# Effects of crosswalk illuminators and rapid rectangular flashing beacons on speed reductions and yielding to pedestrians at night

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**Wen Hu**
Insurance Institute for Highway Safety

**Ron Van Houten**
Centre for Education and Research in Safety

**Jessica B. Cicchino**
Insurance Institute for Highway Safety

**Jacop Engle**
**Louai Al Shomaly**
Western Michigan University

IIHS

Insurance Institute for Highway Safety
4121 Wilson Boulevard, 6th floor
Arlington, VA 22203
researchpapers@iihs.org
+1 703 247 1500

iihs.org

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## ABSTRACT

**Introduction:** Dark conditions are among the circumstances under which pedestrian fatalities have experienced the largest increases. This study examines the nighttime effects of continuous and triggered illuminators at crosswalks on driver behavior: yielding to pedestrians and reducing speeds by 10 mph or more and by 5 mph or more. The study also compares the effects of rectangular rapid flashing beacons (RRFBs) in conjunction with crosswalk illuminators with RRFBs alone and with illuminators alone.

**Method:** Driver yielding to staged pedestrians as well as vehicle speeds were observed at four crosswalks at night under three conditions: baseline with existing street lighting, continuous illuminators, and triggered illuminators. At one site with RRFBs, observations were made in two additional conditions: RRFBs alone and RRFBs in conjunction with triggered illuminators. Logistic regression models evaluated the effects of these conditions on driver yielding and speed reduction.

**Results:** The study found that adding continuous and triggered illuminators at crosswalks with low-existing lighting levels made motorists more likely to yield and to reduce speeds at night. Increases in the likelihood of drivers reducing speeds were greater as speed reductions became larger. RRFBs plus triggered illuminators made drivers more likely to yield and to reduce speeds, compared with RRFBs alone or with illuminators alone.

**Conclusion:** The study findings could help agencies select appropriate nighttime treatments to enhance safety benefits for pedestrians.

**Keywords:** pedestrian safety, nighttime, yielding, crosswalk illuminators, RRFBs

# INTRODUCTION

A total of 7,388 pedestrians were killed in motor vehicle crashes in the United States in 2021, an 80% increase since reaching their lowest point in 2009 (Insurance Institute for Highway Safety, 2023). A large majority (77%) of pedestrian deaths occurred in the dark (National Center for Statistics and Analysis, 2023). Sullivan and Flannagan (2002) found that pedestrians were 3 to 6.8 times more likely to be killed at night than during the day. Dark conditions are among the circumstances under which pedestrian fatalities have experienced the largest increases (Ferenchak & Abadi, 2021; Ferenchak et al., 2022; Hu & Cicchino, 2018; Sanders et al., 2022; Tefft et al., 2021). It has been one of the focus areas for deploying pedestrian safety countermeasures.

Low lighting levels at night reduce a driver's ability to detect and recognize pedestrians. Measures such as road lighting and improved headlights can improve pedestrian visibility at night and reduce pedestrian crashes and injuries (Brumbelow, 2022; Elvik et al., 2009; Wanvik, 2009). The Federal Highway Administration has published lighting design criteria for locations with frequent pedestrian activities (Bhagavathula et al., 2021; Federal Highway Administration, 2022; Gibbons et al., 2008; Terry et al., 2020). For example, it is recommended that crosswalks have an average vertical luminance of 20 lux, and that pedestrians are illuminated in positive contrast by locating lighting in front of the crosswalk in the direction of approaching traffic. Both overhead lighting and illuminators can be used to improve pedestrian nighttime visibility at crosswalks. Overhead lighting is mounted on horizontal poles, while crosswalk illuminators typically use a narrow beam from LED flood lights mounted on poles adjacent to the roadway. Crosswalk illuminators are generally used at short crosswalks such as two-lane crossings, while overhead lighting can be used at wider crossings depending on the type of luminaires, which could provide different light distribution.

Lighting at crosswalks can be continuously on regardless of pedestrian presence or triggered when a pedestrian initiates a crossing. Triggered lighting reduces energy consumption and introduces less light pollution than lights that are continuously on. When lights are triggered, there is a sudden change in lighting intensity, which could alert drivers in addition to improving pedestrian visibility. No known research has compared the safety benefits of these two lighting formats.

At pedestrian -crossing locations, treatments such as rectangular rapid flashing beacons (RRFBs) or flashing signs that provide advanced warning of a pedestrian crossing make drivers more likely to yield during both the day and night (Brewer et al., 2019; Fitzpatrick & Park, 2021; Ross et al., 2011). RRFBs were found to be more effective at night in increasing driver yielding than during the day (Fitzpatrick & Park, 2021; Shurbutt et al., 2009). However, these previous studies did not discuss existing lighting levels at night at sites where these treatments were placed. Although RRFBs and flashing signs do not improve pedestrian detection distances (the distance between a pedestrian and where a driver detects the pedestrian) in low-light conditions, they may be used in conjunction with light treatments at the recommended vertical illuminance to enhance pedestrian visibility at night (Bhagavathula et al., 2021).

