Evaluation of Pedestrian Hybrid Beacons and Rapid Flashing Beacons

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Pedestrian and Bicycle Safety

U.S. Department of Transportation
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Research, Development, and Technology
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FOREWORD

The overall goal of the Federal Highway Administration's (FHWA) Pedestrian and Bicycle Safety Research Program is to improve safety and mobility for pedestrians and bicyclists. The program strives to make it safer and easier for pedestrians, bicyclists, and drivers to share roadways through the development of safer crosswalks, sidewalks, and pedestrian technologies as well as through the expansion of educational and safety programs.

This report documents an FHWA project that includes four studies that investigated how characteristics of rectangular rapid-flashing beacons (RRFBs) and pedestrian hybrid beacons (PHBs) affected the likelihood of drivers yielding to a pedestrian. The results of this project supported the development of two *Manual on Uniform Traffic Control Devices* official interpretations for the RRFB: Official Interpretation #4(09)-41 (I)—*Additional Flash Pattern for RRFBs* and Official Interpretation #4(09)-58 (I)—*Placement of RRFB Units Above Sign*.[1–3] The overall 96 percent high yielding for PHBs identified in this research, along with findings from previous studies, support the use of this device at a variety of locations, such as on high-speed roads, wide roads, and at residential intersections.

This report should be of interest to engineers, planners, and other community authorities who share an interest in safeguarding the lives of roadway users, especially pedestrians.

Monique R. Evans
Director, Office of Safety
Research and Development

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16. Abstract

Two pedestrian treatments receiving national attention are the rectangular rapid-flashing beacon (RRFB) and the pedestrian hybrid beacon (PHB). These devices have unique characteristics that produce improved vehicle stopping and yielding to crossing pedestrians. This Federal Highway Administration (FHWA) project includes multiple studies to help refine these devices. A closed-course RRFB study measured the time to determine the position and direction of a cutout representation of a pedestrian on a crosswalk to identify conditions that produced faster and more accurate recognition. Placing the beacons above rather than below the warning sign produced better recognition. A following open-road study investigated driver yielding when the beacons were located above and below the warning sign at 13 sites. Results indicated that any differences between the above and below positions were minor and statistically insignificant. With the apparent benefits identified from the closed-course study (i.e., lower discomfort and improved ability to detect the pedestrian) and the lack of difference in driver yielding, locating the beacons above the sign could improve the overall effectiveness of this treatment. FHWA issued an official interpretation in early 2016 to permit the placement of the beacons above the sign.(3) An open-road study was also conducted to determine driver yielding for different RRFB flash patterns at eight sites, seven of which were four-lane crossings with 40- or 45-mi/h speed limits. The patterns selected for evaluation were the 2-5 flash pattern (two flashes on one side followed by five flashes on other side) that was currently in use, a pattern using a combination of wig-wag and simultaneous (WW+S) flashes, and a pattern using a combination of long and short flashes called "blocks." The statistical analysis showed no statistical significant difference between patterns; in other words, the newer patterns were as effective as the 2-5 flash pattern. As a result, FHWA issued an official interpretation indicating the preference for the WW+S pattern.(2) In the final study, behaviors at PHBs were investigated. The PHB has shown great potential in improving safety and driver yielding; however, questions have been asked regarding actual driver and pedestrian behavior. For the 20 PHB sites in the open-road study, driver yielding to pedestrians averaged 96 percent. Overall, 91 percent of the pedestrians pushed the pushbutton to activate the PHB in the crosswalk. A greater percentage number of pedestrians activated the device when on 45-mi/h posted speed limit roads as compared to roads with posted speed limits of 40 mi/h or less.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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LIST OF ABBREVIATIONS

ADT	average daily traffic
ANOVA	analysis of variance
BEC	beyond end of cycle
CRFB	circular rapid-flashing beacon
DF	degrees of freedom
FHWA	Federal Highway Administration
GLMM	generalized linear mixed effects model
HAWK	high-intensity activated crosswalk
IA	interim approval
IQR	interquartile range
LED	light-emitting diode
LMM	linear mixed effects model
LT	left-turn movement originating from the major street
LT1	left-turn movement originating from the minor street
MOE	measure of effectiveness
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
NPA	Notice of Proposed Amendment
NCUTCD	National Committee on Uniform Traffic Control Devices
PHB	pedestrian hybrid beacon
RRFB	Rectangular rapid-flashing beacon
RT2	right-turn movement originating from the minor street
SAE	Society of Automotive Engineers
SSD	stopping sight distance
STC	Signals Technical Committee
TAMU	Texas A&M University
TCS	traffic control signal
TH1/TH2	through movements on the minor-street approaches
TTI	Texas A&M Transportation Institute
TWLTL	Two-way left-turn lane
WW+S	wig-wag and simultaneous

CHAPTER 1. INTRODUCTION

BACKGROUND

Two pedestrian treatments receiving national attention are the rectangular rapid-flashing beacon (RRFB) and the pedestrian hybrid beacon (PHB) (originally termed High-intensity Activated crossWalK (HAWK) when developed). These devices have noteworthy characteristics that produce improved vehicle stopping and yielding behavior to crossing pedestrians. Characteristics include brighter indications, unique beacon arrangements and flash patterns, and activation only when pedestrians are present. The PHB was added to the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD).(1) The Federal Highway Administration (FHWA) provided Interim Approval 11 (IA-11) for the optional use of the RRFB at uncontrolled pedestrian and school crosswalks on July 16, 2008.(4)

The Signals Technical Committee (STC) of the National Committee on Uniform Traffic Control Devices (NCUTCD) assists in developing language for chapter 4 of the MUTCD.(1) STC is interested in research and/or assistance in the development or refinement of material on these devices, especially the RRFB, which is being considered for the next edition of the MUTCD. This FHWA project included studies that can help with refining these devices.

STUDY OBJECTIVE

The objectives of the four studies performed under this FHWA project were refined during the course of the research. The revised objectives are based on proposed research plans that were modified using comments from FHWA and the project panel. Specific objectives are highlighted in the following subsections.

Impact of Rapid-Flashing Yellow Light-Emitting Diodes (LEDs) on Detecting Pedestrians in a Closed-Course Setting

The objectives of the closed-course study were as follows:

- Quantify the effect of traffic control device brightness on drivers' ability to detect pedestrians in and around a pedestrian crossing, which is a measure of disability glare.

- Quantify the effect different flashing beacon assembly characteristics have on drivers' ability to detect pedestrians in and around a pedestrian crossing, which is a measure of disability glare.

- Quantify drivers' perception of discomfort and relate it to their ability to detect pedestrians in and around a pedestrian crossing, which is a measure of discomfort glare.

Driver-Yielding Results for Beacons Placed Above or Below Crossing Sign in an Open-Road Setting

The objective of the open-road study was to identify motorist yielding rates for the different test conditions selected at the conclusion of the closed-course study. Specifically, the test conditions selected included placing the rectangular beacons above and below the sign.

Driver-Yielding Results for Three Rectangular Rapid-Flash Patterns in an Open-Road Setting

The objective of the flash pattern study was to determine if simpler flash patterns than the one that was tested prior to the issuance of IA-11 would be equally effective or more effective in encouraging driver yielding at crosswalks.[(4)]

PHB Study

The objective of the PHB study was to evaluate driver and pedestrian behaviors at PHB installations. This study was to provide insight into the actual behavior of motorists, bicyclists, and pedestrians at locations with a PHB.

APPROACH

The research was conducted in a series of tasks as follows:

- **Task 1—Hold Kickoff Meeting and Develop Work Plans**: The research team met with FHWA staff to discuss the project direction, scope, and work plan.
- **Task 2—Develop Research Plan for Each Countermeasure**: The research team revised and expanded the work plans using comments from FHWA and the panel.
- **Task 3—Collect and Analyze Data**: The research team conducted the four studies.
- **Task 4—Develop Draft Marketing, Communications, and Outreach Plan:** The research team identified products that could be developed that would be useful to engineers, planners, and other practitioners who have an interest in implementing pedestrian and bicycle treatments.
- **Task 5—Develop Technical Briefs and Conduct Final Briefing Meeting**: The research team developed a TechBrief for each of the studies. A final briefing meeting was held at FHWA’s Turner-Fairbank Highway Research Center in McLean, VA, in November 2015 that included FHWA, members of the research team, and the panel.
- **Task 6—Develop Final Deliverables**: The research team developed the final deliverables which included this comprehensive technical report that documents all aspects of the project’s activities and findings.

REPORT ORGANIZATION

This report includes the following chapters:

- **Chapter 1. Introduction**: Presents general background information along with the research objectives.
- **Chapter 2. Literature Review**: Presents background and recent findings on RRFBs and a literature review of PHBs.
- **Chapter 3. Impact of Rapid-Flashing Yellow LEDs on Detecting Pedestrians in a Closed-Course Setting**: Describes the methodology and results from the closed-course study that examined LED brightness, position, and flash patterns.
- **Chapter 4. Driver-Yielding Results for Beacons Placed Above or Below Crossing Sign in an Open-Road Setting**: Describes the methodology and results from the open-road study that investigated the effects of the placement of yellow rapid-flashing beacons above or below the pedestrian crossing sign.
- **Chapter 5. Driver-Yielding Results for Three Rectangular Rapid-Flash Patterns in an Open-Road Setting**: Describes the methodology and results from the open-road study that examined different flash patterns for use with yellow rapid-flashing beacons.
- **Chapter 6. PHB Study**: Describes the methodology and results from the study that examined driver and pedestrian behavior at PHBs.
- **Chapter 7. Summary/Conclusions, Discussion, and Future Research Needs**: Provides a summary and the conclusions of the research and presents future research needs.

CHAPTER 2. LITERATURE REVIEW

Efforts during the initial phase of this project included literature reviews of selected pedestrian treatments as needed to build upon a previous FHWA study.[5] The previous FHWA study contains a comprehensive literature review of pedestrian treatments being used at unsignalized pedestrian crossings, and readers are encouraged to review that report if a review of the literature is sought. This chapter provides background information on the RRFB and a review of recently published literature that is relevant to the efforts within this project.

FHWA INTERIM APPROVAL OF RRFBs

On July 16, 2008, FHWA provided IA-11 for the optional use of the RRFB.[4] FHWA approved the use of this device at uncontrolled pedestrian and school crosswalks. As defined in IA-11, the RRFB is to consist of two rapidly and alternately flashing rectangular yellow indicators having LED-array based pulsing light sources.[4] Within the IA-11, there are the following seven items with subsections:

1. General conditions.
2. Allowable uses.
3. Sign/beacon assembly locations.
4. Beacon dimensions and placement in sign assembly.
5. Beacon flashing requirements.
6. Beacon operations.
7. Other.

