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Impact of Crosswalk Lighting Improvements on Pedestrian Safety– A Literature Review

by

Elisabeta Mitran, Ph.D.
Julius Codjoe, Ph.D., P.E.
Emmaline Edwards

LTRC

4101 Gourrier Avenue | Baton Rouge, Louisiana 70808
(225) 767-9131 | (225) 767-9108 fax | www.ltrc.lsu.edu

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2. Author(s)
   Elisabeta Mitran, Julius Codjoe, and Emmaline Edwards

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13. Abstract

This study conducted a nationwide literature review to obtain the state of knowledge on the relationship between lighting conditions and pedestrian crashes, assessing how lighting countermeasures at crosswalks improve pedestrian safety. The study gathered information on crosswalk lighting treatments, existing national guidelines for lighting at pedestrian crossings, and safety effectiveness of pedestrian crosswalks lighting. Reducing pedestrian crashes remains a major challenge in the United States. Pedestrian fatalities have been on the rise in the last 10 years, reaching approximately 6,000 fatalities in 2017, which accounted for 16 percent of all traffic fatalities. Among these pedestrian fatalities, about 75 percent occurred in dark conditions. The high number of crashes during dark conditions advocates for prioritizing lighting countermeasures to improve crosswalks visibility and pedestrian safety. This literature review identified overhead lighting, in-road flashing lights, and bollard level lights as the most used crosswalk lighting treatments. For crosswalk lighting and the amount of light needed to detect pedestrians crossing during nighttime, transportation agencies should consider, wherever feasible, providing adequate lighting at pedestrian crossings, especially where nighttime pedestrian volumes are high. Existing national guidelines recommend the light source to be located at least 10 ft. in front of the crosswalks, a vertical illuminance of 20 lux measured at a height of 5 ft. above the road surface, and street lights to be placed on both sides of the roadway. The review revealed a small number of studies that investigated pedestrian safety with respect to crosswalk lighting. These studies were grouped in three categories: behavioral, modeling, and crash studies. The behavioral studies showed, in general, enhanced lighting at crosswalks led to an improvement in drivers' awareness and yielding to pedestrians, an increase in pedestrian observational behavior, and an increase in the car stopping distance before crosswalks. The modeling studies showed that providing street lighting is associated with lower probabilities of pedestrian fatalities and severe injuries. Crash studies found that providing adequate lighting at intersections helps to reduce the frequency of nighttime crashes and increase safety. Although there is evidence that crosswalk lighting, especially intersection lighting, has a positive impact on nighttime crashes, it is the researchers' conclusion that extensive before-after studies are needed to investigate the safety effects of crosswalks lighting on pedestrian crashes and visibility as well as to develop appropriate crash modification factors. A survey is also recommended to collect information from states or municipalities that may have implemented such countermeasures.

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Introduction

Walking and biking are some of the useful modes of transportation to get to work, school, or other nearby places. Among all road users, pedestrians are the most vulnerable; therefore, adequate pedestrian facilities are essential to improve pedestrian safety and access, and to encourage walking. It is not without reason that pedestrian safety has become a national issue. In recent years, pedestrian fatalities in the United States have increased drastically. According to the National Highway Traffic Safety Administration (NHTSA) Traffic Safety Facts, between the years of 2014 and 2016, pedestrian fatalities rose from 9.8 percent to 13.9 percent on the national level. In 2017 the United States suffered 5,977 pedestrians killed in traffic crashes, accounting for 16 percent of all traffic fatalities [1]. Furthermore, based on the preliminary data reported by all 50 states and the District of Columbia for the first six months of 2018, the Governors Highway Safety Association (GHSA) estimates an increase of 4.0 percent from 2017 in pedestrian fatalities [2]. The trend is no different for Louisiana. In 2017, there were 111 pedestrians killed in traffic crashes, accounting for 14.6 percent of all traffic fatalities. The pedestrian fatality rate of 2.37 per 100,000 population, compared with the national average rate of 1.84, made Louisiana rank in the top 10 states in pedestrian fatalities in 2017. About 46 percent of pedestrian fatalities in Louisiana occurred between 6:00 pm and 12:00 am and almost 20 percent between 12:00 am and 6:00 am, accounting for 66 percent fatalities occurring under dark conditions [3].

Pedestrian crashes are influenced by lighting conditions at both controlled and uncontrolled crossing locations. According to NHTSA, 73 percent of pedestrian crashes occurred at non-intersection and about 75 percent of pedestrian fatalities occurred under dark conditions [1]. The growing prevalence of nighttime pedestrian crashes advocates for prioritizing countermeasures that can improve pedestrian safety at night.

Reducing pedestrian fatalities remains a major challenge in the United States as transportation agencies continue to increase their efforts to mitigate the impact of traffic on pedestrian crashes. The Federal Highway Administration's (FHWA) list of 20 Proven Safety Countermeasures promotes the following pedestrian safety countermeasures: leading pedestrian intervals, medians and pedestrian crossing islands in urban and suburban areas, pedestrian hybrid beacons, road diets, and walkways [4]. Likewise, the FHWA Safe Transportation for Every Pedestrian (STEP) promotes the following proven countermeasures to reduce pedestrian crash rates: crosswalk visibility enhancements, raised crosswalk, pedestrian refuge island, pedestrian hybrid beacon, and road diet [5]. Under the crosswalk visibility enhancements countermeasure, the group of countermeasures recommended by STEP includes improved nighttime lighting, high-visibility crosswalk marking, parking restrictions, advance STOP or YIELD markings and signs, in-street STOP or YIELD signs, and curb extensions.