A majority of previous research on street lighting design and pedestrian safety evaluated the effects of lighting on visual performance measures such as detection distances or pedestrian contrast and did not measure driver behavior such as yielding or slowing. This made it difficult to compare the effects of roadway lighting with other pedestrian safety countermeasures. Patella et al. (2020) found a reduction in vehicle speeds associated with an LED lighting system located in the pavement at a midblock crosswalk. Lighting a crosswalk from below is more expensive than from above, and this countermeasure has not been commonly used in the United States. Nambisan et al. (2009) compared pedestrian and motorist behaviors during morning and evening peak hours (7–9 a.m. and 4–7 p.m.) before and after the installation of a lighting system at a midblock crosswalk in Las Vegas. The lighting system detected pedestrians, triggered increased illumination, and maintained the higher level of illumination for the duration that a pedestrian was detected in the crosswalk. The study found that the percentage of motorists yielding to pedestrians increased with the treatment. However, the study hours were not limited to dark conditions. Larger effects would likely be found in the dark since increased lighting would increase pedestrian visibility more effectively in the dark than during the day.

Given the gaps in existing research, this study aimed to examine the effects of both continuous and triggered illuminators at crosswalks on driver behavior at night: yielding to pedestrians and reducing speeds. The triggered condition was expected to have a larger effect, due to its alerting function associated with the sudden change in lighting intensity. The second goal of the study was to compare the effects of RRFBs in conjunction with crosswalk illuminators with RRFBs alone and with illuminators alone. Since RRFBs alert drivers of pedestrians and illuminators increase pedestrian visibility, it was assumed that the combined treatments would produce larger benefits than either treatment alone. The study findings will facilitate comparison of lighting treatments with other pedestrian safety countermeasures, and help agencies select appropriate nighttime treatments to enhance safety benefits for pedestrians.

## METHOD

Proportions of drivers who yielded to pedestrians and drivers who reduced speeds by 10 mph or more and by 5 mph or more before reaching a crosswalk at night with and without treatments were compared. All pedestrian crossings were made by a staged pedestrian, to assure crossings followed a safe protocol. All driver behavior recorded was publicly observable and no personal-identifying information was collected at any time. This project was reviewed and approved by Western Michigan University's Institutional Review Board (IRB Project Number 21-09-21).

### Study sites

Four crosswalks with continental markings in Kalamazoo, Michigan, including one at a midblock location and three at intersections, were selected (**Table 1**). The midblock crosswalk was located on a street with two lanes per direction and a speed limit of 25 mph. The three crosswalks at intersections were located on major approaches with one lane per direction and a two-way turning lane. The major approaches of intersections had no traffic control and minor approaches were stop-sign controlled with light traffic. The speed limit at intersection crosswalks was 30 mph, and an RRFB treatment was present at one of them.

**Table 1**
Data collection sites

| Site # | Crosswalk location | Location type | Speed limit (mph) | Pedestrian refuge island present | RRFB present |
|---|---|---|---|---|---|
| 1 | On Oakland Dr at W Maple St | T intersection | 30 | Yes | No |
| 2 | On Oakland Dr at Chevy Chase Blvd | Four-way intersection | 30 | No | No |
| 3 | On N Rose St between Eleanor St and W Water St | Midblock | 25 | Yes | No |
| 4 | On Parkview Ave at Barnard Ave | T intersection | 30 | Yes | Yes |

At each site, the distance between the crosswalk and the nearest existing street lighting varied: 14 ft at site #3, 40 ft at site #4, 63 ft at site #1, and 74 ft at site #2. The vertical illumination with existing street lighting was measured at each crosswalk entry location by using an illuminance meter, with the sensor held 3 ft above the ground. Staged pedestrian crossings occurred on the side of the road with the lower light level, which were less than 3 lux at sites #1, #2, and #4, and 20 lux at site #3. Only the existing street lighting at site #3 provided the recommended illuminance.

## Conditions

Data were collected under three conditions at each site: baseline condition with existing street lighting, crosswalk illuminators continuously on regardless of a pedestrian presence (referred to as continuous illuminators), and crosswalk illuminators triggered when a pedestrian initiated a crossing. At the site with RRFBs, two additional conditions were evaluated: RRFBs alone under the baseline condition and RRFBs plus triggered illuminators when a pedestrian initiated a crossing. Illuminators were used instead of overhead lighting in this study since they were portable and could be easily moved from site to site for data collection. **Table 2** summarizes the conditions tested at each site.