FHWA OFFICIAL INTERPRETATIONS

As of November 2015, FHWA has released several official interpretations concerning the interim approval of RRFBs, including the following:

- 4-376 (I) on overhead mounting of RRFBs (December 9, 2009).[6]
- 4(09)-5 (I) on using RRFBs with the W11-15 sign (August 12, 2010).[7]
- 4(09)-17 (I) on RRFB light intensity (January 9, 2012).[8]
- 4(09)-21 (I) on clarification of RRFB flashing pattern (June 13, 2012).[9]
- 4(09)-22 (I) on flashing pattern for existing RRFBs (August 8, 2012).[10]
- 4(09)-24 (I) on daytime dimming of RRFBs (September 27, 2012).[11]

- 4(09)-37 (I) on the definition of dimming (October 9, 2013).[12]
- 4(09)-38 (I) on RRFB flashing extensions and delays (October 22, 2013).[13]
- 4(09)-41 (I) on additional flash patterns for RRFBs (July 25, 2014).[2]

Another interpretation letter that may be of interest is 4(09)-11 (I) on flashing beacons maximum mounting height, which was released on June 29, 2011.[14]

Table 1 summarizes key components for each of the official interpretations released prior to 2014. Table 2 summarizes the interpretations that were developed using results from this FHWA research study.

Table 1. Summary of RRFB official interpretations released prior to 2014.

Number	Summary of Key Characteristics Relevant to this Study
4-376 (I)[6]	Interpretation letter 4-376 (I) indicates that overhead mounting of the pedestrian crossing (W11-2) warning sign or school crossing (S1-1) warning sign with a RRFB is appropriate. When the W11-2 or S1-1 sign is mounted overhead, only a minimum of one such sign per approach is required, and it should be located over the approximate center of the lanes of the approach. It also indicates that "for roadside signs, the MUTCD establishes no maximum mounting height. Therefore, W11-2 or S1-1 signs with W16-7P plaques could be installed at a mounting height much higher than the normal 7 feet, perhaps 15 to 17 feet or more, and still comply with the MUTCD and the IA-11 technical provisions."[6](pg. 2)
4(09)-5 (I)[7]	Interpretation letter 4(09)-5 (I) states that the "RRFB may be used to supplement a W11-15 sign at a shared-use trail crossing if the W11-15 substitutes for the W11-2 and is placed at the crosswalk."[7](pg. 1)
4(09)-11 (I)[14]	Interpretation letter 4(09)-11 (I) states that "the maximum mounting height of a flashing warning beacon mounted over the roadway shall be 25.6 ft, measured from pavement surface to the top of the housing of the beacon."[14](pg. 1)
4(09)-17 (I)[8]	Official interpretation number 4(09)-17 (I) clarifies that the light intensity of RRFBs shall meet the minimum intensity requirements for class 1 optical warning devices within SAE Standard J595, as opposed to classes 2 or 3 minimum intensity requirements.[15] The SAE J595 peak luminous intensity requirements for classes 2 and 3 are only about 25 and 10 percent, respectively, of the peak luminous intensity requirement for class 1.[15]
4(09)-21 (I)[9]	A detailed review of the flash pattern used with the original RRFB installation resulted in a change in the requirements. Official interpretation 4(09)-21 (I) changes item 5b to read, "b. As a specific exception to 2003 MUTCD Section 4k.01 requirements for the flash rate of beacons, RRFBs shall use a much faster flash rate. Each of the two yellow indication of an RRFB shall have 70 to 80 periods of flashing per minute and shall have alternating, but approximately equal, periods of rapid pulsing light emissions and dark operation. During each of its 70 to 80 flashing periods per minute, the yellow indication on the left side of the RRFB shall emit two slow pulses of light after which the yellow indication on the right side of the RRFB shall emit four rapid pulses of light followed by a long pulse."[9](pg. 2)

4(09)-22 (I)[10]	Official interpretation 4(09)-22 (I) clarifies that agencies do not have to update the flash pattern for devices already deployed in the field and that official interpretation 4(09)-21 (I) only applies to new deployments.
4(09)-24 (I)[11]	Official interpretation 4(09)-24 (I) states that "it is not acceptable to dim the RRFB signal indications during daytime conditions and that the light output from the RRFB signal indications must meet the SAE J595 requirements for peak luminous intensity (candelas) for Class 1 at all times during daylight hours."[11](pg. 1) Information on SAE J595 is available in *Surface Vehicle Recommended Practice.*[15]
4(09)-37 (I)[12]	Official interpretation 4(09)-37 (I) states that "It is the FHWA's official interpretation that dimming occurs only when the light output from a traffic control signal indication or an RRFB signal indication falls below the minimum specified intensity for daytime conditions."[12](pg. 1)
4(09)-38 (I)[13]	Official interpretation 4(09)-38 (I) states that "It is the FHWA's official interpretation that the predetermined flash period should be initiated each and every time that a pedestrian is detected either through passive detection or as a result of a pedestrian pressing a pushbutton detector. This would include pedestrians who are detected while the RRFBs are already flashing and who are detected immediately after the RRFBs have ceased flashing."[13](pg. 1)

Table 2. Summary of RRFB official interpretation developed using the results of this research project.

Number	Summary of Key Characteristics Relevant to this Study
4(09)-41[2]	Official interpretation 4(09)-41 (I) states that, "…the FHWA favors the WW+S (wig-wag plus simultaneous) flash pattern because it has a greater percentage of dark time when both beacons of the RRFB are off and because the beacons are on for less total time. The greater percentage of dark time is important because this will make it easier for drivers to read the sign and to see the waiting pedestrian, especially under nighttime conditions. The less total on time will make the RRFB more energy efficient, which is important since they are usually powered by solar energy."[2](pg. 1)
4(09)-58 (I)[3]	Official interpretation 4(09)-58 (I) states that, "…it is the FHWA's official interpretation that any new RRFB units that are installed under the terms of Interim Approval 11 may be placed either above or below the crossing warning sign. Existing RRFB units that are placed below the crossing warning sign may be retained in their current position or may be relocated to be above the sign."[3](pg. 1)

RRFB

RRFBs flash in an eye-catching sequence to draw drivers' attention to the sign and the need to yield to a waiting pedestrian. It may be located on the side of the road below the pedestrian crosswalk or school crossing signs or overhead with a sign and can be activated actively (pushing a button) or passively (detected by sensors) by pedestrians. Several studies have examined the effectiveness of the device or elements contained within the device, including the following:

- An FHWA study in the early 2000s included 22 RRFB sites.[16]
- A 2009 FHWA study considered two sites in Miami, FL.[17]
- A 2009 study reported on an uncontrolled trail crossing of a four-lane urban street in St. Petersburg, FL.[18]
- A 2011 study considered an uncontrolled crossing in Garland, TX.[19]
- A 2011 Oregon Department of Transportation study examined three crosswalks in Bend, OR.[20]
- A 2013 pilot project in Calgary, Canada, included six sites.[21]
- A 2014 Michigan study examined a bike trail crossing.[22]

All of these studies used a before (none or continuously flashing beacon treatment) to after (RRFB installed) design and found an improvement in driver yielding after the RRFBs were installed. (See references 16–22.)

Other studies focused on examining how different features of the rapid-flashing beacons affect driver yielding. A study of two sites in Santa Monica, CA, compared the effect of an RRFB and a circular rapid-flashing beacon (CRFB) on yielding behavior at two crossings.[23] The RRFB was installed at one site, and the CRFB was installed at the other. After an evaluation period, they were switched and evaluated again. The study evaluated driver yielding rates both when the beacons were actuated and when they were not actuated. In all cases, driver yielding rates were higher when the beacons were activated.

An FHWA study also investigated differences between RRFBs and CRFBs.[5,24] Both were installed at 12 sites located in 4 cities. The statistical results indicated that there were no significant differences between the two beacon shapes.

For a subset of the 12 sites used in the FHWA study to evaluate the beacon shape, the luminous intensity (also called brightness) of the beacons was measured.[24] For those sites, there was evidence of an increasing yielding rate with increasing intensity at night.

Additional research was done at those 12 sites to evaluate the effect of the activation of the beacons and traffic volumes on driver yielding behavior when a crossing pedestrian was present.[25] The results of the analysis suggest that when a beacon—whether rectangular or circular—was activated, a driver was 3.68 times more likely to yield to pedestrians than when it was not activated. The results of an analysis of the relationship between traffic volume and driver yielding suggested that driver yielding behavior was not influenced by traffic volume at the study sites; however, the sample size available may have limited the ability to identify a relationship.

PHB

In a FHWA study, researchers conducted a before-after evaluation of the safety performance of the PHB.[26] Using an empirical Bayes method, the evaluations compared the crash prediction for the before period without the treatment to the observed crash frequency after installation of the treatment. To develop the datasets used in the evaluation, researchers counted the crashes occurring 3 years before and up to 3 years after the installation of the PHB. The crash categories examined in the study included total, severe, and pedestrian crashes. From the evaluation considering data for 21 treatment sites and 102 unsignalized intersections (reference group), the researchers found the following changes in crashes following installation of the PHBs:

- A 29 percent reduction in total crashes (statistically significant).
- A 15 percent reduction in severe crashes (not statistically significant).
- A 69 percent reduction in pedestrian crashes (statistically significant).

In a 2006 study, drivers yielding at five PHBs (known as HAWK sites at the time of the study) had an average driver yielding value of 97 percent.(27,28) For the sites included in the study, the number of lanes (two, four, or six lanes) did not affect performance. The driver yielding was very high compared to the other pedestrian devices included for the speed limits (either 35 or 40 mi/h) and intersection configurations (four-legged, T, offset T, or midblock crossings) represented in the dataset.

PHBs generally rest in a dark mode. A concern has been expressed that drivers may believe there is a power outage present and that the device is malfunctioning due to its dark resting mode, resulting in the need to come to a complete stop at the crossing. A study of driver behavior in Tucson, AZ, which had over 60 PHBs installed at the time of the study, investigated this concern and did not find evidence of confusion.(29) Driver perception of PHBs was studied in Kansas to identify drivers' knowledge of each phase of the device.(30) Surveys were distributed to drivers in stopped vehicles at a midblock PHB crossing and at a nearby signalized intersection. The results of the survey showed that drivers understood the dark (94 percent) and steady red (91 percent) signals well, understood the flashing yellow (76 percent) and steady yellow signals (67 percent) moderately well, and had poor understanding of the flashing red signal (58 percent).

A study in Oregon was conducted where three 1-h visits were made to a PHB site.(31) Compliance was observed to be very high; however, no records were made. They noted that drivers of queued vehicles sometimes proceeded through the crossing when the beacons changed to flashing red "without checking to see if the crossing was clear."(31)(pg. 67) Additionally, a 2014 Vermont study reported on a site near a hospital where, following installation of the PHB, yielding compliance increased by 18 percent, and there was an 83 percent increase in the number of vehicles slowing as they approached within 300 ft of the crosswalk.(32) PHB installation in San Antonio, TX, resulted in driver yielding increasing from 0 (i.e., no drivers yielding to staged pedestrians in 39 crossing attempts) to 95 percent for 60 staged pedestrian crossings.(33) All of the non-staged pedestrians at this site activated the treatment. An increase in the number of non-staged pedestrian crossings was observed after the PHB was installed. Finally, a study of three PHB installations in Charlotte, NC, found an increase in the number of motorists yielding to pedestrians.(34) Because data were collected for several periods after installation, they were able to conclude that improvements seemed to be relatively more consistent 3 mo after the installation of the PHB. In other words, it may take 3 mo for pedestrians and motorists to adapt to the new device.