This literature review focuses on studies that investigated improved nighttime lighting countermeasures only. It reviews published literature nationwide to obtain the state of knowledge relationship between lighting conditions and pedestrian crashes, and to assess how lighting countermeasures improve pedestrian safety at crosswalks. It was prepared in response to the request of Project Review Committee (PRC) of LTRC proposed project 19-2SA *Reduce Pedestrian Fatal Crashes in Louisiana by Improving Lighting Conditions*.

Objective and Scope

The objective of this study was to conduct a literature review to shed light on the following research questions:

1. Does adequate lighting at crosswalks increase pedestrian safety?
2. What level of lighting at crosswalks will be deemed adequate?
3. What are some of the lighting countermeasures that have been implemented to improve pedestrian safety at crosswalks and how effective are they?

It is anticipated that findings from the literature review will equip PRC members of the LTRC 19-2SA proposed research project to make an informed decision on developing the scope of work. The scope of this research was limited to studies published in the United States, and no new research was conducted.

Methodology

This study comprised of a literature review only. The main sources used to access publication and research papers were the Transportation Research International Documentation (TRID) database, Transportation Research Record (TRR), University Transportation Centers' published materials, Google Scholar, Research Gate, and Crash Modification Factors Clearinghouse. These resources were queried using multiple keywords: crosswalk lighting, intersection crosswalk lighting, pedestrian fatalities, pedestrian lighting, illuminance levels, evaluation of crosswalk lighting, crosswalk lighting countermeasures, nighttime pedestrian crashes, guidelines for crosswalk lighting, safety effects of crosswalk lighting, crash modification factors, and pedestrian crash assessment. Relevant articles published in the last 20 years were included in this review.

Literature Review

The research team conducted extensive research to obtain state-of-the-art knowledge on the relationship between lighting conditions and pedestrian crashes and also on the safety impact of crosswalks lighting countermeasures installed to increase pedestrians' visibility and safety. Specifically, the literature review in this report is organized into four topics: background, pedestrian crosswalks lighting treatments, existing guidelines for lighting pedestrian crossings, and existing research studies that evaluated the effectiveness of pedestrian crossings lighting in improving pedestrians' safety and reducing crashes.

Background

Before reviewing the literature, it is important to provide background information about roadway lighting and visibility concepts. The objective of lighting at crosswalks and intersections is to make pedestrians in and near the road visible to drivers during the dark hours at a longer range than vehicle headlights typically provide. Studies have shown that the visibility of pedestrians at night is affected by many varied factors such as availability of street lighting, lamp type, motor vehicle headlamp aim, ambient lighting, background conditions, glare from the traffic headlights and street lamps, clothing color of pedestrians, and atmospheric conditions [6].

Pedestrian visibility distance (the distance at which a driver can see a pedestrian and react) is the main goal to consider when choosing lighting design features such as the amount of light, lamp type, lamp height, placement of lamp, and glare levels [6]. Quantifiable data for lighting designs are measured by illuminance and luminance. Illuminance is the measurement of light that hits the surface per unit area, the incident ray, while luminance is the amount of light that is reflected off the surface, the reflected ray. The reflected ray is what people see with their eyes—the brightness of the light. The illuminance is quantified in footcandles (lumens/ft2) or lux (lumens/m2) and luminance in candela/m2 [6]. Vertical illuminance is one of the most important factors considered when determining the contrast and visibility of pedestrians crossing the street. Pedestrian crosswalk lighting, therefore, needs to be located properly in order to increase pedestrian visibility at night.

Visibility in outdoor application is defined as the distance at which an object can be just perceived by the eye [7]. The fundamentals of visibility are determined by contrast, glare, perception reaction time, and spectral effect models, as documented in FHWA *Lighting Handbook* [7]. A person can see objects by contrast—the visible difference between the object of interest and background—and can be either positive or negative depending on the brightness of the object. With positive contrast, the approach side of the pedestrian in the crosswalk is lit and the vehicle headlights help in improving the visibility of the pedestrian. However, with negative contrast design (silhouette), the intersection lights are placed on the opposite side of the intersections and the vehicle headlights sometimes diminish the visibility of pedestrian [8]. This is typically used for crosswalks at intersections. The luminance contrast of an object is known as a contrast value and depends on a number of factors such as size of the object of interest, person's age, length of observation time, and adaptation luminance. Glare happens when the luminance of an object is higher than what the driver's eye is adapted for [7].

Lighting Treatments at Crosswalks to Increase Pedestrian Safety

It is generally recognized that roadway lighting benefits the public in many ways by increasing visibility, improving safety and security, improving traffic flow, and improving ability to see roadway geometry and objects in the road. Implementing street lighting treatments at crosswalks can increase driver awareness and pedestrian visibility by illuminating the area around a crosswalk better than the car headlights.