**Table 2**

Conditions at each site

| Conditions | Site #1 | Site #2 | Site #3 | Site #4 |
|---|---|---|---|---|
| Baseline | X | X | X | X |
| Continuous illuminators | X | X | X | X |
| Triggered illuminators | X | X | X | X |
| RRFBs alone | | | | X |
| RRFBs plus triggered illuminators | | | | X |

TAPCO Safewalk® crosswalk illuminators provided enhanced lighting at the four sites. Bhagavathula et al. (2021) measured that the same illuminators could provide a vertical illuminance of 20 lux at a crosswalk entrance. Commercially available illuminators, including the TAPCO products, can be activated automatically when the system passively detects pedestrians, or by pedestrians pushing a button. They are powered by connecting to solar panels or the electric grid. For data collection in this study, illuminators were mounted on tripods and powered by batteries for portability purposes. At each site, one illuminator was placed at each crosswalk entry location on each side of the road. At sites where there was a pedestrian refuge island (sites #1, #3, and #4), two additional illuminators were used, one at each side of the refuge island. Illuminators were placed on the side of the crosswalk closer to approaching vehicles, so that pedestrians were rendered in positive contrast. When a staged pedestrian pressed a key fob, illuminators were activated all together. Figure 1 shows two study sites under the baseline condition and with illuminators on.

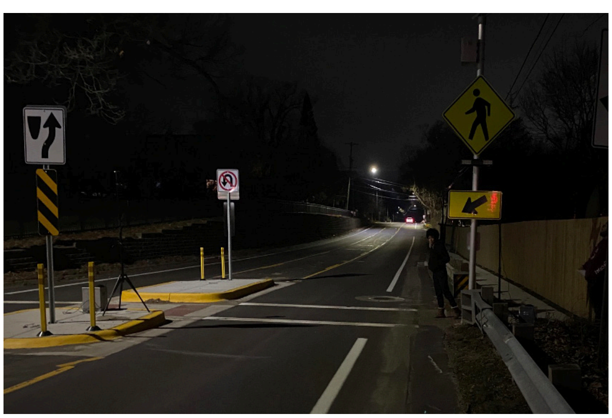
Under the continuous illuminators condition, lighting was briefly turned off after the last vehicle passed the crosswalk when there was a gap in traffic to conserve the battery. The lighting was turned back on when no vehicle was in view, so the illuminators would be active when the next vehicle appeared.

**Figure 1**

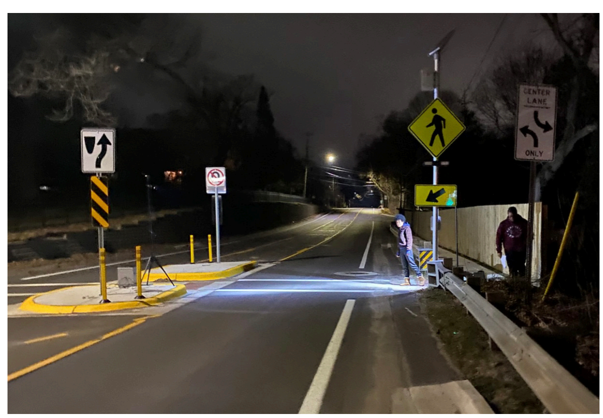
A staged pedestrian entering the crosswalk under the baseline condition and with illuminators on at sites #1 and #4

Baseline condition at site #1

Illuminators on at site #1



Baseline condition at site #4



Illuminators on at site #4

## Data collection

Data were collected beginning 1 hour after sunset under clear and dry conditions during March to May at site #1, the end of August to October at site #2, October to November at site #3, and November to December at site #4 in 2022. Summer was skipped due to the extended daytime and late sunset. Data collection started as early as 7:25 p.m. depending on the time of sunset, and ended as late as 11:30 p.m.

At each site, a stopping distance from the crosswalk was calculated based on the speed limit and was marked on the pavement, so that vehicles traveling at the speed limit could safely stop before reaching the crosswalk if they braked at or before reaching this marking. The calculated distances were 104 ft at site #3 and 141 ft at sites #1, #2, and #4, by assuming a driver reaction time of 1 sec and a deceleration rate of 10 ft/sec$^2$ as recommended by the Institute of Transportation Engineers.

Only one direction of traffic on the side with a lower lighting level was observed. As a vehicle was about to reach the distance marking, a staged pedestrian initiated a crossing by placing a foot in the crosswalk, indicating an intent to cross. The pedestrian waited until a motorist yielded, or until the vehicle had passed if no yielding occurred, before beginning to cross. The staged pedestrian wore dark clothing without any reflective material. Staged crossing trials were not conducted when natural pedestrians were present. Only straight-moving vehicles (no turning vehicles) were recorded. If there was a line of vehicles approaching, only the first vehicle in line was observed.

Speeds of all the observed vehicles at the distance marking were measured with a handheld laser device. If a vehicle stopped in front of a crosswalk, it was recorded as yielding. For vehicles that did not yield to the staged pedestrian, a second speed measurement was obtained as they reached the crosswalk. To minimize motorists' awareness of the speed observation, the person who measured speeds stayed beside or behind an object in a poorly lighted area away from the road.

On each night of data collection at each site, conditions were provided in a random order, and the same number of staged crossings were conducted under each condition. The number of crossings per condition per night ranged between 5 and 55, depending on traffic volumes. A total of 960, 888, 480, and

900 crossings were recorded at sites #1, #2, #3, and #4, respectively. Speeds at the distance marking were missing for 35 vehicles that yielded and 115 vehicles that did not yield, and speeds at the crosswalk were missing for 109 vehicles that did not yield.