MULTIPLE PEDESTRIAN TREATMENTS

A Texas Department of Transportation study explored the factors associated with drivers yielding to pedestrian crossings with traffic control signals (TCSs), PHBs, and RRFBs in Texas.[35,36] The percentage of drivers who yielded to a staged pedestrian was collected at 7 TCS sites, 22 RRFB sites, and 32 PHB sites. Overall, TCSs in Texas had the highest driver yielding rates, with an average of 98 percent. The average driver yielding for RRFB in Texas was 86 percent, while the average for PHB was 96 percent. All of the RRFB sites had school crossing (S1-1) signs. The number of devices within a city may have an impact on driver yielding. Those cities with a greater number of a particular device (i.e., Austin, TX, for the PHB and Garland, TX, for the RRFB) had higher driver yielding rates as compared to cities where the device was only used at a few crossings. Comparing the number of days since installation revealed statistically significant higher driver yielding rates for those PHBs that had been installed longer. The authors concluded that based on the statistical evaluation of the 32 PHB sites, the results support the use of the PHB on roadways with multiple lanes or a wide crossing. For RRFBs, the posted speed limit, total crossing distance, one-way versus two-way traffic, and location were all statistically significant. The data revealed a trend of lower driver yielding rates for wider crossing distances as compared to shorter crossing distances. This finding indicates that there is a crossing distance width where a device other than the RRFB should be considered.

CHAPTER 3. IMPACT OF RAPID-FLASHING YELLOW LEDs ON DETECTING PEDESTRIANS IN A CLOSED-COURSE SETTING

INTRODUCTION

This chapter describes the methodology and results from the closed-course study that examined LED brightness, position, and flash patterns. The brightness of LEDs, whether used within beacons or embedded in a sign, can help draw drivers' attention to a device and the area around the device. However, LED brightness can also make it more difficult for drivers to see objects around a device (disability glare) or result in drivers looking away from a device (discomfort glare). Either condition—disability glare or discomfort glare—may result in drivers missing hazards located near the source of the glare. In the case of LEDs used at pedestrian crossings, this may affect drivers' ability to detect pedestrians.

In general, disability glare impairs a driver's ability to detect hazards near a device even in situations where the driver is not experiencing discomfort glare. This results from light striking photoreceptors within the eye in a manner that diminishes the eye's ability to discern contrast. In low-contrast situations, such as nighttime conditions, disability glare caused by bright LEDs may affect drivers' ability to detect pedestrians. Conversely, discomfort glare is the perceived discomfort of the light source and may result in drivers looking away from a device.

To prevent devices from being set at brightness levels that produce disability or discomfort glare, the profession needs to quantify the effect of bright traffic control devices on a driver's ability to detect pedestrians in and around the crosswalk. This closed-course study was designed to examine drivers' ability to detect pedestrians in and around crosswalks. Specifically, it examined the effect of traffic control device brightness and other characteristics on drivers' ability to quickly and accurately identify the presence of a pedestrian and then discern the pedestrian's direction of travel.

For flashing traffic control devices, there are two important and competing considerations in designing the brightness of traffic control devices:

- Is the brightness high enough to command the driver's attention and elicit the desired response (e.g., yielding to pedestrians)?
- Is the brightness low enough that it does not impair a driver's ability to see pedestrians because of disability or discomfort glare?

For a well-designed traffic control device, the answers to both questions need to be yes, yet the measure of brightness associated with these two questions may not be the same.

At the conclusion of the closed-course study, crossing sign assemblies were identified for evaluation in the field (open-road phase).

Study Objective

The objective of this study was to investigate how LED brightness and the flash pattern used with LEDs affect the ability to detect pedestrians. The measures of effectiveness for the closed-course study were as follows:

- Time to correctly identify pedestrian walking direction.
- Percentage of the tests where the participant correctly identified the cutout pedestrian walking direction.
- Participants' rating of discomfort glare.

Overview of Study Approach

The intent of the static closed-course study was to quantify drivers' ability to detect pedestrians within and around a crosswalk (a measure of disability glare) and quantify discomfort glare ratings associated with LEDs in traffic control devices. Participants drove the study vehicle to the starting location where they parked the vehicle at a set distance of 200 ft away from the sign assemblies that consisted of a pedestrian crossing sign with LEDs within the sign face and LEDs in rectangular beacons above and below the sign. After the participants placed the vehicle into park, they were asked to wear occlusion glasses, which obscure the participants' vision by becoming opaque when there is no power supplied to them or clear when power is supplied. Wearing these glasses was similar to wearing sunglasses and involved no more risk than that typically encountered while sitting in a parked vehicle.

Once the participants' vision was occluded, technicians placed a static cutout photo of a pedestrian (either 54 inches tall to represent a child or 70 inches tall to represent an adult) within the crosswalk located near the sign assemblies. An experimenter then restored the participants' vision, and they were asked to identify the direction the pedestrian was traveling (i.e., to the left, to the right, or not present) as quickly as possible using a button box. This type of research approach—identifying the walking direction of a pedestrian in a photo cutout—has been used previously to examine crosswalk lighting.[(37)] When the participants pressed a button on the button box, the glasses turned opaque again. Following the identification of the pedestrian's direction, the researcher asked the participants to rate the intensity of the LED (comfortable, irritating, or unbearable) before asking the field crew to set up the next condition. This process was repeated for various combinations of LED brightness, LED locations, pedestrian positions, and flash patterns. This portion of the study was stationary, and, after completion, the participants drove to the check-in location and completed a laptop survey that asked a series of queries to obtain the participants' opinions regarding flash patterns for LEDs used with signs. At the end of the study, the participants were compensated for their participation.

To increase the number of flash patterns tested in the study but to keep within a reasonable testing period, data were collected within two sets. Within each set, two flash patterns were tested for the LEDs in rectangular beacons, and two flash patterns were tested for the LEDs within the sign. For pattern set I (descriptions provided in the following Course Development section), the study was conducted during both the daytime and nighttime. For pattern set II, the study was only conducted during the nighttime. During the testing of set I, it was determined that nighttime was the more critical condition, which is why only nighttime data were collected during set II.

COURSE DEVELOPMENT

Riverside Campus

The runway system on the Texas A&M University (TAMU) Riverside campus served as the test roadway for data collection. The runways offered a mixture of long straightaways, short intersecting segments, and curves. Researchers selected one of the taxiways so that the study site would look more similar to a two-lane road rather than a wider paved surface area, which is a characteristic of the runways. The location selected was approximately 40 ft wide. Edgeline and centerline markings were added to give the site a more urban feel. Each lane was approximately 12 ft wide.

Pedestrian Crossing Assemblies Selected for Study

Initially, researchers planned to have the different study assemblies located in different parts of the TAMU Riverside campus. During development, the researchers realized that a single assembly could include LEDs in the beacons above and below the sign and that the sign could have the LEDs embedded within the sign (see figure 1). Having all device combinations on one post decreased the amount of participant time that had to be spent driving between the different study locations, which meant more tests could be conducted per participant. Having all device combinations at one site also decreased the course preparation efforts in that only one site rather than several sites had to be prepared to have the desired urban feel, such as adding edgeline and centerline markings.

Figure 1. Photo. Study assembly containing LEDs above, below, and within the sign.

The location of the LEDs used in this study included the following:

- LEDs in rectangular beacons located above the sign. The bottom edge of the beacon housing was approximately 11.6 ft from the pavement.
- LEDs in rectangular beacons located below the sign. The bottom edge of the beacon housing was approximately 7.0 ft from the pavement.
- LEDs embedded within the sign. The height to the middle of the sign was approximately 9.5 ft.

Study Site

At the beginning of each participant run, the participants drove a Texas A&M Transportation Institute (TTI) vehicle to the study site (see figure 2) and parked the vehicle near the orange barrel (see figure 3 and figure 4). Figure 4 shows a photograph of the view for the participants. At the site, the participants saw two study assemblies: one on each side of the two-lane street. Vehicles were parked on the cross street upstream and downstream of the study site to aid in giving the urban feel and to provide a hiding space for the technicians that were changing the LED settings and moving the pedestrian cutout. Transverse white pavement crosswalk markings were installed at the site (see figure 5).

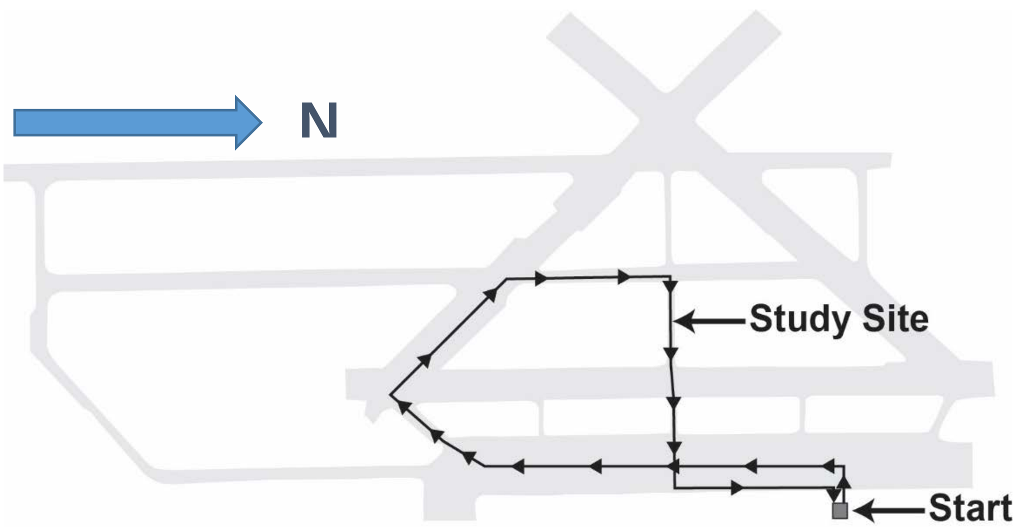


Figure 2. Illustration. Route for closed-course study.