The 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) defines a crosswalk as [9]: *(a) That part of a roadway at an intersection included within the connections of the lateral lines of the sidewalks on opposite sides of the highway measured from the curbs or in the absence of curbs, from the edges of the traversable roadway, and in the absence of a sidewalk on one side of the roadway, the part of a roadway included within the extension of the lateral lines of the sidewalk at right angles to the center line; (b) any portion of a roadway at an intersection or elsewhere distinctly indicated as a pedestrian crossing by pavement marking lines on the surface, which might be supplemented by contrasting pavement texture, style, or color.*

Crosswalks advise pedestrians where to cross the street and also serve as right-of-way across a street for pedestrians. Crosswalks can be categorized in the following types: controlled, uncontrolled, unmarked, and marked. Controlled crosswalks have a device that require vehicles to stop, such as traffic signals and traffic signs. Uncontrolled locations do not use any form of device to halt vehicles. Marked crosswalks have white lines to indicate location. Intersections may have marked crosswalks, but all midblock crossings must be marked. Therefore, unmarked crosswalks may only exist at intersections, while marked crosswalks can be installed at uncontrolled or controlled locations. According to Louisiana's state law LA Rev Stat § 32:212 *Pedestrians right-of-way in crosswalks, the driver of a vehicle shall stop and yield the right-of-way, to a pedestrian crossing the roadway within a crosswalk when the pedestrian is upon the roadway upon which the vehicle is traveling or the roadway onto which the vehicle is turning [10]*. When deciding on which style of crosswalk to use, an engineering study must be performed to determine which crosswalk would be most effective in that location [9]. There are several factors that need to be considered when deciding whether to create a marked crosswalk: school zone location, volume of disabled pedestrians, high pedestrian volumes, and vehicle volumes [11].

Numerous lighting countermeasures, including overhead lighting, illuminated crosswalk signs, flashing warning beacons, and in pavement flashing lights, adaptive lighting, and bollards have been used in the United States in an attempt to increase visibility of pedestrians and to reduce nighttime pedestrian crashes.

Overhead street lighting, used for visibility of both pedestrian and vehicles, is one of the recommended pedestrian safety countermeasures designed to enhance the crosswalk visibility and produce an adequate level of roadway surface luminance [12]. In general, the overhead street lighting is designed to illuminate both the street and the crosswalk areas and to produce a particular level of roadway surface luminance. However, in areas where the volume of pedestrian is high, consideration should be given to pedestrian scale lighting. In traditional crosswalk lighting, transportation agencies have installed a single luminaire directly over the crosswalk. However, studies have shown that installing a luminaire on the approaching driver side of the crosswalk before an intersection, at least 10 ft. ahead of the crosswalk, provides enough light for drivers to detect the pedestrians and also eliminates silhouette [6]. This form of lighting is suitable for controlled crossings, regardless of whether the crosswalk is marked or not.

In-roadway lighting (known as in-pavement flashers, in-pavement flashing lights, crosswalk pavement lights, and pedestrian crosswalk lights, among others) at crosswalks has been used by several transportation agencies for the benefit of both drivers and pedestrians [13, 14]. The in-roadway lighting provides drivers with a visualization of crosswalk and pedestrians with a lit path. It consists of a series of durable lighting units embedded in the pavement parallel to the marked crosswalk, which are activated by pedestrians either by pushbutton or passive detection. This countermeasure is designed to enhance driver's awareness and improve drivers yielding to pedestrians. This form of lighting is suitable for marked crosswalks and can be used at both intersections and mid-block crossings.

Adaptive lighting is a new type of lighting technology that allows street lighting to be adapted (turned off or reduced) based on the road-user needs and provided only when and where it is needed [15]. The light level can be managed and controlled in two ways: by reducing the luminaire light output to the lighting design level or by adjusting the light level to the current street conditions that can include factors such as traffic volume, pedestrian activity, and weather. The main benefit of adaptive lighting involves reduction of energy use. This form of lighting is suitable at crosswalks with low levels of pedestrian activity.

Bollard lighting is another type of lighting treatment that has been tested for illuminating pedestrian crosswalks and is being promoted as having advantages over traditional crosswalk lighting [16, 17]. The bollard lighting utilizes short vertical posts that have inside linear light sources designed to provide low-level pedestrian lighting and increase crosswalk visibility. This type of lighting is suited for crossings where the roadway requires a median to act as a refuge for pedestrians.

Several other types of flashing beacons installed to improve crossing conditions for pedestrians include overhead and side-mounted beacons at the pedestrian crossing as well as in advance of the pedestrian crossing. Studies have shown that pedestrian hybrid beacon, and rectangular rapid-flashing beacon, improve driver yielding rates at crossing locations [18]. These are particularly useful at midblocks with marked crosswalks.

The primary light source used for roadway lighting is the high pressure sodium lamp, which has a long operating life and low cost. Several other light sources have been also used such as ceramic metal halide, light emitting diode (LED), and induction fluorescent [19]. LED roadway lighting is showing promises in energy saving and a life-cycle cost reduction in the long term. Perceived brightness levels provided by some light sources were found to be strongly correlated with a sense of security provided by the roadway lighting [20].

Existing Guidelines for Lighting at Pedestrian Crossings

Although lighting at crosswalks is up to the engineer's judgment, different federal and private agencies have evaluated the need for light and made recommendations for lighting at crosswalks. The traditional light plan states the luminaires to be placed directly above the crosswalk for crosswalks at midblock locations and on all corners of the intersection angled towards the center for intersections. The typical method in selecting a lighting level for street lighting is to look first at road classification followed by the potential for conflict.