## Analysis

Logistic regression models evaluated the effects of the triggered and continuous illuminators compared with the baseline condition on driver yielding, by using data collected at sites #1–2 and at site #3. Separate models were estimated for sites #1–2 and for site #3 since site #3 had a much higher baseline lighting level than sites #1–2. Another logistic regression model was estimated to examine the effects of RRFBs alone and RRFBs plus triggered illuminators, in addition to continuous and triggered illuminators, by using data collected at site #4.

In all three models, the dependent variable was a binary indicator of whether a driver yielded to the staged pedestrian (1 if yielding, 0 if not). The independent variables included observed speeds at the distance marking and indicators of data collection hours (9 p.m.–12 a.m. vs. 7–9 p.m.), data collection site (Site #2 vs. #1, in the model of sites #1–2 only), and condition. The data collection site indicator in the model of sites #1–2 was included to account for differences between the two sites such as months of data collection and road geometries.

In the models for sites #1–2 and site #3, the condition categories were continuous illuminators and triggered illuminators, with the baseline condition as the reference. In the model for site #4, the condition categories were continuous illuminators, triggered illuminators, RRFBs alone, and RRFBs plus triggered illuminators, with the baseline as the reference. Effects of the conditions compared with the baseline were calculated based on estimated parameters of the condition indicators. To compare effects between non-baseline conditions, these models were re-run by using a non-baseline condition as the reference for the condition indicators, while keeping all the other variables the same. Model estimates of the other independent variables remained the same regardless of the reference category of conditions since this was a reparameterization of a variable without interaction terms.

Similarly, logistic regression models were estimated to examine the effects of treatments on the likelihood that a driver, including those who yielded, reduced speeds by 10 mph or more and by 5 mph or more before reaching the crosswalk. Separate models were estimated for sites #1–2, site #3, and site #4. The dependent variable of the models was a binary indicator of speed reduction (1 if speed reduced by 10 mph or more/by 5 mph or more, 0 if not). The independent variables were the same as in the models of drivers yielding.

Odds ratios (ORs) derived from logistic regression models are not good approximations for relative risk ratios (RRs) when the incidence of an outcome is not rare in the study population (i.e., greater than 10%), as is true for motorists yielding and reducing speeds to pedestrians. As a result, odds ratios were transformed into relative risks as $RR = OR/[(1 - P_0) + (P_0 \times OR)]$, where $P_0$ represents the proportion of vehicles yielding to pedestrians or the proportion of non-yielding vehicles reducing speeds under the baseline condition (Zhang & Yu, 1998). Variables with *p* values less than 0.05 were considered statistically significant.

## RESULTS

At sites #1 and #2, the proportions of drivers who yielded to pedestrians and the proportions who reduced speeds by 10 mph or more and by 5 mph or more before reaching the crosswalk increased with the illuminators on (continuous or triggered), compared with the baseline condition (**Table 3**). These proportions were slightly smaller under the triggered than under the continuous illuminators condition.

At site #3 where existing street lighting had provided the recommended illuminance, the proportions were the lowest under the baseline condition, and the highest under the triggered illuminators condition. Differences in proportions under the three conditions were relatively small. Under the baseline condition, the proportions of drivers yielding and drivers reducing speeds by 10 mph or more at site #3 were much higher than the baseline proportions at the other sites.

At site #4, these proportions were the lowest under the baseline condition, followed by triggered illuminators, RRFBs alone, and continuous illuminators, and the highest under the RRFBs plus triggered illuminators condition.

At sites #1, #2, and #4 with a speed limit of 30 mph, the mean measured speeds at the distance markings were all 34 mph and the 85th percentile speeds were 38 mph, 39 mph, and 38 mph, respectively. At site #3 with a 25-mph speed limit, the mean speed at the distance marking was 25 mph and the 85th percentile speed was 31 mph.

**Table 3**

Proportions of drivers who yielded to a pedestrian and who reduced speeds by ≥ 10 mph and by ≥ 5 mph, by condition