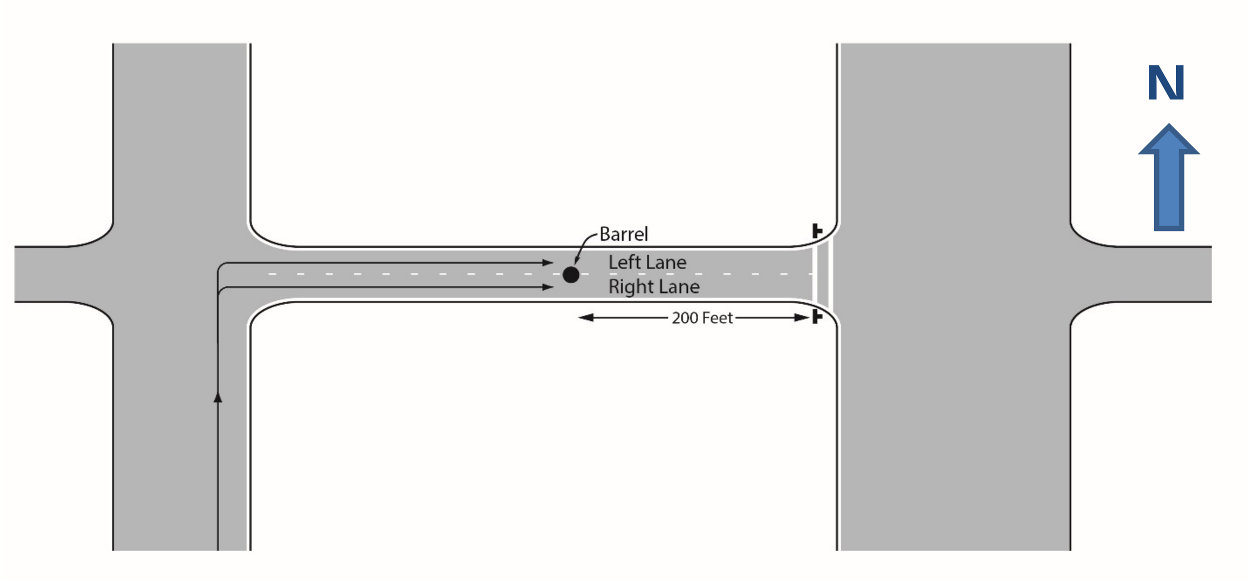


Figure 3. Illustration. Layout for the study site.

Figure 4. Photo. View of the study assemblies.

Figure 5. Photo. Back view of study site.

To be more efficient, the study was designed so that data were collected from two participants simultaneously. Each participant was in a unique car so that a participant's response would not be heard by the other participant. The vehicles were parked next to each other at the study site, thus simulating vehicles approaching a pedestrian crossing on a multilane roadway (see figure 3 and figure 4, which illustrate how the vehicles were parked). The participants were located 200 ft from the LED assemblies. The 200-ft distance was selected because it represents stopping sight distance (SSD) when traveling 30 mi/h.[38]

Street lighting was present at the site for the nighttime testing. Two work zone light towers were rented for the study and placed on either side of the approach on the cross street. During course preparation, researchers positioned these light towers in a manner that simulated street lighting. Prior to collecting data for each set of nighttime participants, the luminance reading at the three pedestrian positions were taken to ensure a consistent street lighting level was present. The average of these readings was about 26 lux.

Cutout Pedestrian

To ensure consistency with the pedestrian characteristics, the research team decided to use a photograph of a pedestrian. The photograph was cut out to mimic the shape of a walking pedestrian (see figure 6). Two cutouts were created to reflect two heights: adult and child. The 70-inch version reflected the average height of adults between 1999 and 2002, while the 54-inch version reflected the average height of a child in the same time period.[39] Figure 7 shows a researcher removing the short cutout photograph (center of road) after installing the tall cutout photograph (right side of road).

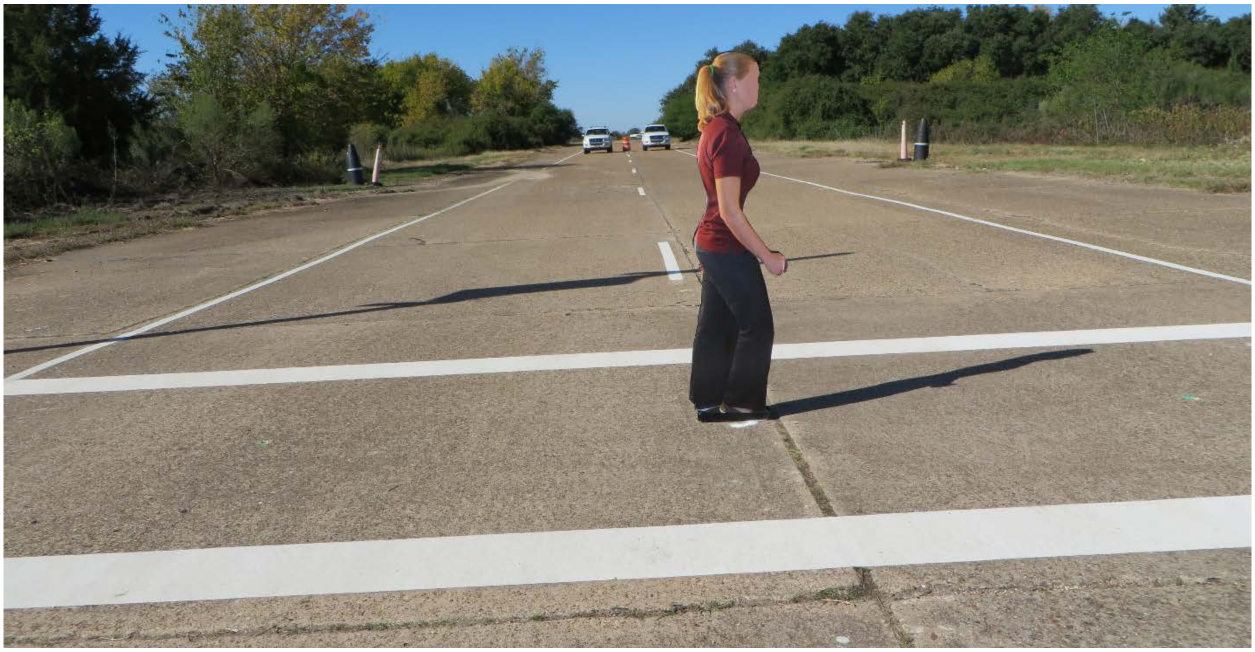


Figure 6. Photo. View of 54-inch cutout pedestrian used in study.

Figure 7. Photo. Researcher removing short cutout pedestrian after placing tall cutout pedestrian.

The cutout photographs were glued on both sides of a pole that extended a few inches below the shoe in the photograph. This extension was placed into one of three holes drilled into the pavement. The holes were located just to the right of the edgeline in the center of the road (i.e., on the lane line) and just to the left of the edgeline, as shown in figure 8. The positions near the edgeline pavement markings reflected the condition of a pedestrian waiting to cross the street. The center of the street represented a pedestrian in the crosswalk. The holes were drilled between the two crosswalk lines, as shown in figure 6 and figure 8. Because the photographs were glued to both sides of the pole, the cutout pedestrian could be rotated to appear to be walking to the left or to the right.

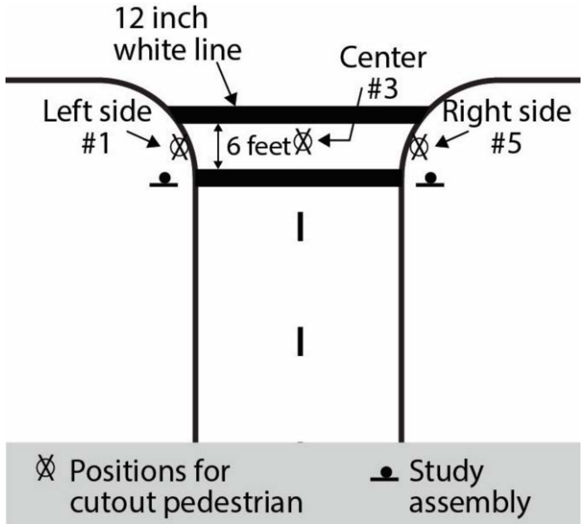


Figure 8. Illustration. Plan view showing pedestrian cutout positions.

Flash Pattern for Assemblies

Several flash patterns were used within the study. For the LEDs in rectangular beacons, the patterns shown in table 3 were used. The light bar containing the rectangular beacons had two unique beacons (with each beacon containing eight LEDs). When the beacon was turned on varied depending on the beacon location (i.e., left side or right side), as illustrated in table 3.

Table 3. Flash patterns used with LEDs located in rectangular beacons above or below the sign.

Cumulative Time (ms)	Sets I and II: No Flashes Dark		Set I: Wig-Wag Alternating		Sets I and II: 2-5 Flash Pattern		Set II: Two 125-ms Simultaneous Pulses	
	Left Time On (ms)	Right Time On (ms)	Left Time On (ms)	Right Time On (ms)	Left Time On (ms)	Right Time On (ms)	Left Time On (ms)	Right Time On (ms)
0	0	0	25	0	25	0	25	25
25	0	0	25	0	25	0	25	25
50	0	0	25	0	25	0	25	25
75	0	0	25	0	25	0	25	25
100	0	0	25	0	25	0	25	25
125	0	0	25	0	0	0	0	0
150	0	0	25	0	0	0	0	0
175	0	0	25	0	0	0	0	0
200	0	0	25	0	25	0	25	25
225	0	0	25	0	25	0	25	25
250	0	0	25	0	25	0	25	25
275	0	0	25	0	25	0	25	25
300	0	0	25	0	25	0	25	25
325	0	0	25	0	0	0	0	0
350	0	0	25	0	0	0	0	0
375	0	0	25	0	0	0	0	0
400	0	0	25	0	0	25	0	0
425	0	0	25	0	0	0	0	0
450	0	0	25	0	0	25	0	0
475	0	0	25	0	0	0	0	0
500	0	0	0	25	0	25	0	0
525	0	0	0	25	0	0	0	0
550	0	0	0	25	0	25	0	0
575	0	0	0	25	0	0	0	0
600	0	0	0	25	0	25	0	0
625	0	0	0	25	0	25	0	0
650	0	0	0	25	0	25	0	0
675	0	0	0	25	0	25	0	0
700	0	0	0	25	0	25	0	0
725	0	0	0	25	0	25	0	0
750	0	0	0	25	0	25	0	0
775	0	0	0	25	0	25	0	0
800	0	0	0	25	BEC	BEC	BEC	BEC
825	0	0	0	25	BEC	BEC	BEC	BEC
850	0	0	0	25	BEC	BEC	BEC	BEC
875	0	0	0	25	BEC	BEC	BEC	BEC
900	0	0	0	25	BEC	BEC	BEC	BEC

925	0	0	0	25	BEC	BEC	BEC	BEC
950	0	0	0	25	BEC	BEC	BEC	BEC
975	0	0	0	25	BEC	BEC	BEC	BEC
Cycle length (ms)	N/A		1,000		800		800	
Number of cycles/min	N/A		60		75		75	

BEC = Beyond end of cycle.
N/A = Not applicable.
Note: Yellow shading represents when the beacons were on.

Table 4 shows the flash pattern used for the LEDs within the sign. While there are eight unique points of lights within an embedded diamond sign, the researchers decided that all eight LEDs would be illuminated at the same time within the sign as is currently used in practice. Therefore, there was not a left and right designation for the LEDs within the sign. The 2-5 flash pattern used with the assemblies was selected based on FHWA official interpretation 4(09)-21 (I) released on June 13, 2012, regarding the RRFB.(9) It has two slower flashes on one side followed by five rapid flashes on other side.

Table 4. Flash patterns used with LEDs within sign.