The *Guide for the Planning, Design, and Operation of Pedestrian Facilities*, published in 2004 by the American Association of State Highway and Transportation Officials (AASHTO), recommends lighting, at the minimum, at intersections and pedestrian crossing areas where there are high concentrations of dusk and nighttime pedestrian activities. It provides the following information for lighting at pedestrian facilities: placing streetlights on both sides of the street along wide arterials with sidewalks on both sides of the street to provide a uniform light distribution, lighting at intersections and other pedestrian crossings in urbanized areas, and supplementing street lights with pedestrian-scale lighting in shopping districts or downtown areas [12].

The FHWA *Informational Report on Lighting Design for Midblock Crossings* provides information on lighting parameters and design criteria for lighting of crosswalks at midblock locations [6]. The report recommends the light source to be located 10 ft. in front of the crosswalk at midblock locations and a vertical illuminance of 20 lux measured at a height of 5 ft. above the road surface. If glare is naturally greater where crosswalk is located, such as a city, the vertical lux can be increased. The report also recommends metal halide lamps for the crosswalk lighting because it helps the driver differentiate where a crosswalk is located [6].

Another FHWA document, *Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations,* recommends that transportation agencies should consider providing appropriate lighting at all pedestrian crossings and, in order to enhance light on the front of the pedestrian and avoid silhouette, the lighting should be placed 10 to 15 ft. before the crosswalk on both sides of the street and on both approaches [21].

The 2011 Green Book published by AASHTO recommends providing enough lighting based on engineering judgment and to "provide lighting and eliminate glare sources at locations that demand multiple information gathering" in order to aid older pedestrians and road users [22].

The FHWA *Lighting Handbook* and the FHWA *Handbook for Designing Roadways for the Aging Population* recommend, wherever feasible, installing lights at intersections where the potential for wrong-way movements is indicated through crash experience or engineering judgment for where twilight or nighttime pedestrian volumes are high, as well as for places with shifting lane alignments, turn-only lane assignments, or where pavement-width transitions force a path-following adjustment at or near an intersection [7, 23]. Other important factors (such as traffic volumes, presence of marked crosswalks, nighttime crashes caused by lack of illumination, and presence of raised medians) need to be considered when providing lighting at intersections and selecting the level of light (full, partial, or delineation lighting).

The 2018 AASHTO *Roadway Lighting Design Guide* recommends that the intersections lighting design (crosswalks should be considered part of the intersection) should consider positive contrast for pedestrians by installing poles in advance of the crosswalk [8]. Roundabout crosswalks should have light poles located 10 to 30 ft. in front of the crosswalk to increase pedestrian contrast from the background. Roundabouts should be lit from the outer edge of the roadway, to a level that is 1.3 to 2 times the values used on the approach with the greatest light level. It also states that a master lighting plan should address goals to improve roadway safety, increase personal security, provide nighttime aesthetics, consider environmental issues, use energy efficiently, and plan maintenance.

The NCHRP Report 672: *Roundabouts: An Informational Guide*, Second Edition recommends adequate lighting should be provided for pedestrian crossings and bicycle merging areas at roundabouts [24].

FHWA *Guidelines for the Implementation of Reduced Lighting on Roadways* provides guidelines for the implementation of adaptive lighting system for roadway lighting [15]. The application of adaptive lighting is recommended based on the road facility type. For example, for residential/pedestrian areas, it is recommended that lighting be adapted to a single lighting level. For streets that include major, collector, and local roads on which pedestrians and cyclists are generally present, each street should be evaluated with the recommendation that the difference in lighting classes for streets in a given vicinity should be no more than two. The report established adaptive lighting criteria that can be used to identify appropriate lighting levels for given roadway characteristics and usage. For example, depending on the street class, for streets the recommended lighting design level for average luminance can be adjusted from 1.2 cd/m2 for class S1 to 0.3 cd/m2 for class S5. Similarly, for residential/pedestrian facilities types, the recommended average illuminance can be adjusted from 10 lux for class P1 to 2 lux for class P5.

Besides street overhead lighting and adaptive lighting, designed to illuminate the roadway and improve the conspicuity of pedestrians, there are other countermeasures installed to improve the visibility of crosswalks and alert drivers of a crosswalk presence, such as in roadway lighting and hybrid beacons. According to part 4F of the MUTCD, pedestrian hybrid beacons, also known as HAWK (High Intensity Activated Crosswalk) beacons in other publications, shall only be used at unsignalized locations that have a marked crosswalk. Part 4N of the MUTCD provides guidance for in-roadway lights in that they shall not be taller than ¾ in., and the lights have to be flashing, and not be a continuous illumination [9].

Effectiveness of Lighting at Pedestrian Crosswalks

In this section, the existing literature on pedestrian crosswalk lighting is reviewed with respect to three aspects: behavioral studies that analyze driver and pedestrian behavior when a new lighting system is installed, modeling studies that calculate pedestrian crash probabilities by using crash databases, and crash studies that evaluated the effectiveness of intersections/crosswalks lighting in reducing pedestrian crashes.

Behavioral Studies

The purpose of behavioral studies is to gain insight into the reactions of drivers and pedestrians to a new variable, such as a new lighting system, designed to improve pedestrian safety. Behavioral studies utilized observations and surveys of drivers and pedestrians as a core source of information. In general, the observed behaviors included driver yielding, driver awareness, pedestrian visibility to drivers, pedestrian crossing locations, and pedestrian delay. The following paragraphs present the findings of some behavioral studies that were reviewed, grouped under two categories: crosswalk lighting treatments that improve the visibility of pedestrians and the treatments that improve the visibility of crosswalks.