| Conditions | All observed vehicles | Those who yielded | | Those who reduced speeds by ≥ 10 mph[a] | | Those who reduced speeds by ≥ 5 mph[a] | |
|---|---|---|---|---|---|---|---|
| | No. | No. | % | No. | %* | No. | %[b] |
| **Site #1** | | | | | | | |
| Baseline | 320 | 38 | 11.9 | 54 | 19.4 | 101 | 36.2 |
| Continuous illuminators | 320 | 135 | 42.2 | 142 | 50.4 | 188 | 66.7 |
| Triggered illuminators | 320 | 121 | 37.8 | 139 | 48.6 | 178 | 62.0 |
| **Site #2** | | | | | | | |
| Baseline | 296 | 22 | 7.4 | 24 | 8.6 | 36 | 12.9 |
| Continuous illuminators | 296 | 78 | 26.4 | 83 | 28.8 | 103 | 35.8 |
| Triggered illuminators | 296 | 65 | 22.0 | 67 | 23.8 | 82 | 29.1 |
| **Site #3** | | | | | | | |
| Baseline | 160 | 44 | 27.5 | 43 | 28.7 | 53 | 35.3 |
| Continuous illuminators | 160 | 51 | 31.9 | 52 | 34.0 | 63 | 40.9 |
| Triggered illuminators | 160 | 56 | 35.0 | 57 | 37.8 | 63 | 41.5 |
| **Site #4** | | | | | | | |
| Baseline | 180 | 8 | 4.4 | 18 | 10.1 | 38 | 21.2 |
| Continuous illuminators | 180 | 49 | 27.2 | 70 | 39.3 | 107 | 60.1 |
| Triggered illuminators | 180 | 45 | 25.0 | 54 | 30.0 | 90 | 50.0 |
| RRFBs alone | 180 | 48 | 26.7 | 66 | 37.1 | 107 | 60.1 |
| RRFBs plus triggered illuminators | 180 | 101 | 56.1 | 119 | 66.9 | 144 | 80.9 |

[a] Includes those who yielded.

[b] The calculation of these proportions excluded observations with missing speed measurements.

## Logistic regression results on drivers yielding and reducing speeds

Based on logistic regression modeling results (**Tables A1–A2** in the Appendix), the estimated effects of continuous and triggered illuminators, RRFBs alone, and RRFBs plus triggered illuminators on the likelihood that a driver yielded to pedestrians and that a driver reduced the speed are summarized in **Table 4** for sites #1–2, Table 5 for site #3, and Table 6 for site #4.

***Sites #1–2 (suboptimal baseline lighting)***

At sites #1 and 2, the likelihoods that a driver yielded to a pedestrian were 275.5% higher with the continuous illuminators and 222.4% higher with the triggered illuminators, compared with the baseline condition (**Table 4**). Both effects were statistically significant. A driver was 14.5% less likely to yield under the triggered than under the continuous illuminators condition, but the difference was not significant.

The likelihood that a driver reduced the speed by 10 mph or more was significantly higher under continuous and triggered illuminators (211.6% and 182.3%, respectively) than under the baseline condition. A driver was 9.8% less likely to reduce the speed by 10 mph or more under the triggered than under the continuous illuminators condition, but the difference was not significant.

When compared with the baseline condition, the likelihood that a driver reduced the speed by 5 mph or more was 130.9% higher with the continuous illuminators, and 102.0% higher with the triggered illuminators. Both increases were statistically significant. A driver was 13.5% less likely to reduce the speed by 5 mph or more under the triggered than under the continuous illuminators condition, and the difference was significant.

***Site #3 (optimal baseline lighting)***

At site #3, the likelihoods of a driver yielding and slowing were 14.7% to 29.9% higher under continuous and triggered illuminators, compared with the baseline condition, but none of the increases were statistically significant (**Table 5**). Under the triggered relative to the continuous lighting condition, drivers were more likely to yield or to reduce speeds by 10 mph or more, and slightly less likely to reduce speeds by 5 mph or more. None of the differences were statistically significant.

***Site #4 (with RRFBs, suboptimal baseline lighting)***

At site #4, the likelihoods that a driver yielded to a pedestrian increased significantly under all the treatment conditions compared with the baseline, with the highest increase of 1,211.2% associated with the RRFBs plus triggered illuminators condition (**Table 6**). Increases in the likelihoods relative to the baseline did not differ significantly among continuous and triggered illuminators and RRFBs alone. Under the RRFBs plus triggered illuminators condition, a driver was 109.1% to 125.1% more likely to yield than under the other non-baseline conditions, and these differences were statistically significant.

All the treatments significantly increased the likelihood that a driver reduced the speed by 10 mph or more and by 5 mph or more, compared with the baseline condition. The triggered illuminators condition was associated with the smallest increases. Under this condition, a driver was 204.0% more likely to reduce the speed by 10 mph or more and 136.7% more likely to reduce the speed by 5 mph or more. The continuous lighting condition and RRFBs alone were associated with similar increases in the likelihoods that a driver reduced the speed by 10 mph or more (294.7% vs. 267.2%) and by 5 mph or more (184.2% vs. 184.0%). The largest increases in the likelihoods that a driver reduced the speed occurred under the RRFBs plus triggered illuminators condition: 570.3% (by 10 mph or more) and 282.3% (by 5 mph or more).

Drivers were more likely to reduce speeds under the RRFBs plus triggered illuminators condition than under the other non-baseline conditions: 70.9% to 123.2% more likely to reduce speeds by 10 mph or more, and 34.7% to 61.9% more likely to reduce speeds by 5 mph or more. The speed-reducing effects were not significantly different among the continuous illuminators, triggered illuminators, and RRFBs alone.

While not summarized in **Tables 4–6**, speed at the distance marking was consistently a significant variable in these models: the higher the speed, the less likely a driver yielded to a pedestrian or reduced speed at all four sites (**Tables A1–A2**).