Cumulative Time (ms)	Sets I and II: No Flashing Time On (ms)	Set I: Five Pulses Similar to Right Side of RRFB Time On (ms)	Sets I and II: One 100-ms Pulse Time On (ms)	Set II: Two 125-ms Pulses Similar to Left Side of RRFB Time On (ms)
0	0	0	25	25
25	0	0	25	25
50	0	0	25	25
75	0	0	25	25
100	0	0	0	25
125	0	0	0	0
150	0	0	0	0
175	0	0	0	0
200	0	0	0	25
225	0	0	0	25
250	0	0	0	25
275	0	0	0	25
300	0	0	0	25
325	0	0	0	0
350	0	0	0	0
375	0	0	0	0
400	0	25	0	0
425	0	0	0	0
450	0	25	0	0
475	0	0	0	0
500	0	25	0	0
525	0	0	0	0

550	0	25	0	0
575	0	0	0	0
600	0	25	0	0
625	0	25	0	0
650	0	25	0	0
675	0	25	0	0
700	0	25	0	0
725	0	25	0	0
750	0	25	0	0
775	0	25	0	0
800	0	BEC	0	BEC
825	0	BEC	0	BEC
850	0	BEC	0	BEC
875	0	BEC	0	BEC
900	0	BEC	0	BEC
925	0	BEC	0	BEC
950	0	BEC	0	BEC
975	0	BEC	0	BEC
Cycle length (ms)	N/A	800	1,000	800
Number of cycles/min	N/A	75	60	75

N/A = Not applicable.
Note: Yellow shading represents when the beacons were on.

Brightness of LEDs

The characteristics of the LEDs may affect the detection of pedestrians. Table 5 lists the characteristics of the LEDs used with pattern set I, while table 6 provides similar values for pattern set II. To quantify the brightness of the pulsing lights, researchers used the photometric range within the TTI Visibility Laboratory. For each RRFB beacon and LED sign, a technician measured the 95th percentile peak intensity (called "measured intensity" in table 5 and table 6) and the optical power of the device. The researcher took the measurements at a vertical angle of 0 degrees and a horizontal angle of 0 degrees.

Peak luminous intensity is defined as the maximum luminous intensity for a given flash. The peak intensity can be much higher than the typical intensity within a pulse. Therefore, the 95th percentile intensity is used to provide a more representative value. The 95th percentile luminous intensity is the luminous intensity that 95 percent of the instantaneous intensity measurements are less than or equal to during the duration of the flash; instantaneous intensities measured during the dark period are not included in this measurement.

According to SAE Standard J595, *optical power* is defined as the integrated total of all flashes in a minute, in candela-s/min.[15] Stated in a general way, optical power represents the area under the curve. It provides an appreciation of both the intensity of the pulses and the amount of time the LEDs are illuminated.

Table 5. LED characteristics for set I.

LED Location	Flash Pattern	Target Intensity (Candela)	Measured Intensity (Candela)	Optical Power (Candela-s/min)	Pulse Rate (Number of Pulses/Cycle Length)	On Ratio (Percent)
Above	2-5	600	622	25,600	8.75	69
Above	2-5	1,400	1,426	58,800	8.75	69
Above	2-5	2,200	2,207	91,000	8.75	69
Above	Wig-wag	600	605	36,300	2.00	100
Above	Wig-wag	1,400	1,442	86,500	2.00	100
Above	Wig-wag	2,200	2,237	134,200	2.00	100
Below	2-5	600	675	27,900	8.75	69
Below	2-5	1,400	1,450	59,800	8.75	69
Below	2-5	2,200	2,249	92,700	8.75	69
Below	Wig-wag	600	633	38,000	2.00	100
Below	Wig-wag	1,400	1,458	87,400	2.00	100
Below	Wig-wag	2,200	2,256	135,300	2.00	100
Within	100	600	649	3,900	1.00	10
Within	100	1,400	1,471	8,800	1.00	10
Within	100	2,200	2,225	13,300	1.00	10
Within	Five pulses	600	652	14,700	6.25	38
Within	Five pulses	1,400	1,454	32,700	6.25	38
Within	Five pulses	2,200	2,216	49,900	6.25	38

Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; wig-wag = wig-wag flash pattern; and 100 = one 100-ms flash pattern.

Table 6. LED characteristics for set II.

LED Location	Flash Pattern	Target Intensity (Candela)	Measured Intensity (Candela)	Optical Power (Candela-s/min)	Pulse Rate (Number of Pulses/Cycle Length)	On Ratio (Percent)
Above	125(2)	600	622	11,700	2.50	31
Above	125(2)	1,400	1,441	27,000	2.50	31
Above	125(2)	2,200	2,308	43,300	2.50	31
Above	2-5	600	622	25,600	8.75	69
Above	2-5	1,400	1,426	58,800	8.75	69
Above	2-5	2,200	2,207	91,000	8.75	69
Below	125(2)	600	619	11,600	2.50	31
Below	125(2)	1,400	1,436	26,900	2.50	31
Below	125(2)	2,200	2,269	42,500	2.50	31
Below	2-5	600	675	27,900	8.75	69
Below	2-5	1,400	1,450	59,800	8.75	69
Below	2-5	2,200	2,249	92,700	8.75	69
Within	100	600	652	3,900	1.00	10
Within	100	1,400	1,469	8,800	1.00	10
Within	100	2,200	2,227	13,400	1.00	10
Within	125(2)	600	646	12,100	2.50	31
Within	125(2)	1,400	1,464	27,400	2.50	31
Within	125(2)	2,200	2,227	41,800	2.50	31

Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; wig-wag = wig-wag flash pattern; 100 = one 100-ms flash pattern; and 125(2) = two 125-ms flashes.

Previous research has demonstrated that LED characteristics can influence whether an object is detected.[40] Because the amount of time the LEDs are on may influence a driver's ability to detect a pedestrian, a measure of the on time was developed. The *on ratio variable* (see table 5 and table 6) is defined to be the percentage of the 25-ms increments within a cycle where the LEDs within the beacon or sign are illuminated. The percentage of the cycle where the LEDs are dark would be determined as 1 minus the on ratio. For example, the 2-5 pattern would have an off ratio of 31 percent (100 percent – 69 percent). In the wig-wag pattern, there was no dark period, as demonstrated by having an on ratio of 100 percent. To provide an appreciation of how often the LEDs are pulsing, the pulse rate was determined as the number of pulses divided by the cycle length. For example, the 2-5 pattern had 7 pulses within the 0.8-s cycle for a pulse rate of 8.75, while the rapid-flashing LEDs within a sign had 5 pulses within the 0.8-s cycle for a pulse rate of 6.25.

Combinations Studied

The variables for participant characteristics and site characteristics presented within this closed-course study are as follows:

- **Lighting**: Day (natural lighting) or night (street lighting).
- **Gender**: Male or female.

- **Age**: Young (less than 55 years old) or old (55 years old or greater).
- **Lane**: Left lane or right lane.
- **Viewing position**: 200 ft upstream from assemblies.

Study assemblies characteristics included the following:

- **LED location**: LEDs in a rectangular beacon below the sign, LEDs in a rectangular beacon above the sign, or LEDs within the sign.
- **Flash pattern (three per set; see table 3 and table 4)**:
  - **Set I**: No rectangular beacon above or below the sign, 2-5 pattern, or wig-wag (alternating) pattern.
  - **Set I**: No LEDs within the sign, five pulses (five pulses similar to the right side of the RRFB), or one 100-ms pulse (single pulse).
  - **Set II**: No rectangular beacon above or below the sign, 2-5 pattern, or two 125-ms pulses (simultaneous).
  - **Set II**: No LEDs within sign, five pulses (rapid right side of RRFB), or two 125-ms pulses (two pulses similar to left side of RRFB).
- **Target intensity (i.e., brightness)**: 0, 600, 1,400, and 2,200 candelas.

The cutout pedestrian characteristics include the following:

- **Pedestrian position**: None, right side, center, or left side.
- **Pedestrian height (when present)**: Tall (70 inches) or short (54 inches).
- **Pedestrian direction (when present)**: Left or right.

Over 260 tests would be needed for a participant to see all possible combinations of study assembly and pedestrian characteristics. Preliminary data collection efforts demonstrated that about 100 tests could be conducted within the available 60-min data collection period.

A presentation order of the possible combinations between the study assembly and cutout pedestrian characteristics was developed using a random number generator in a spreadsheet. The order was then modified so that a participant would only see a particular combination once and so that a similar number of viewings per combination would occur. Table 7 shows the combinations tested. A total of 15 tests were conducted for each combination of pedestrian height and position. For example, the short cutout pedestrian when located in the center of the roadway was viewed in 15 tests. For the 7 combinations possible when considering pedestrian position and height, the 15 tests per combination resulted in a total of 105 tests per participant. For those tests when a cutout pedestrian was present (105 – 15 = 90 tests), half of the tests had the cutout pedestrian moving toward the left, while the other half of the tests had the cutout pedestrian moving toward the right.

Initially, the goal was to randomize the presentation order for all characteristics tested (i.e., LED location, flash pattern, brightness level, and cutout pedestrian position, height, and direction). Preliminary efforts demonstrated that the changes required of the technicians to switch from one LED location to another would consume too much time. Therefore, the study was subdivided into three blocks. Within the first block, all the tests associated with one of the LED locations would be conducted (e.g., rectangular below). A short break would be provided to the participant while the field crew switched the wires to operate the next LED location (e.g., LED within sign). Another break would divide the second block from the third block. Each block included 35 tests. The presentation of the device order was different for different sets of participants; some participants saw the above block first, some saw the below block first, and others saw the LED sign block first.

Table 7. Number of variable combinations tested during the closed-course study.

Location of LED	Flash Pattern	Target Intensity (Candela)	Number of Tests: No Pedestrian Cutout Present	Short Pedestrian Cutout Position: Left Side	Short Pedestrian Cutout Position: Center	Short Pedestrian Cutout Position: Right Side	Tall Pedestrian Cutout Position: Left Side	Tall Pedestrian Cutout Position: Center	Tall Pedestrian Cutout Position: Right Side	Total
Within	None	0	1	1	1			1	1	5
	Other	600	1	1	1	1	1			5
		1,400	1			1	1	1	1	5
		2,200	1	1	1	1		1		5
	Rapid	600		1	1		1	1	1	5
		1,400	1	1			1	1	1	5
		2,200	1	1	1	1			1	5
Below	None	0	1	1		1		1	1	5
	Other	600		1	1		1	1	1	5
		1,400	1		1		1	1	1	5
		2,200		1		1	1	1	1	5
	Rapid	600	1		1	1	1		1	5
		1,400	1	1		1	1	1		5
		2,200	1	1	1	1		1		5
Above	None	0	1		1	1	1		1	5
	Other	600			1	1	1	1	1	5
		1,400	1		1	1		1	1	5
		2,200	1	1	1		1		1	5
	Rapid	600		1		1	1	1	1	5
		1,400	1	1	1	1	1			5
		2,200		1	1	1	1	1		5
Grand Total			**15**	**15**	**15**	**15**	**15**	**15**	**15**	**105**

Note: Blank cells indicate that the combination was not tested.