Crosswalk Lighting Treatments that Improve the Visibility of Pedestrians

Several studies investigated the role of the bollard lighting systems in improving visibility of pedestrians at crosswalks. For example, Bullough et al., in a study conducted for the New Jersey Department of Transportation, evaluated three lighting scenarios: traditional lighting with luminaires placed above the crosswalk, luminaires positioned 15 ft. in front of the crosswalk, and bollard lights placed on each side of the crosswalk, to assess the visibility of pedestrians at crosswalks [17]. The team used photometrically accurate lighting simulations to evaluate a virtual scenario with a crosswalk and an approaching vehicle. The driving speed for the test was 30 mph. Each design was virtually tested from 100 ft. away, the recommended AASHTO viewing distance. The study showed that the bollard lights located at the ends of a crosswalk create better contrast between the pedestrian and the background without causing glare. The one-night field experiment at an intersection in New Jersey, where the bollard lights were tested and judged by pedestrians and drivers in the area, confirmed the practicality of these lights. However, the study showed that the use of bollard-based fluorescent luminaires is not practical for all locations and further optimizations are needed. A later field study that surveyed pedestrians, conducted at a midblock crosswalk location equipped with an improved prototype bollard luminaire (LED and push button control that produced a vertical illuminance of 12 lux), confirmed the potential of the bollard lighting system to improve pedestrian's visibility at crosswalks [16]. Furthermore, the bollard luminaire field study demonstrations in Aspen, Colorado and Schenectady, New York that produced at least 10 lux of vertical illuminance in the center of crosswalk at a height of 3 ft. above the ground used no more than 7 W of electrical power when operating at full light output resulting in energy saving compared with conventional overhead lighting [25].

Nambisan et al. evaluated the effectiveness of an automatic pedestrian detection device with smart lighting at a midblock location in Las Vegas, Nevada, by using a field observational study [26]. Automatic pedestrian detection devices detect whenever a pedestrian is present and activates the smart lighting system. Smart lighting systems use high-intensity lights and, when triggered, increases the illumination of the crosswalk to alert motorists. The field observation study, which focused on both pedestrian behavior and motorist compliance at the marked crosswalk before and after installation of the countermeasure, collected seven measures of effectiveness: if the pedestrian looked left before beginning crossing the street, if the pedestrian looked right before crossing the second half of the street, if they diverted their route to use the crosswalk, if there were any trapped pedestrians in roadway, pedestrian delay, if the driver yielded, and the stopping distance that the driver yielded before the crosswalk. Observations were done before the countermeasures were implemented and three weeks after. The results showed an increase in observational behavior of pedestrians, a 17 percent increase in diverted pedestrians, and a decrease in pedestrians getting trapped in the roadway. Furthermore, after the countermeasures were installed, the percentage of drivers yielding to pedestrians increased by 13 percent and the distance a driver stops/yields before the crosswalk also increased. Average pedestrian delay and average vehicle delay decreased in time resulting in a positive effect for the countermeasures. The results from this study showed that automatic pedestrian detection devices and smart lighting have positive safety benefits, improving pedestrian safety at a midblock location by alerting the drivers of present pedestrians [26].

Gibbons et al. evaluated drivers' ability to correctly identify pedestrians at crosswalks under certain lighting conditions [27]. This static test was conducted on the Virginia Smart Road, a state-of-the-art testing facility equipped with a lighting system that stretches 0.75 miles long. The study tested vertical illuminance levels (60, 40, 20, and 5 vertical lx), lamp types (metal halide and high pressure sodium), glare levels (present or not), the use of overhead lighting, and pedestrian clothing (white, black, and denim). Although this study has some limitations (static pedestrians, rural and dark crosswalk background, and limited scan pattern), the results indicated that a vertical illuminance of 20lx can be sufficient to clearly identify pedestrians in the crosswalk. Using both overhead lighting and crosswalk lighting can improve or degrade the visibility of pedestrians depending on the color of the object and the background. The white clothing of pedestrians were the least influenced by the changes in the lighting designs. Even though the results showed no significant impact of the lamp type and no influence of lighting design on the glare, the study recommends further investigations into these factors.

Crosswalk Lighting Treatments that Improve the Visibility of Crosswalks

Kannel and Jansen evaluated the effectiveness of in-pavement flashing lights installed at a crosswalk in Cedar Rapids, Iowa [13]. Based on the before-after field observations and survey of the drivers and pedestrians, this study showed an improvement in motorists yielding to pedestrians as well as an increase in motorist awareness. The study also noted that the system could be operational in both summer and winter conditions.

Another study that tested in-pavement flashing lights, installed at an uncontrolled location in San Jose, California, recorded the braking distance and driver yielding rates before and one month after the in-pavement lights were installed at night [28]. The results showed that after one month of installation, the stopping distance of the drivers doubled from the before period. The driver yielding rate increased by 60 percent at night.

In summary, behavioral studies investigated pedestrians and drivers' behaviors with respect to new crosswalk lighting treatments, such as bollard luminaire, smart lighting automatic pedestrian detection device, and in-pavement flashing lights. The findings showed an improvement in drivers yielding to pedestrians, an increase in drivers as well as pedestrians' awareness, an increase in pedestrian observational behavior, and an increase in the car stopping distance before crosswalks, revealing that providing crosswalk lighting has a positive impact on pedestrian visibility and safety.