**Table 4**

Summary of results from logistic regression models of percentage changes in the likelihood that drivers yielded to pedestrians and reduced speeds by ≥ 10 mph and by ≥ 5 mph at sites #1–2

| Effects of | Vs. baseline | | Vs. continuous illuminators | |
|---|---|---|---|---|
| | % change in likelihood | P value | % change in likelihood | P value |
| **Likelihood that a driver yielded to a pedestrian at sites #1–2** | | | | |
| Continuous illuminators | 275.5 | <.0001 | | |
| Triggered illuminators | 222.4 | <.0001 | −14.5 | 0.0880 |
| **Likelihood that a driver reduced speeds by ≥ 10 mph at sites #1–2**[a] | | | | |
| Continuous illuminators | 211.6 | <.0001 | | |
| Triggered illuminators | 182.3 | <.0001 | −9.8 | 0.2240 |
| **Likelihood that a driver reduced speeds by ≥ 5 mph at sites #1–2**[a] | | | | |
| Continuous illuminators | 130.9 | <.0001 | | |
| Triggered illuminators | 102.0 | <.0001 | −13.5 | 0.0425 |

[a] Includes those who yielded.

**Table 5**

Summary of results from logistic regression models of percentage changes in the likelihood that drivers yielded to pedestrians and reduced speeds by ≥ 10 mph and by ≥ 5 mph at site #3

| Effects of | Vs. baseline | | Vs. continuous illuminators | |
|---|---|---|---|---|
| | % change in likelihood | P value | % change in likelihood | P value |
| **Likelihood that a driver yielded to a pedestrian at site #3** | | | | |
| Continuous illuminators | 17.9 | 0.3801 | | |
| Triggered illuminators | 25.1 | 0.2197 | 6.2 | 0.7280 |
| **Likelihood that a driver reduced speeds by ≥ 10 mph at site #3** [a] | | | | |
| Continuous illuminators | 18.9 | 0.3323 | | |
| Triggered illuminators | 29.9 | 0.1317 | 9.2 | 0.5879 |
| **Likelihood that a driver reduced speeds by ≥ 5 mph at site #3** [a] | | | | |
| Continuous illuminators | 15.6 | 0.3403 | | |
| Triggered illuminators | 14.7 | 0.3700 | −0.8 | 0.9549 |

[a] Includes those who yielded.

**Table 6**

Summary of results from logistic regression models of percentage changes in the likelihood that drivers yielded to pedestrians and reduced speeds by ≥ 10 mph and by ≥ 5 mph at site #4

| Effects of | Vs. baseline | | Vs. continuous illuminators | | Vs. triggered illuminators | | Vs. RRFBs alone | |
|---|---|---|---|---|---|---|---|---|
| | % change in likelihood | P value | % change in likelihood | P value | % change in likelihood | P value | % change in likelihood | P value |
| **Likelihood that a driver yielded to a pedestrian at site #4** | | | | | | | | |
| Continuous illuminators | 533.4 | <.0001 | | | | | | |
| Triggered illuminators | 493.3 | <.0001 | −6.4 | 0.7165 | | | | |
| RRFBs alone | 487.2 | <.0001 | −7.3 | 0.6737 | −1.0 | 0.9557 | | |
| RRFBs plus triggered illuminators | 1,211.2 | <.0001 | 109.1 | <.0001 | 125.1 | <0.0001 | 120.1 | <.0001 |
| **Likelihood that a driver reduced speed by ≥ 10 mph at site #4** [a] | | | | | | | | |
| Continuous illuminators | 294.7 | <.0001 | | | | | | |
| Triggered illuminators | 204.0 | <.0001 | −23.1 | 0.0751 | | | | |
| RRFBs alone | 267.2 | <.0001 | −7.0 | 0.5960 | 21.0 | 0.2101 | | |
| RRFBs plus triggered illuminators | 570.3 | <.0001 | 70.9 | <.0001 | 123.2 | <.0001 | 82.5 | <.0001 |
| **Likelihood that a driver reduced speed by ≥ 5 mph at site #4** [a] | | | | | | | | |
| Continuous illuminators | 184.2 | <.0001 | | | | | | |
| Triggered illuminators | 136.7 | <.0001 | −16.8 | 0.0570 | | | | |
| RRFBs alone | 184.0 | <.0001 | −0.1 | 0.9953 | 20.1 | 0.0581 | | |
| RRFBs plus triggered illuminators | 282.3 | <.0001 | 34.7 | <.0001 | 61.9 | <.0001 | 34.7 | <.0001 |

[a] Includes those who yielded.

## DISCUSSION

This study found that adding crosswalk illuminators at sites with low-existing lighting levels made motorists more likely to yield to pedestrians and to reduce speeds before reaching the crosswalk at night. Increases in the likelihoods of drivers reducing speeds were greater as speed reductions became larger. Bhagavathula et al. (2021) found that crosswalk illuminators including the TAPCO product provided optimal nighttime visibility of pedestrians and long pedestrian detection distances. The current study further confirmed the pedestrian safety benefits of crosswalk illuminators by providing direct measures of improvements in driver behavior at night.