Note that within the table, flash patterns are defined as follows:

- **None**: LEDs were not illuminated.
- **Rapid**: The 2-5 pattern was used when LEDs were above or below the sign, while five pulses (five pulses similar to the right side of the RRFB) were used when the LEDs were located within the sign.
- **Other**:
  - **Set I**: Wig-wag (alternating) was used when LEDs were above or below the sign, and a 100-ms pulse (single pulse) was used when LEDs were within the sign.
  - **Set II**: Two 125-ms pulses (simultaneous) were used when LEDs were above or below the sign, while two 125-ms pulses (two pulses similar to left side of RRFB) were used when LEDs were within the sign.

Concluding Survey

After participants completed the closed-course portion of the study, they were asked to complete a laptop survey that asked a series of queries to obtain the participants' opinions regarding flash patterns for beacons used with pedestrian crossing signs. The two initial queries included a video filmed from a driver's position as the vehicle moved toward a crosswalk with a waiting pedestrian. The participants always saw the same sign assembly; however, the LEDs and flash pattern used (if any) varied between the two queries. The same question was used with each query. Figure 9 shows the starting view for the first two queries (a close-up example of the sign assembly is shown in figure 1). The wording of the question and answers used with queries 1 and 2 are as follows:

As a driver of an automobile approaching the crosswalk shown in the video, how would you react in this situation?

1. I would **slow** and allow the pedestrian to cross the roadway.
2. I would **stop** and allow the pedestrian to cross the roadway.
3. I would **confirm** the pedestrian is not crossing before proceeding.
4. I would **continue driving** at the same speed.

Figure 9. Photo. View at start of the driving video for the concluding survey for queries 1 and 2.

Researchers wanted to determine how drivers viewed the requirement to yield to the pedestrian when a pedestrian crossing sign did not have active supplemental LEDs. Therefore, the video for one of the two initial queries for all participants had no LEDs active (condition termed “sign” within the survey and is similar to the flash pattern “none” when wearing the occlusion glasses). About half of the participants had the sign-only video with their first query, while the other half of the participants had the sign-only video with their second query. Table 8 lists the videos shown for each query by participant group.

Table 9 identifies the flash pattern used with queries 1 and 2, which were the moving videos shown from a driver’s perspective. Table 10 shows illustrations of the flash patterns used with queries 3 and 4, which were stationary videos showing a close-up of the pedestrian crossing assembly.

Table 8. Video assignments and flash patterns for each query by participant group.

Participant Group	Driving Video Flash Pattern		Stationary Video Flash Pattern			
	Query 1	Query 2	Query 3		Query 4	
	Video at Top of Screen	Video at Top of Screen	Video A at Left Side of Screen	Video B at Right Side of Screen	Video A at Left Side of Screen	Video B at Right Side of Screen
A	Sign	Below; 2-5	Within; 100	Below; 25(4)+200	Within; 125(2)	Below; 125(2)
B	Sign	Below; wig-wag	Below; 25(4)+200	Within; 25(4)+200	Sign	Within; 125(2)
C	Sign	Within; 100	Below; 25(4)+200	Within; 100	Below; 25(4)+200	Within; 125(2)
D	Below; 2-5	Sign	Below; 125(2)	Below; 2-5	Within; 25(4)+200	Within; 125(2)
E	Below; wig-wag	Sign	Within; 100	Within; 25(4)+200	Within; 100	Within; 125(2)
F	Within; 100	Sign	Within; 100	Below; 2-5	Sign	Within; 25(4)+200
G	Sign	Below; 2-5	Within; 125(2)	Within; 25(4)+200	Sign	Within; 100
H	Sign	Below; wig-wag	Sign	Below; 125(2)	Within; 25(4)+200	Sign
I	Sign	Within; 100	Below; 125(2)	Within; 25(4)+200	Below; 2-5	Sign
J	Below; 2-5	Sign	Within; 25(4)+200	Below; 125(2)	Below; 2-5	Within; 125(2)
K	Below; wig-wag	Sign	Below; 125(2)	Within; 100	Within; 25(4)+200	Below; 2-5
L	Within; 100	Sign	Within; 125(2)	Sign	Within; 125(2)	Within; 100
M	Sign	Below; 2-5	Below; 125(2)	Below; 25(4)+200	Below 25(4)+200	Below; 125(2)
N	Sign	Below; wig-wag	Below; 2-5	Within; 100	Within; 25(4)+200	Within; 100
O	Sign	Within; 100	Below; 2-5	Within; 25(4)+200	Within; 25(4)+200	Below; 25(4)+200
P	Below; 2-5	Sign	Below; 25(4)+200	Sign	Within; 100	Sign
Q	Below; wig-wag	Sign	Within; 125(2)	Below; 25(4)+200	Below; 2-5	Below; 25(4)+200
R	Within; 100	Sign	Sign	Below; 2-5	Within; 100	Below; 125(2)
S	Sign	Below; 2-5	Below; 125(2)	Sign	Within; 125(2)	Below; 2-5
T	Sign	Below; wig-wag	Sign	Below; 25(4)+200	Below; 25(4)+200	Below; 2-5
U	Sign	Within; 100	Below; 2-5	Below; 125(2)	Below; 125(2)	Within; 125(2)

Note: Flash patterns are defined as follows: sign = no active LEDs; 2-5 = 2-5 flash pattern; wig-wag = wig-wag flash pattern; 100 = one 100-ms flash pattern; 25(4)+200 = four 25-ms flashes and one 200-ms flash; and 125(2) = two 125-ms flashes.

Table 9. Flash patterns for queries 1 and 2 showing moving videos from driver perspective.

Cumulative Time (ms)	Below; Wig-Wag Flash Pattern		Below; 2-5 Flash Pattern		Within; 100-ms Flash Pattern	No LEDs or Flash Pattern
	Left Time On (ms)	Right Time On (ms)	Left Time On (ms)	Right Time On (ms)	Time On (ms)	Time On (ms)
0	25	0	25	0	25	0
25	25	0	25	0	25	0
50	25	0	25	0	25	0
75	25	0	25	0	25	0
100	25	0	25	0	0	0
125	25	0	0	0	0	0
150	25	0	0	0	0	0
175	25	0	0	0	0	0
200	25	0	25	0	0	0
225	25	0	25	0	0	0
250	25	0	25	0	0	0
275	25	0	25	0	0	0
300	25	0	25	0	0	0
325	25	0	0	0	0	0
350	25	0	0	0	0	0
375	25	0	0	0	0	0
400	25	0	0	25	0	0
425	25	0	0	0	0	0
450	25	0	0	25	0	0
475	25	0	0	0	0	0
500	0	25	0	25	0	0
525	0	25	0	0	0	0
550	0	25	0	25	0	0
575	0	25	0	0	0	0
600	0	25	0	25	0	0
625	0	25	0	25	0	0
650	0	25	0	25	0	0
675	0	25	0	25	0	0
700	0	25	0	25	0	0
725	0	25	0	25	0	0
750	0	25	0	25	0	0
775	0	25	0	25	0	0
800	0	25	BEC	BEC	BEC	0
825	0	25	BEC	BEC	BEC	0
850	0	25	BEC	BEC	BEC	0
875	0	25	BEC	BEC	BEC	0
900	0	25	BEC	BEC	BEC	0
925	0	25	BEC	BEC	BEC	0
950	0	25	BEC	BEC	BEC	0
975	0	25	BEC	BEC	BEC	0

Note: Yellow shading represents when the beacons were on.

Table 10. Flash patterns used for queries 3 and 4 with the video showing a close-up view.

Cumulative Time (ms)	Below; 2-5 Flash Pattern		Below; Two 125-ms Flashes		Below; Four 25-ms Flashes and One 200-ms Flash		Within; 100-ms Flash Pattern	Within; Two 125-ms Flashes	Within; Four 25-ms Flashes and One 200-ms Flash	No Flash Pattern
	Left Time On (ms)	Right Time On (ms)	Left Time On (ms)	Right Time On (ms)	Left Time On (ms)	Right Time On (ms)	Time On (ms)	Time On (ms)	Time On (ms)	Time On (ms)
0	25	0	25	25	0	0	25	25	0	0
25	25	0	25	25	0	0	25	25	0	0
50	25	0	25	25	0	0	25	25	0	0
75	25	0	25	25	0	0	25	25	0	0
100	25	0	25	25	0	0	0	25	0	0
125	0	0	0	0	0	0	0	0	0	0
150	0	0	0	0	0	0	0	0	0	0
175	0	0	0	0	0	0	0	0	0	0
200	25	0	25	25	0	0	0	25	0	0
225	25	0	25	25	0	0	0	25	0	0
250	25	0	25	25	0	0	0	25	0	0
275	25	0	25	25	0	0	0	25	0	0
300	25	0	25	25	0	0	0	25	0	0
325	0	0	0	0	0	0	0	0	0	0
350	0	0	0	0	0	0	0	0	0	0
375	0	0	0	0	0	0	0	0	0	0
400	0	25	0	0	25	25	0	0	25	0
425	0	0	0	0	0	0	0	0	0	0
450	0	25	0	0	25	25	0	0	25	0
475	0	0	0	0	0	0	0	0	0	0
500	0	25	0	0	25	25	0	0	25	0
525	0	0	0	0	0	0	0	0	0	0
550	0	25	0	0	25	25	0	0	25	0
575	0	0	0	0	0	0	0	0	0	0
600	0	25	0	0	25	25	0	0	25	0
625	0	25	0	0	25	25	0	0	25	0
650	0	25	0	0	25	25	0	0	25	0
675	0	25	0	0	25	25	0	0	25	0
700	0	25	0	0	25	25	0	0	25	0
725	0	25	0	0	25	25	0	0	25	0
750	0	25	0	0	25	25	0	0	25	0
775	0	25	0	0	25	25	0	0	25	0

Note: Yellow shading represents when the beacons were on.

Queries 3 and 4 asked the participants to judge the urgency of the message conveyed by the crosswalk treatment. The participants saw a close-up of two side-by-side assemblies labeled video A and video B. The flash patterns and which LEDs were active varied, as listed in table 8. The design of the study resulted in four to five participants seeing each pair with the specific placement on the screen (i.e., left side or right side). If placement on the screen was not considered, then each device pair was viewed, on average, by nine participants. The wording of the question and answers used with queries 3 and 4 were as follows:

In your opinion, which video conveys a more urgent need for a driver to yield to a pedestrian?

1. Video A conveys a more urgent need.
2. Video B conveys a more urgent need.
3. The level of urgency is similar in both videos.
4. Neither video conveys an urgent need for a driver to yield to a pedestrian.

The final query asked the participants to count how many flashes they observed in the left and right beacons for a light bar that was located in the room with them.

DATA COLLECTION

Study Periods

The study was conducted under both daytime and nighttime conditions between Wednesday, November 13, 2013, and Thursday, December 12, 2013, with several days lost due to rain. Sunset occurred at approximately 5:30 p.m. during the study. The study took about 1.5 h from meeting the participant to the participant receiving their payment. About one-third of the participants drove during daylight hours, and two-thirds drove during nighttime conditions with an approximately even split between flash pattern sets I and II. The following start times were used:

- 12 p.m.
- 1:30 p.m.
- 6:30 p.m.
- 8 p.m.