Modeling Studies

Modeling is used for large amounts of data to extract repeating characteristics that can be used to separate information. From models, statistics can be taken out to help predict how often events happen, like whether a crash occurred during the day or at night, and if lighting was present at the crosswalk.

Several studies used multivariate regression models to assess the role of lighting conditions at pedestrian crossings in reducing the injury severity of pedestrian crashes. For example, Chu et al. and Siddiqui et al. used the ordered probit model to calculate probabilities of a pedestrian injury severity occurring at midblock and intersection crossings with and without street lighting [29, 30]. The study used Florida crash data from 1986 through 2003 and five attributes: pedestrian, driver, road, vehicle, and weather. The model included crosswalk locations (midblock and intersection) and light conditions (daylight, dark with street lighting, and dark without street lighting) as interactive variables. It was found that the odds of a pedestrian fatality occurring at a midblock crosswalk with street lighting is 42 percent lower compared to no street lighting. The odds of a fatality at an intersection crosswalk with street lighting is 54 percent lower than at a location without street lighting. Comparing the two crosswalk locations, the risk of a fatality at an intersection at night with street lights is 24 percent lower than at a midblock location. The study showed that providing adequate lighting at pedestrian crossings has significant benefits in reducing pedestrian injury severity.

Haleem et al. used a mixed logit model to evaluate significant factors affecting the pedestrian crash injury severity at signalized and non-signalized intersections in Florida [31]. The study used three years of pedestrian crash data (including in the analysis a total of 3038 pedestrian crashes) and found that among other factors the dark lighting factor (with no street lights) was associated with higher pedestrian severity risk. Out of 2360 pedestrian crashes that occurred at signalized intersections, almost 35 percent occurred in the dark with street light present and almost 6 percent in the dark with no street light. For unsignalized intersections, out of 678 crashes, 20 percent occurred in the dark with street light present and almost 10 percent occurred in the dark with no street light. An approximately 2.5 percent increase in pedestrian severity was observed at unsignalized intersections with no street light and a 1.5 percent increase at signalized intersections.

Pour-Rouholamin et al. analyzed Illinois pedestrian crash data from 2010 to 2013 using ordered response models to gather factors associated with pedestrian injury severity [32]. Besides other characteristics, lighting conditions (daylight, dawn/dusk, dark with or without lighting) and location (street or crosswalk) were variables of the models. The results from this study show that 21.9 percent of severe pedestrian crashes occurred at night with crosswalk lighting and 30.1 percent of severe pedestrian crashes occurred without crosswalk lighting. The findings suggest that there is a higher probability to sustain a severe injury at pedestrian crosswalks when lighting is not present.

In summary, the findings of these modeling studies reveal that providing adequate lighting at midblock and intersection crosswalks is associated with lower probability of pedestrian fatalities and injury severity.

Crash Studies

Pedestrian fatalities in the United States have increased more than 30 percent in the last 10 years [1]. Due to the large number of pedestrian fatalities, a number of states have started to perform pedestrian crash assessments to understand the predominant factors that affect the frequency and severity of pedestrian crashes. Existing studies revealed dark conditions/poor lighting as one of the contributing factors to high pedestrian crashes besides other factors such as speeding, insufficient sight distance, improper location of bus stops, and other geometric features [18, 33, 34]. The percentage of severe crashes that occurred in the evening and night hours were significantly higher than that of morning and day hours.

Research exploring the effectiveness of street lighting on pedestrian crashes is limited. The review of existing literature did not find any study that looked at pedestrian crashes before and after installation of lighting at crosswalks. Very few studies were found on evaluating the safety effectiveness of street lighting at intersections; although these studies do not pertain to pedestrians at intersections, it is generally a state law that crosswalks legally exist at intersections, marked or unmarked. At these locations, pedestrians have the right of way in the absence of pedestrian tunnels or overhead pedestrian crossings [10].

Isebrands et al. evaluated the safety effects of street lighting in reducing nighttime crashes in Minnesota by doing a comparative analysis of 3,622 rural lighted and unlighted intersections and a before and after study at 48 isolated rural intersections [35]. The comparative study showed that the ratio of night crashes to total crashes at unlighted intersections was 27 percent higher than at lighted intersections. The regression models indicated that factors such as presence of lighting, daily entering volume, approach speed, and the number of approach legs for the intersections affect the ratio of nighttime crashes to total crashes. For the before and after crash study, the Poisson analysis identified that the crash rate before lighting installation was 59 percent higher than the crash rate after installation. Although this study does not pertain to pedestrians, it shows the increase in safety after lighting has been installed at intersections.

In a similar study performed by Green et al., a total of nine intersections were studied four years before installation of lighting and three years after. The results showed that the percentage of nighttime vehicle crashes decreased by 45 percent when lighting was installed [36].

Another Minnesota study assessed the effectiveness of intersection lighting in reducing nighttime crashes by measuring the horizontal illuminance at 63 isolated intersections [37]. The crash data was collected for five years. The negative binomial regression models that compared horizontal lighting levels and the nighttime crash ratio showed that increasing the average illuminance at intersections decreased the occurrence of crashes at those intersections. This study showed that the intersections with lighting had a better night-to-day crash ratio. Also, a unit increase in horizontal illuminance had a substantial impact in reducing crash ratios. For instance, for every 1 lux above the average horizontal illuminance, the crash ratio decreased by 20 percent at lighted intersections and by 94 percent at unlit intersections.