RRFBs plus triggered illuminators made drivers more likely to yield and to reduce speeds in the presence of pedestrians, compared with RRFBs alone or illuminators alone. RRFBs flash with an alternating high frequency when activated. Flashing lights effectively capture drivers' visual attention and alert them to the presence of pedestrians as a bottom-up system (Costa et al., 2018; Costa et al., 2020; Vignali et al., 2019). However, they serve more of a warning than a lighting purpose (Costa et al., 2020). RRFBs and flashing signs do not illuminate pedestrians in any way and could not help drivers see pedestrians in low-light conditions (Bhagavathula et al., 2021). When RRFBs are used together with illuminators at the recommended illuminance at night, drivers' awareness and pedestrian visibility both improve and as a result, the combined treatments lead to greater benefits than RRFBs alone or illuminators alone. Although previous research has shown the safety benefits of RRFBs at night, it was not clear what the existing lighting conditions were at the study sites. Based on the current finding and Bhagavathula et al. (2021), it is suggested that when installing RRFBs at sites that are not well-lit, agencies should consider adding lighting to ensure optimal visibility of pedestrians and to maximize the safety benefits of RRFBs. There are commercially available products that combine RRFBs and illuminators.

The effects of the continuous illuminators were found to be generally larger than the triggered illuminators, although the differences were small and not always significant. When designing the current study, we expected larger effects for the triggered rather than the continuous light condition because a sudden increase in light intensity could alert drivers in addition to an increase in the lighting level. However, the results indicate that the alerting effect might not be as significant as was expected at study sites. When used together with RRFBs, the effectiveness of triggered illuminators significantly increased, indicating that flashing lights could provide a more effective warning than a sudden change in lighting intensity. How triggered lighting could be implemented in the real world would also impact its effectiveness. For example, if it is triggered by pedestrians pushing a button, there may be even smaller benefits than what the current study found since some pedestrians would not activate it (Al-Kaisy et al., 2018; Kutela & Teng, 2020). The underuse of triggered lighting can be overcome by a lighting system that automatically turns on when it detects pedestrians.

At the site with the optimal baseline lighting condition and a much higher baseline yielding rate than the other sites, adding the illuminators (triggered or continuous) did not significantly improve driver yielding or slowing. Higher lighting levels than recommended at crosswalks did not significantly increase pedestrian visibility (Bhagavathula et al., 2021) and as a result, may not provide much additional pedestrian safety benefit. This site differed from the other sites in additional ways (midblock vs. intersections, a lower speed limit), which might also have contributed to the different findings. Even though the treatments significantly improved driver behavior at the three study crosswalks with poor baseline lighting conditions, the percentages of drivers yielding with treatments in place were lower than nighttime yielding levels reported in some previous research of RRFBs; over 90% by Shurbutt et al. (2009), for example. It is possible that the differences in driver yielding rates among the previous and current studies were due to differences in study site characteristics. Given that the current study only examined one site with optimal baseline lighting and one with RRFBs, future research could investigate the robustness of the effects reported here by collecting data at a larger number of sites with diverse characteristics that allow for control of environmental conditions like speed limits, location types (e.g., intersection vs. midblock), numbers of lanes, land use or nearby development, and street lighting levels.

Speeds are an important factor in pedestrian safety, as higher speeds substantially increase the risk of severe and fatal injury to a pedestrian (Tefft, 2013). The faster a vehicle travels, the longer it takes for the vehicle to stop. The current study also found that the faster a driver was traveling, the less likely that the driver yielded to a pedestrian. Even if the lighting enhancement helps motorists see pedestrians better, a fast-traveling driver may not be able to stop the vehicle in time to avoid hitting the pedestrian. At all the crosswalks selected for the current study, the 85th percentile speeds were 6–9 mph over the speed limits. Measures to reduce speeds such as traffic-calming devices (Hu & Cicchino, 2020a; Retting et al., 2003; Rothman et al., 2015), lowering speed limits in urban areas (Hu & Cicchino, 2020b, 2024), and speed safety cameras (Hu & McCartt, 2016; Retting & Farmer, 2003; Retting et al., 2008; Wilson et al., 2010) can increase yielding and pedestrian safety. In addition to improved lighting, other crosswalk visibility enhancements such as highly reflective crosswalk markings and advance yield or stop markings and signs can also help make pedestrians more visible and improve yielding rates (Chen et al., 2012; Zegeer et al., 2017).

Safe vehicles together with other safe system elements such as safe speeds and safe roads provide layers of protection to promote the safety of all road users. Pedestrian automatic emergency braking (AEB) systems can detect pedestrians and mitigate or avoid a crash with a pedestrian by warning the driver and automatically applying the brakes if the driver does not respond. Such systems have been found to reduce pedestrian crashes (Cicchino, 2022; Wakeman et al., 2019). These benefits were observed in dark and lighted conditions, but not under dark conditions without street lighting (Cicchino, 2022). Research that evaluates how different types of lighting treatments affect pedestrian AEB performance would help further improve these systems and pedestrian safety.