Participants

Participants were recruited from the area using TTI's pool of previous research subjects list. Over the phone, the potential participants were told that the study was confidential and the records of the study would be kept private. They were also told that their participation was voluntary and that they were free to withdraw from the study at any time.

The initial intent was to recruit a group of participants composed of one-quarter males over the age of 55, one-quarter females over the age of 55, one-quarter males under the age of 55, and one-quarter females under the age of 55. Within each of those demographic groups, the goal was to have an even distribution between those who participated during the daytime and nighttime within pattern set I. Therefore, the following divisions were used in structuring participant recruitment:

- **Light level**: Day or night.
- **Age group**: Young (younger than 55 years old) and old (55 years old or older).
- **Gender**: Male or female.

When pattern set II was added to the study, data were only collected during the nighttime.

The male/female, young/old divisions resulted in four participant categories. The research goal was to have 8 participants in each of these categories, resulting in 32 participants per day or per night. Table 11 summarizes the number of participants by pattern set (I or II) and light level (day or night) that participated in the study.

Participants were at least 18 years old and possessed a valid driver's license with no restrictions. Upon completion of the survey, participants received monetary compensation of $50.

Table 11. Distribution of participants.

Day or Night	Pattern Set	Old Female	Old Male	Old Total	Young Female	Young Male	Young Total	Young Total
Day	I	9	8	17	8	7	15	32
Night	I	8	7	15	8	9	17	32
Night	II	8	8	16	9	9	18	34
Grand Total		**25**	**23**	**48**	**25**	**25**	**50**	**98**

Participant's Tasks

The tasks for the participants for this closed-course study were as follows:

1. After vision was restored by the occlusion glasses, participants were asked to indicate via a button push whether the pedestrian was walking to the left or to the right.
2. Following the driver's identification of the pedestrian direction, participants were asked to state whether the intensity of the LEDs was comfortable, irritating, or unbearable.
3. Participants responded to survey queries presented in a conference room at the conclusion of the study.

Instrumented Vehicle

Two similar vehicles—2009 sports utility vehicles—served as the participant cars for this experiment. The headlamps for these vehicles were 35 inches from the ground and 27 inches from center of the vehicle. Prior to the start of the study, the headlamps on both vehicles were properly aligned by TTI staff members.

Participant Intake

Participant intake was headquartered at TTI's Environmental Emissions Research Facility on the Riverside campus. This location was selected because it was near the driving route, had public parking available, included restroom facilities, and was available for both daytime and nighttime use during the data collection period. After meeting with a member of the research team to review the informed consent documentation and complete the demographic questionnaire, participants were given an overview of the study, including how the data were to be collected. They were also given a Dvorine color vision test.

To ensure consistency, the research team used scripts and slide shows to aid in providing instructions to each participant. The script used during intake was as follows:

"Now, let me tell you a little about your tasks. There are two parts. For the first part, you will be driving a State-owned passenger vehicle on a closed course we have set up on airport runways, taxiway, and roadways here at the Riverside campus. The vehicle is specially equipped to record and measure various driving characteristics, but drives just like a normal car. A researcher will be in the car with you at all times and will direct you when, where, and how fast you will need to go. The fastest you will be asked to drive is 40 mi/h.

For one part, you will be driving a course marked with white and yellow striping just as you would see on an actual road. Part of the route is not striped, and when we reach these segments, I will point you to the reflective pavement markings/line in the pavement that will act as our road's "center line." Once we arrive to the study location, we will ask you to park your vehicle next to the orange barrels. There will be another participant in a vehicle next to you. We are running two participants simultaneously to more efficiently collect data for this study.

Once the vehicle is in position we will ask you to place it into park. We will then ask you to place the occlusion glasses over your eyes and glasses if you have glasses. The occlusion glasses will block your vision until the start of the test. When you are ready, we will clear the occlusion glasses and restore your vision. You are to tell us via a button push whether the pedestrian in the downstream crosswalk is walking to the left, to the right, or is not present. We will practice the button pushes prior to driving to the study sites. After you indicate which way the pedestrian is walking, I will ask you to indicate if the beacon glare is comfortable, irritating, or unbearable.

- *Comfortable (where the glare is not annoying and the signal is easy to look at).*
- *Irritating (where the glare is uncomfortable, however you are still able to look at it without the urge to look away).*
- *Unbearable (where the glare is so intense that you want to avoid looking at it).*

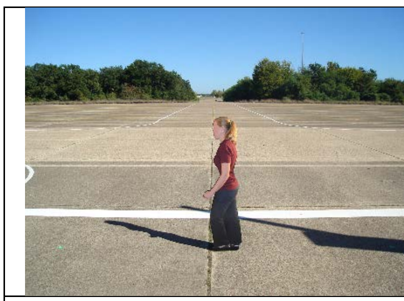
After completing the tests you will return here for a brief laptop survey. After the laptop survey we will provide your payment."

Initial Button Push Training

As part of the intake process, the participants practiced with a button box while responding to photographs of the crossing. The objectives for this part of the study were as follows:

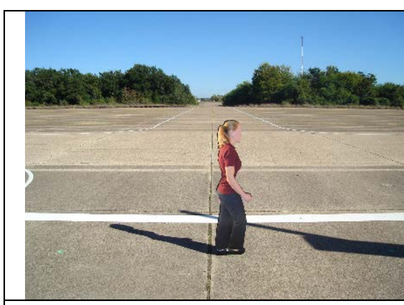
- Train participants to recognize the pedestrians as well as absence of the pedestrians.
- Provide the opportunity for the participants to become familiar with using three buttons to record their responses.

During the training tests, the participant pressed a button when they determined the direction the pedestrian was walking. Because of the software used for this test and available response pads for this software, the button box used for this training had seven buttons. Figure 10 through figure 12 show three of the photos along with the accompanying instructions used in the initial training. A random mix of tall and short cutout pedestrians moving to the right and to the left and in positions 1, 3, or 5 (illustrated in figure 8) were used within the training.



When the pedestrian in the crosswalk is moving to the left (as shown) please press (3) (do so now).

Figure 10. Photo. Training example with pedestrian facing left.



When the pedestrian in the crosswalk is moving to the right (as shown) please press (5) (do so now).

Figure 11. Photo. Training example with pedestrian facing right.

When no pedestrian is present in the crosswalk (as shown) please press (4) (do so now).

Figure 12. Photo. Training example with no pedestrian.

Vehicle Review

Participants were escorted to the TTI vehicle and given a walk-through of the vehicle's features. They were provided with the opportunity to adjust the seat and mirrors and to become accustomed to the controls of the vehicle.

Participants were informed that they would drive the vehicle on a closed course and were told to drive at a speed not exceeding 40 mi/h on the runways. They were asked to drive the runway system as though it was a regular roadway and were reminded that they had complete control of the vehicle at all times. A researcher accompanied the participant in the back seat, controlling the data collection equipment and providing direction. Participants were told to keep the vehicle's headlamps on the low setting if testing at night. They were told to drive to the study site and to position the vehicle by the barrel. Once in position, they were told to place the vehicle into park.

Data Collection at Study Site

At the study site, the participants were reminded that they would be wearing occlusion glasses that would block their vision until the start of the test and that they would provide responses via a three-button box within the vehicle. The researcher handed the participant the button box and asked them to become acquainted with the button box and to determine how best to hold the box comfortably in their hands. When the participant indicated they were comfortable with the box, they were provided the occlusion glasses, which they placed on their face over their eyeglasses if they were wearing any.

After the participants indicated that the glasses and button box were comfortable, the practice testing began for at least three scenarios. After the practice, the testing began. When the participant had indicated readiness and the field crew indicated readiness for the cutout pedestrian and study assembly, the researcher cleared the glasses and restored vision. The participants were then asked to indicate via a pushbutton whether the pedestrian in the downstream crosswalk was walking to the left or to the right or whether the pedestrian was not present.

The participants were provided the following instruction in case they felt the brightness was too bright for them:

If you find the brightness level of the beacons to be agonizing and you are not comfortable completing the task for a particular test, please look away from the crosswalk and tell me. I will block your vision for that test and will radio the field crew to setup for the next test.

After the participants pushed a button on the button box, which would darken the glasses, they were to provide their rating of the brightness of the lights on the traffic control device. The three rating levels used were as follows:

- **Comfortable**: The glare was not annoying, and the signal was easy to look at.
- **Irritating**: The glare was uncomfortable; however, participants could still look at it without the urge to look away.
- **Unbearable**: The glare was so intense that participants wanted to avoid looking at it.

After the participants indicated the rating level, the researcher radioed the field crew and told them to set up for the next test. This process was repeated until the participants had completed all the tests at the site.

The participants were also provided these additional instructions:

If at any point in time you wish to stop, or would like a break, let me know and we will stop or allow you an opportunity to rest.

Please leave the vehicle in park during these tests and while you are wearing the occlusion glasses.

DATA REDUCTION

Participant Demographics

Table 12 lists the demographic information for the 98 participants. The large number that selected retired for employment (34 percent) is a reflection of the emphasis on having half of the drivers over 55 years old.

Table 12. Demographic information for participants.

Characteristic		Set I, Day		Set I, Night		Set II, Night		Total	
		Number	Percent	Number	Percent	Number	Percent	Number	Percent
Gender	Female	17	53	16	50	17	50	50	51
	Male	15	47	16	50	17	50	48	49
Age group	< 55 years old	17	53	15	47	16	47	48	49
	≥ 55 years old	15	47	17	53	18	53	50	51
Employment	Full time	11	34	12	37	13	38	36	37
	Part time	4	13	2	6	4	12	10	10
	Retired	13	41	10	31	10	29	33	34
	Student/part time	1	3	4	13	5	15	10	10
	Other	3	9	4	13	2	6	9	9
Miles driven per year	< 10,000 mi	5	16	5	16	6	18	16	16
	10,000–15,000 mi	14	44	14	44	15	44	43	44
	> 15,000 mi	13	41	13	41	13	38	39	40
Normal driving conditions	Rural roads	9	28	7	22	11	32	27	28
	City streets	15	47	16	50	12	35	43	44
	Freeways	1	3	3	9	0	0	4	4
	Mixed	7	22	6	19	11	32	24	24

Data Cleaning

Before proceeding with the statistical analyses, the data were reviewed to identify and remove tests that needed to be eliminated due to miscoded information regarding the response type, the wrong LEDs being activated in the assembly, or incorrect pedestrian size, position, or direction. In a few cases, participants would self-correct a button push. To have all response times only reflect initial reactions, the detection time results for a given test with duplicate responses were eliminated. These data were included in the detection accuracy evaluations. Instances where animals crossed in front of the vehicles were eliminated as well.

Responses

The computer software program along with the response pad unit were used to record the time between the occlusion glasses being cleared and the participants pressing a button in the response pad. These data were recorded within a spreadsheet that contained an experiment label, a time stamp, and the corresponding detection time. For each experiment, the researcher asked about the glare immediately after each participant pressed a button in the response pad. The experimenters manually recorded discomfort glare ratings using preprinted data sheets.

