benefits from the reduction in all night time crashes

6 CONCLUSIONS AND RECOMMENDATIONS

According to NHTSA, on average about 72% of pedestrian fatalities recorded between 2011 and 2020 occurred after dark nationally, and 77% occurred at night in 2021 (Petraglia, & Macek, 2023); in Michigan, the estimate is 73%. Most of the fatalities in 2022 occurred under dark conditions (79%) when overall all exposure was relatively lower (NHTSA National Center for Statistics and Analysis, 2024). The analysis of FARS data show that most of these increases occurred at night on urban arterials and collector roads (Tefft, et al (2021); Hu, & Cicchino, (2018). These data support an increasing trend in night pedestrian fatal crashes.

Lighting and visibility are important components of a safety strategy for pedestrians. Several recent studies show that fatal and serious night pedestrian crashes occur at locations with poor lighting with additional factors such as speeding vehicles, and rain (Ammar, et al, 2022; Hossain et al, 2023). Thus, improved lighting may be one way to decrease pedestrian crashes at night. LED lighting has many advantages over traditional lighting systems because it produces the best color rendering and can be easily aimed to critical areas to make pedestrians more visible.

Night crashes are categorized in police crash reports as occurring either at Dark Unlighted or Dark Lighted locations. Because police do not have access to light meters to measure the light level at the precise crash locations, they typically categorize the crash based on whether street lighting was absent or present on the roadway where the crash occurred. The first experiment in the research project precisely measured the light level at serious night crashes (K&A) crashes at all dark unlighted and dark lighted locations. Light levels were measured at fatal and incapacitating crash locations from the beginning of 2018 to the end of 2022 in 17 cities in SE and SW Michigan. The results showed that 64% of night crashes reported to have occurred in under lighted conditions occurred at very low lighting levels (less than 5 lux). The results of this research clearly show the important of determining the actual light level at locations with a fatal or incapacitating pedestrian crash to decide whether lighting should be added to the site. This might be accomplished by having police measure the light level with an accurate light level meter at the location of all fatal or incapacitating pedestrian crashes. It is also the case that the

FARS data reporting system does not capture light-level data but instead relies on police crash reports. It should be recommended that FARS investigators consider taking accurate light-level measures for all fatal pedestrian crashes to determine the effect of lighting on K&A pedestrian crashes.

The review of the literature also shows that LED lighting is superior to legacy lighting and provides excellent color rendering. Another major advantage of LED lighting is that it can be more effectively aimed to place light where it is required. For example, LED light bars can adequately illuminate an entire crosswalk including both entry points. This is a major advantage over legacy lighting systems.

Another advantage of LED lighting offers is that it can be powered with a battery and solar cells in locations where electricity is either unavailable or too costly to bring to the location where it is required. For example, LED lighting powered by solar cells and a battery can be used to light crosswalks when a pedestrian is crossing at RRFB sites. It can also be used to illuminate a marked crosswalk that does not have adequate lighting provided a push button or other pedestrian detector can be installed to activate it, or at traffic signal locations when the pedestrian call button is pressed.

The data from two locations treated with the large eight-foot-long light bars mounted under the four mast arms at each location showed uniform lighting of each of the crosswalks. However, it should be noted that the mast arms at these two sites were located close to each crosswalk. If the mast arms are not located above or very close to a crosswalk, they would not likely produce such uniform lighting. Because light bars are relatively new treatment *Appendix 1* provides instructions on the steps to be follow when installing the light bars. At signal locations without light bars, it is also possible that the use of two arms with luminaires on each light pole might lead to better lighting than the standard practice of using one on each of four posts. This would provide 2 rather than 1 luminaire for each of four crosswalks at a signalized intersection. If the 8 luminaires were only activated by a pedestrian call button there would be significant energy savings over the use of only 4 luminaires that were on all night.

In the third study RRFBs equipped with smart lighting devices were installed at three crosswalks. Each device was purchased from a different manufacturer that sold

RRFBs that include an on demand smart lighting system. Measures included: the light level during baseline under street lighting conditions, and the light levels when the smart lighting was activated; yielding without the RRFB, when the RRFB was activated alone; and when the RRFB was activated with the smart lighting; and speed reductions of vehicles driven by drivers who did not yield to pedestrians during baseline, when the RRFB was activated alone, and when the RRFB was activated with the smart lighting.

The smart lighting produced large increases in lighting at all departure points and the middle of all lanes at two of the RRFB locations and less robust increases at the third location which had better streetlighting. The introduction of the RRFB alone increased the percentage of drivers yielding to pedestrians from 1% to 25% at the first location. The introduction of smart lighting further increased yielding 61%. At the second site the introduction of the RRFB alone increased the percentage of driver yielding to pedestrians from 9% to 42%. The introduction of smart lighting increased yielding further to 67%. At the third site with better street lighting the introduction of the RRFB increased driver yielding from 10% to 20%. The introduction of smart lighting further increased yielding to 26%.