In a similar study, Wei et al. investigated the safety effects of horizontal illuminance at 91 urban signalized intersections in the Tampa Bay region in Florida [38]. The study concluded that nighttime crash frequency and night-to-day crash ratio could decrease by 50 percent when the intersection illuminance is increased from low to medium (<0.2fc to

0.2–1.1 fc). Also, the study showed that a street illuminance of 0.9 fc or higher could considerably reduce the risk of fatality and severe injury for pedestrians.

Bhagavathula et al. calculated the safety effects of quality of light and level of lighting on the ratio of nighttime to day crashes at 99 lighted and unlighted rural intersections in Virginia [39]. The findings showed that average horizontal illuminance influenced significantly the ratio of nighttime to day crashes. For example, 1 lux increase in average horizontal illuminance corresponds to a 9 percent, 21 percent, and 7 percent decrease in the night to day crash ratio for lighted intersections, unlighted intersections, and all rural intersections, respectively.

In summary, these crash studies found that providing lighting at intersections helps to reduce nighttime crashes; however, none of these studies pertained to pedestrians. Also, the findings showed that increasing the average illuminance at intersections with at least 1 lux has a substantial impact in reducing night-to-day crash ratios, especially for unlighted intersections.

Crash Modification Factors

This section explores what has been found in the literature regarding crash modification factors for installing lighting at crosswalks. The *Highway Safety Manual* (HSM) defines crash modification factor (CMF) as "a factor estimating the potential changes in crash frequency or crash severity due to installing a particular treatment" [40]. Research on developing CMFs is aggressively growing and the information on all available CMFs is recorded in the CMF clearinghouse [41]. The CMF clearinghouse also presents the crash reduction factor (CRF), which provides an estimate of the percentage reduction in crashes after implementing a safety countermeasure. Based on the available data, various methods can be used to develop CMFs such as before-after, cross-sectional, case-control, meta-analysis, cohort, and surrogate measures [42]. The rigorous before-after methods are usually preferred in developing CMFs. However, these are not practical when insufficient before-after data is available.

In a review of CMFs clearinghouse, the research team could not find any information related to the impact of installing crosswalk lighting on pedestrian crashes. However, when "illumination" and "lighting" were queried, several CMFs regarding intersection lighting were found. Table 1 summarizes the CMFs related to "Install lighting" and "Provide intersection illumination" countermeasures that considered the vehicle/pedestrian crash type. These studies used either meta-analysis or cross-sectional methodology to estimate the CMFs. The quality star rating reported with the CMF is an indication of the confidence in the results of the study and is based on a scale of 1 to 5, where 5 indicates the most reliable rating [41]. As can be seen in Table 1, when meta-analysis methodology is used, for serious injuries and minor injuries, the reported CMFs vary from 0.30 to 0.58, and for fatalities the CMFs for vehicle pedestrian crash type are close to 0.20. For all crash severity types, a CMF of 0.56 was found using the regression cross-section methodology. A CRF percentage associated with each CMF is also presented in the Table 1.

Table 1. Summary of crash modification factors as found in the CMF clearinghouse

Countermeasure	CMF	CRF (%)	Quality (#stars out of 5)	Crash Type	Crash Severity	Methodology Used	Reference
Install lighting	0.3	70	2	Nighttime, Vehicle/pedestrian	Serious injuries, minor injuries	Meta-analysis	[43]
Provide intersection illumination	0.58	42	4	Nighttime, Vehicle/pedestrian	Serious injuries, minor injuries	Meta-analysis	[44]
	0.41	59	4	Vehicle/pedestrian	Serious injuries, minor injuries	Meta-analysis	[44]
	0.19	82	3	Vehicle/pedestrian	Fatal	Meta-analysis	[44]
	0.22	78	1	Vehicle/pedestrian	Fatal	Meta-analysis	[44]
	0.56	43.8	3	Vehicle/pedestrian	All	Regression cross-section	[45]

Several other studies estimated the safety effectiveness of intersection lighting in reducing crashes. Donnell et al. estimated the safety effects of fixed lighting at different types of intersections using Minnesota intersection data [46]. By using a cross-sectional approach, the study estimated a CMF value of 0.881 for all crash severity during nighttime, indicating that the expected night-day crash ratio at intersection with lighting is approximately 12 percent lower than the expected night-day crash ratio at intersections without lighting. Torbic et al. used an Empirical Bayes observational before-after approach to estimate the effectiveness of installing single luminaire at unsignalized intersection in reducing crashes for different severity levels and crash types [47]. The study estimated the safety effectiveness of single luminaire across combined three- and four-leg intersections in Minnesota on rural two-lane roads and found CMF of 0.29 for all nighttime crashes and all crash severity, indicating a 71 percent reduction in total nighttime crashes.

In summary, several CMFs have been developed for lighting at intersections but not for lighting at crosswalks. These studies showed at least 43 percent reduction in total crashes and 42 percent in serious and minor injuries for vehicle/pedestrian crashes. Studies that looked at intersection lighting also showed a reduction in total nighttime crashes.