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## APPENDIX: LOGISTIC REGRESSION MODELING RESULTS

**Table A1**

Logistic regression results of whether a driver yielded to a pedestrian

| Parameter | | Estimate | P value |
|---|---|---|---|
| **Sites #1–2** | | | |
| Intercept | | 3.8162 | <.0001 |
| Condition | Continuous illuminators vs. baseline | 1.6759 | <.0001 |
| | Triggered illuminators vs. baseline | 1.4450 | <.0001 |
| Speeds at the distance marking (mph) | | −0.1744 | <.0001 |
| Hours | 9 p.m.–12 a.m. vs. 7–9 p.m. | 0.1286 | 0.6683 |
| Site | Site #2 vs. #1 | −0.8314 | <.0001 |
| **Site #3** | | | |
| Intercept | | 2.1597 | <.0001 |
| Condition | Continuous illuminators vs. baseline | 0.2344 | 0.3801 |
| | Triggered illuminators vs. baseline | 0.3246 | 0.2197 |
| Speed at the distance marking (mph) | | −0.1248 | <.0001 |
| Hours | 9 p.m.–12 a.m. vs. 7–9 p.m. | −0.2783 | 0.2044 |
| **Site #4, with RRFBs** | | | |
| Intercept | | 0.3961 | 0.5858 |
| Condition | Continuous illuminators vs. baseline | 2.1276 | <.0001 |
| | Triggered illuminators vs. baseline | 2.0380 | <.0001 |
| | RRFBs alone vs. baseline | 2.0242 | <.0001 |
| | RRFBs plus triggered illuminators vs. baseline | 3.3887 | <.0001 |
| Speed at the distance marking (mph) | | −0.1105 | <.0001 |
| Hours | 9 p.m.–12 a.m. vs. 7–9 p.m. | 0.3933 | 0.0175 |

*Note.* Modeling results shown in the table used baseline as the treatment reference category. When a different reference treatment category was used, estimates of all other independent variables remained the same.

**Table A2**

Logistic regression results of whether drivers reduced speeds by ≥ 10 mph and by ≥ 5 mph

| Parameter | | Modeling likelihood that a driver reduced speed: by ≥ 10 mph Estimate | by ≥ 10 mph P value | | by ≥ 5 mph Estimate | by ≥ 5 mph P value |
|---|---|---|---|---|---|---|
| **Sites #1–2** | | | | | | |
| Intercept | | 2.7082 | <.0001 | | 2.1996 | <.0001 |
| Condition | Continuous illuminators vs. baseline | 1.5030 | <.0001 | | 1.3060 | <.0001 |
| | Triggered illuminators vs. baseline | 1.3444 | <.0001 | | 1.0473 | <.0001 |
| Speed at the distance marking (mph) | | −0.1299 | <.0001 | | −0.0851 | <.0001 |
| Hours | 9 p.m.–12 a.m. vs. 7–9 p.m. | 0.2685 | 0.3624 | | 0.1345 | 0.6116 |
| Site | Site #2 vs. #1 | −1.0758 | <.0001 | | −1.3791 | <.0001 |
| **Site #3** | | | | | | |
| Intercept | | 1.8715 | <.0001 | | 1.7127 | 0.0001 |
| Condition | Continuous illuminators vs. baseline | 0.2527 | 0.3323 | | 0.2340 | 0.3403 |
| | Triggered illuminators vs. baseline | 0.3897 | 0.1317 | | 0.2204 | 0.3700 |
| Speed at the distance marking (mph) | | −0.1059 | <.0001 | | −0.0866 | <.0001 |
| Hours | 9 p.m.–12 a.m. vs. 7–9 p.m. | −0.3579 | 0.0939 | | −0.3072 | 0.1324 |
| **Site #4, with RRFBs** | | | | | | |
| Intercept | | −0.6247 | 0.3200 | | −1.0699 | 0.0679 |
| Condition | Continuous illuminators vs. baseline | 1.7752 | <.0001 | | 1.7286 | <.0001 |
| | Triggered illuminators vs. baseline | 1.3722 | <.0001 | | 1.3201 | <.0001 |
| | RRFBs alone vs. baseline | 1.6578 | <.0001 | | 1.7273 | <.0001 |
| | RRFBs plus triggered illuminators vs. baseline | 2.9260 | <.0001 | | 2.7664 | <.0001 |
| Speed at the distance marking (mph) | | −0.0538 | 0.0019 | | −0.0120 | 0.4621 |
| Hours | 9 p.m.–12 a.m. vs. 7–9 p.m. | 0.4911 | 0.0013 | | 0.3556 | 0.0163 |

*Note*. Modeling results shown in the table used baseline as the treatment reference category. When a different reference treatment category was used, estimates of all other independent variables remained the same.