Data for slowing for drivers who did not yield to the pedestrian produced mixed results. At the first site drivers slowed 0.2 mph at during baseline, 2.6 mph when the RRFB was activated and 6.9 mph when the RRFB was activated along with the smart lighting. At the second site drivers slowed an average of 0.4 mph during baseline, 2.6 mph when the RRFB was activated, and 9.3 mph when the RRFB was activated along with smart lighting. At the third site with better street lighting drivers slowed 3.1 mph during baseline 9.3 mph when the RRFB was activated alone and 7.6 mph when the RRFB was activated with smart lighting. This study showed smart lighting had produced the largest increases driver yielding behavior and the largest reduction in speed by non-yielding drivers at the two sites with poor street lighting. At the third site with better initial lighting conditions the smart lighting produced the smallest percent increase yielding behavior and did not produce a reduction in the speed of drivers that did not yield to pedestrians. These data seem to indicate that light levels may be the major factor associated with speed reductions of nonyielding drivers.

However, two important human factors principles can be at work here which could change these results over time. One of them is discrimination learning. If two stimuli are correlated over time, people will learn to discriminate this predictive relationship: that an illuminated crosswalk means a pedestrian is present. The second principle is that of habituation, if something is present all the time there is a tendency for it to be ignored. Thus, there is a strong prediction that if lighting of a crosswalk comes on only when a pedestrian is about to cross, drivers will eventually learn to look for a pedestrian when the light comes on. However, if the crosswalk is always lighted and pedestrians are usually not present drivers may eventually stop looking for pedestrians. In the present study smart lighting was only installed near the end of the project so is not likely that drivers would have time to learn that pedestrians are always present when the lights come on. Therefore, a complete evaluation of whether lighting that comes on only when pedestrians are present is more effective than one that is on all the time is warranted, but would require a lengthy period of data collection at many locations. Of course, the activation of an RRFB predicting the presence of a pedestrian has had plenty of time for discrimination training to have occurred. However, the long-term predictive value of crosswalk lighting that only come on when a pedestrian is present at night has not been available for a sufficient amount of time for drivers to learn the discrimination in our study.

Data indicate that adding lighting without an RRFB at a midblock location did not produce a large increase in yielding right of way to pedestrians and only produced a relatively small decrease in the speed of drivers who did not yield to pedestrians. Pedestrian activated LED lighting at a traffic signal produced good increases in lighting levels but were not evaluated regarding the yielding behavior of drivers turning right at the crosswalk. It should be noted that other variable beside the presence of an RRFB can influence yielding at a crosswalk. Examples are the installation of a pedestrian refuge island and the use of advance stop lines. A standalone outreach material for MDOT regions and municipal traffic authorities that discuss new LED treatments currently available was also produced.

The replacement of traditional streetlights which produced poor crosswalk lighting during baseline with LED luminaires activated on demand produced large increase in overall lighting levels, but this system did not produce the overwhelming change at all crosswalk curb locations and lane positions similar to that produced by the light bars in the first study. Many measurement positions still had lower lighting than the recommended standard. Because each crosswalk was illuminated by one luminaire mounted on each of four light poles this situation could be remedied by mounting two arms on each pole for a total of 8 luminaries. This would greatly improve lighting levels at all locations. On demand lighting has another advantage at these sites. Since the lights were only on when pedestrians cross rather than continuously throughout the night, there would be substantial energy savings.

Specific recommendations from this study are as follows:

- Police consider investigating lighting for all pedestrian crashes and develop new criteria to determine whether a crash location is lighted or unlighted.
- MDOT consider measuring lighting using a light meter for all K&A pedestrian crashes.
- Consider using LED Light bars mounted on mast arms at signalized crosswalks when the mast arms are located above the crosswalks even when streetlights are present. Activation on button push is recommended.
- Encourage manufacturers to develop robust 8 ft. long LED light bars.
- Encourage manufactures to develop multiple luminaires for mounting on a single pole to aim light to both sides of a crosswalk.
- Promote installation of LED lighting as part of RRFBs particularly if they are used at night.
- Consider installing LED light bars at Hybrid Beacon locations.

7 GUIDANCE ON ACT 51

Michigan's Act 51 Restrictions on Street Lighting

Michigan's Act 51 of 1951, also known as the **Michigan Transportation Fund Act**, governs the allocation of state-collected transportation funds to local and state agencies for roads, highways, and related infrastructure. Revenue for Act 51 is derived from state fuel taxes, vehicle registration fees, and related sources. Allocated funds are distributed to state, county, city, and village road agencies based on a formula that considers factors like population, road mileage, and traffic volume. Act 51 includes provisions for street lighting as part of maintaining a safe and efficient transportation systems. The primary responsibility for lighting on non-state roads lies with counties, cities, and villages, which receive their own allocations of Act 51 funds. Local governments can use Act 51 funds to cover the installation, operation, and maintenance of street lighting on public roads and streets. The act emphasizes enhancing safety for drivers, pedestrians, and cyclists by ensuring adequate lighting on roadways and intersections. Although funds are available, local municipalities are often responsible for the prioritization and execution of street lighting projects. They may combine Act 51 funds with other local or federal sources to meet project costs. Over time, there has been encouragement for municipalities to adopt energy-efficient lighting technologies, such as LED systems, to reduce long-term operational costs and environmental impacts. However, decisions on specific lighting systems and upgrades are typically made at the local level.