Conclusions

This study conducted a nationwide literature review to obtain the state of knowledge on the relationship between lighting conditions and pedestrian crashes and on the effectiveness of crosswalk lighting in improving pedestrian safety. The study focused on obtaining information on crosswalk lighting treatments, existing national guidelines for lighting at pedestrian crossings, and effectiveness of crosswalk lighting on pedestrian safety.

In the United States, pedestrian fatalities increased drastically in the past few years, from 9.8 percent in 2014 to 13.9 percent in 2016. In 2017 there were almost 6,000 pedestrians killed in traffic crashes and based on preliminary data for 2018 GHSA estimated a 4-percent increase for the first six months of 2018. According to the NHTSA 2017 Traffic Safety Facts, more pedestrian fatalities occurred in the dark (75 percent) than in daylight (21 percent). Also, the majority of pedestrian fatalities (73 percent) did not occur at intersections. Therefore, the growing prevalence of pedestrian nighttime crashes advocates for prioritizing countermeasures that improve pedestrian visibility at crosswalks, especially at midblock crossings.

One of the purposes of providing lighting at crosswalks and intersections is to make pedestrians in and near the road visible to drivers during the dark hours at a longer range than vehicle headlights typically provide. In general, visibility of pedestrians at night is affected by several factors such as street and ambient lighting, lamp type, background conditions, glare from the traffic headlights and street lamps, pedestrian clothing color, and environmental conditions. In order to increase crosswalks and pedestrian visibility, the most used crosswalks lighting countermeasure is overhead lighting. Alternative lighting technologies such as in-road flashing lights and bollard level lights have also proven to increase visibility of pedestrians or crosswalks and change driver behaviors.

Regarding the crosswalk lighting and the amount of light needed to detect pedestrians crossing during nighttime, existing national guidelines provide some recommendations to help form an engineering judgment. The FHWA guidelines recommend the light source to be located 10 ft. in front of the crosswalk at midblock locations and a vertical illuminance of 20 lux measured at a height of 5 ft. above the road surface. At uncontrolled crossing locations, the lighting should be placed 10 to 15 ft. before the crosswalk on both sides of the street and on both approaches in order to enhance light on the front of the pedestrian and avoid silhouette. AASHTO guidelines also recommend street lights to be placed on both sides of the roadway, sufficient light for pedestrian and drivers at intersections, and installing poles in advance of the crosswalk. For roundabout crosswalks, the light poles should be located 10 to 30 ft. before the crosswalk. Overall, the national guidelines recommend that transportation agencies should consider, wherever feasible, to provide adequate lighting at pedestrian crossings especially where nighttime pedestrian volumes are high.

The review of existing literature revealed a small number of studies that investigated pedestrian crashes with respect to crosswalk lighting. Effectiveness of crosswalk lighting on pedestrian safety tends to fall into one of the three categories: behavioral, modeling, and crash studies. According to the literature review, few studies looked at crashes before and after installing lighting at intersections but none with emphasis on pedestrian crosswalk lighting. The behavioral studies that investigated pedestrians and drivers' behaviors with respect to crosswalk lighting (bollard luminaire, smart lighting automatic pedestrian detection device, and in-pavement flashing lights) showed an improvement in driver awareness and yielding to pedestrians, an increase in pedestrian observational behavior, and an increase in car stopping distances before crosswalks, revealing that providing crosswalk lighting has a positive impact on pedestrian visibility and safety.

The effectiveness of crosswalk lighting based on crash database modeling studies has primarily relied upon comparing lighted crosswalks/intersections to unlighted ones using multivariate regression models. These modeling studies reveal that providing adequate lighting at midblock and intersection crosswalks is associated with lower probability of pedestrian fatalities and severe injuries.

Existing studies also revealed a variety of contributing factors to high pedestrian crashes, including dark conditions or poor lighting. However, studies that specifically looked at before-after studies of lighting improvement projects at crosswalks were lacking. Such studies are essential to fully understand which lighting countermeasures effectively impact pedestrian safety at crosswalks. Nevertheless, studies that looked at safety effectiveness of intersection lighting found that providing lighting at intersections helps to reduce nighttime crashes and increase safety. Also, the findings showed that increasing the average horizontal illuminance at intersection with at least 1 lux has a substantial impact in reducing night to day crash ratios, especially for unlighted intersections.

Although there is some evidence that the presence of crosswalk lighting, especially intersection lighting, has a positive impact on nighttime crashes, extensive before-after studies are needed to investigate the safety effects of crosswalks lighting on pedestrian visibility and crashes. Furthermore, such before-after studies are needed to develop appropriate CMFs for crosswalk lighting countermeasures for which the literature review found to be lacking. In addition, due to the possibility of unpublished studies by state agencies and smaller regional agencies or municipalities, it may be useful to conduct a survey of the states to collect information on pedestrian safety lighting countermeasures that have been implemented to improve pedestrian safety at crosswalks and rated for their effectiveness.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway and Transportation Officials
CMF	Crash Modification Factor
CRF	Crash Reduction Factor
DOTD	Department of Transportation and Development
FHWA	Federal Highway Administration
ft.	foot (feet)
GHSA	Governors Highway Safety Association
HSM	Highway Safety Manual
in.	inch(es)
LED	Light Emitting Diode
LTRC	Louisiana Transportation Research Center
lx	lux
ms	millisecond
mph	miles per hour
MUTCD	Manual on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
STEP	Safe Transportation for Every Pedestrian
TRID	Transportation Research International Documentation
TRR	Transportation Research Record

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