The Michigan Department of Transportation (MDOT) can use Act 51 funds for street lighting projects, but only under specific circumstances. Per Act 51, "…*maintaining of state trunk line highways shall include all freeway lighting for traffic safety*." Act 51 states that maintaining of state trunk line highways shall include, among others, "…*the trunk line share of the erection and maintenance of traffic signals*…." Furthermore, Act 51 states that MDOT may install or maintain lighting to preserve the aesthetic or historic character of areas designated as national historic landmarks, but this does not create an obligation to provide lighting for vehicular traffic on highways. Act 51 has specific provisions discussing facilities and services for nonmotorized transportation including bicycling. One provision states that "*Of the funds allocated from the Michigan transportation fund to the* *state trunk line fund and to the counties, cities, and villages, a reasonable amount, but not less than 1% of those funds shall be expended for nonmotorized transportation services and facilities*." It states that appropriate measure(s) which facilitate nonmotorized transportation shall be considered to be a qualified nonmotorized facility under Act 51. Since lighting crosswalks, including those at signalized intersections, is aimed at facilitating nonmotorized transportation, and is not necessarily street lighting, an argument can be made to use Act 51 funds on state trunkline highways.

Arguments for the Use of Lighting as a Pedestrian Safety Treatment

The argument is particularly strong in cases where vendors sell highly cost-effective lighting as part of crosswalk treatment systems. These systems are typically designed to directly improve the safety of pedestrians while street lighting is designed more with the driver in mind. For example, systems designed for pedestrians that illuminate the entire crosswalk as well as the departure points where the pedestrian enters the roadway. Examples of this type of system are lights that illuminate the crosswalk when pedestrians enter a crosswalk at RRFB locations. LED light bars can also be mounted on signal mast arms at crosswalks with traffic control devices to illuminate crosswalks and pedestrian departure points. Light bars can also be installed on mast arms at locations where pedestrian hybrid beacons are installed. Without these treatments marked crosswalks at midblock locations must rely on street lighting which may not be located close to the crosswalk. This argument is most cogent when the crosswalk lighting is pedestrian activated. In this case it is clearly a pedestrian treatment since it signals drivers that a pedestrian is crossing the road. This would apply to the lighting devices sold with an RRFB, the use of a similar lighting system at a hybrid beacon, and crosswalk lighting at a marked midblock crosswalk or at a traffic signal that are only activated when a pedestrian presses a call button or activates the lights with a pedestrian sensor device. Another advantage of on demand pedestrian lighting is that pedestrians crossing outside the crosswalk do not activate the system. One could argue that a system that is on all of the time could reduce the likelihood of a motorist seeing a pedestrian who is crossing outside the crosswalk. This problem is solved by using a smart lighting approach which only illuminates the crosswalk when someone is crossing.

The results of the research presented above in section 3.2.1 found that fatal and incapacitating pedestrian crashes at traffic signal locations categorized as lighted on police reports are unlighted or have very low lighting conditions. These data also make a strong case of installing lighting as part of a pedestrian crossing treatment.

A somewhat weaker case can be made for placing crosswalk lighting at intersections at unmarked crosswalks which are also legal crosswalks unless otherwise signed and marked. However, on demand lighting would not likely be installed at such locations unless they are also signed and marked as a crosswalk. However, one can make the case that lighting treatments should also be placed at such locations on arterial roads and connectors if they are frequently used by pedestrians. However, a strong case for lighting as a pedestrian treatment can only be made if the crosswalk is also marked and signed and only illuminated on demand.

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9 APPENDICES

9.1 Appendix 1. Instructions on how to install lightbars.

Installing Light Bars to Mast Arms for Crosswalk Lighting

- Pull wire from the controller cabinet to the end of each arm, then mount and wire the light bars.
- Use two sign clips for 2-foot light bars and three sign clips for 8-foot light bars.
- Secure the light bars to the arm using banding and clips.
- Install a photocell on top of the controller cabinet.
- Connect the load side of the photocell to two relays, allowing the coils to be powered after dark via the relay power feed.
- On the normally open (N/O) side of the power relay, connect it to the yellow wire of the pedestrian drive. Configure the controller to activate the lights during the walk and don't-walk phases, ensuring they
operate only after dark.