Each of the experiment labels corresponded to predetermined combinations of pedestrian height, position, brightness, and flash pattern. The sequence of experiments was random within the blocking structure described previously in this report. The spreadsheet with detection time data was later combined with the corresponding experiment conditions and discomfort data per experiment label.

Box Plots

For some analyses, results were presented visually in the form of box plots or quantitatively in the form of statistical analysis. Box plots presented in this report were generated using the convention that the central line in the box represents the median data point (see figure 13). The top of the box represents the 75th percentile, and the bottom represents the 25th percentile. Thus, the relative position of the median score within the 75th and 25th percentiles can give some indication about the skewness of the data. The height of the box is known as the "interquartile range" (IQR). The "whiskers" represent the data that lie 1.5 times beyond the IQR. If all data below the 25th percentile and above the 75th percentile are within 1.5 times the IQR, then the end of the whisker represents the greatest or smallest value. Otherwise, all outliers beyond 1.5 times the IQR, added or subtracted from the 25th and 75th percentiles, respectively, are plotted using small black open circles.

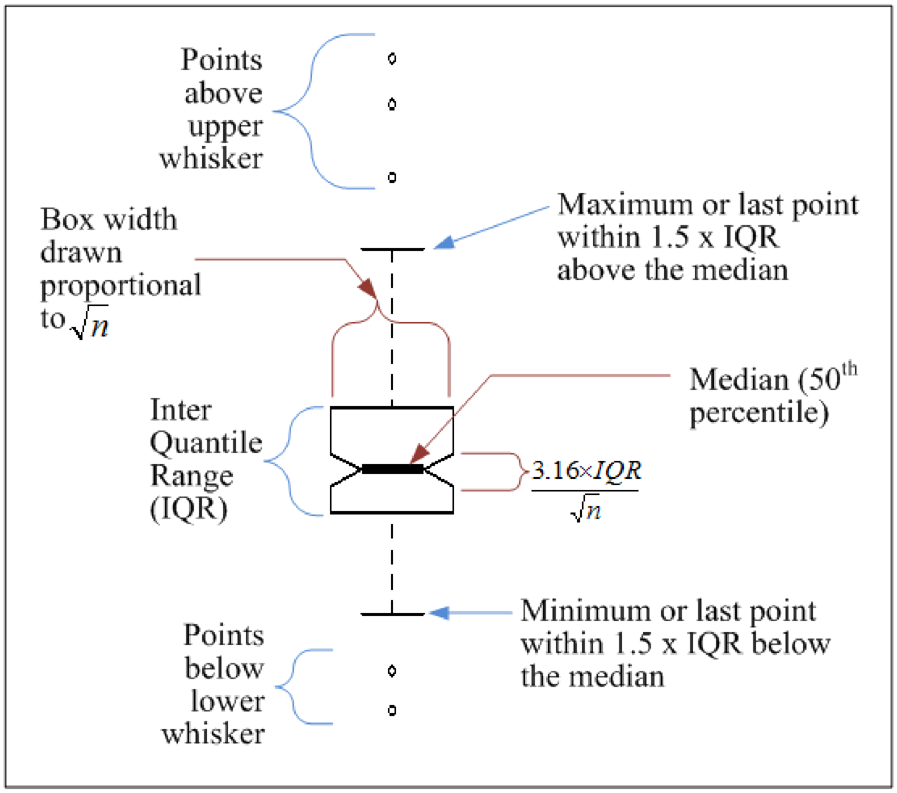


Figure 13. Illustration. Box plot details.

Additionally, it should be noted that a box plot representing a large sample provides more confidence on its quartiles than another box plot representing a smaller sample. For this reason, when two or more box plots are drawn together, the following two metrics of sample sizes are represented:

- The box plot width is drawn proportional to the square root of the sample size, *n*.

- A triangular notch is symmetrically cut around the median and has a total width of $\frac{3.16 \times \text{IQR}}{\sqrt{n}}$. This feature allows a preliminary graphic assessment of differences of medians, since such notch width has been proposed to roughly represent a 95 percent confidence interval around the median.[41] For example, two medians are significantly different if the notches of two box plots do not overlap, but nothing can be said (that is, preliminarily) if there is overlap between notches.

Mosaic Plots

For some analyses, results were presented visually in the form of mosaic plots. Mosaic plots divide each dimension of a rectangular space in sizes relative of the levels of a variable assigned to that dimension. Thus, this type of plot can represent two variables at the time, where each variable may have two or more levels. Figure 14 shows the details of a mosaic plot when the variable assigned to the height is the number of correct/incorrect pedestrian detections.

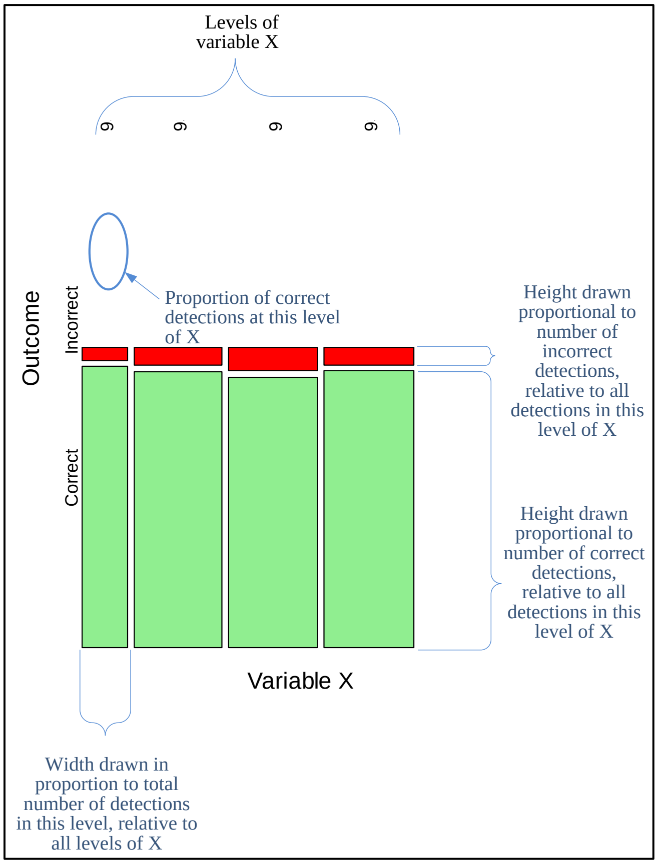


Figure 14. Illustration. Mosaic plot details.

Potential Outliers

Preliminary statistical analyses were examined for outlying data points in the fit. Data points identified in this way were tested for their impact on the analysis. Most of the cases identified in this stage came from a young participant with distinctive fast detection times and high accuracy in the daytime dataset. The data from this participant were identified in the analysis stage. The analysis was tested for sensitivity to this subset, but it was verified that the conclusions remained virtually unchanged, with or without these data. For robustness, results in this report include the data from this participant.

FINDINGS

Detection Time to Correctly Identify Pedestrian Walking Direction

During the daytime, the average detection time to pedestrian direction was 1,137 ms from a sample of 2,998 correct detections. At night, the average detection time was notably longer—1,376 ms from a sample of 6,091 correct detections. This roughly represents a 25 percent increase in detection time at night. Table 13 shows the average detection time for the daytime data, while table 14 provides the nighttime average detection time for pattern set I. Nighttime average detection time for pattern set II is in table 15 along with nighttime average for both pattern sets I and II.

Table 13. Daytime average detection time for set I.

Target Intensity (Candela)	Flash Pattern	Location of LED	Older Participants: Number of Participants	Older Participants: Average Detection Time (ms)	Younger Participants: Number of Participants	Younger Participants: Average Detection Time (ms)	Combined Participants: Number of Participants	Combined Participants: Average Detection Time (ms)
600	100	Within	70	1,356	66	967	136	1,167
600	Five pulses	Within	73	1,170	65	1,015	138	1,097
600	2-5	Above	71	1,219	70	929	141	1,075
600	2-5	Below	82	1,336	63	1,068	145	1,220
600	Wig-wag	Above	74	1,197	70	907	144	1,056
600	Wig-wag	Below	81	1,200	63	963	144	1,096
1,400	100	Within	72	1,311	66	972	138	1,149
1,400	Five pulses	Within	73	1,211	67	968	140	1,095
1,400	2-5	Above	76	1,339	70	979	146	1,166
1,400	2-5	Below	82	1,276	62	969	144	1,144
1,400	Wig-wag	Above	75	1,318	70	960	145	1,145
1,400	Wig-wag	Below	79	1,247	65	938	144	1,107
2,200	100	Within	75	1,311	67	1,013	142	1,170
2,200	Five pulses	Within	74	1,286	68	972	142	1,136
2,200	2-5	Above	79	1,291	69	966	148	1,140
2,200	2-5	Below	81	1,566	62	1,065	143	1,349
2,200	Wig-wag	Above	77	1,333	70	912	147	1,132
2,200	Wig-wag	Below	81	1,332	62	1,025	143	1,199
None	Sign	Above	71	1,190	69	910	140	1,052
None	Sign	Below	83	1,240	65	985	148	1,128
None	Sign	Within	72	1,145	68	940	140	1,046
Total			**1,601**	**1,281**	**1,397**	**971**	**2,998**	**1,137**

Note: Flash patterns are defined as follows: 100 = one 100-ms flash pattern; 2-5 = 2-5 flash pattern; wig-wag = wig-wag flash pattern; and sign = no active LEDs.

Table 14. Nighttime average detection time for set I.

Target Intensity (Candela)	Flash Pattern	Location of LED	Older Participants		Younger Participants		Combined Participants	
			Number of Participants	Average Detection Time (ms)	Number of Participants	Average Detection Time (ms)	Number of Participants	Average Detection Time (ms)
600	100	Within	70	1,781	81	1,106	151	1,419
600	Five pulses	Within	67	1,609	83	1,120	150	1,338
600	2-5	Above	69	1,525	83	1,208	152	1,352
600	2-5	Below	65	1,700	79	1,270	144	1,464
600	Wig-wag	Above	72	1,654	79	1,215	151	1,424
600	Wig-wag	Below	71	1,900	80	1,459	151	1,666
1,400	100	Within	69	1,609	80	1,184	149	1,380
1,400	Five pulses	Within	70	1,596	84	1,147	154	1,351
1,400	2-5	Above	68	1,511	81	1,237	149	1,362
1,400	2-5	Below	68	1,822	79	1,527	147	1,663
1,400	Wig-wag	Above	67	1,495	78	1,240	145	1,358
1,400	Wig-wag	Below	61	1,870	76	1,520	137	1,676
2,200	100	Within	70	1,526	85	1,098	155	1,291
2,200	Five pulses	Within	67	1,603	81	1,231	148	1,399
2,200	2-5	Above	67	1,623	82	1,298	149	1,444
2,200	2-5	Below	61	1,706	75	1,363	136	1,517
2,200	Wig-wag	Above	71	1,745	78	1,277	149	1,500
2,200	Wig-wag	Below	57	2,567	71	1,979	128	2,241
None	Sign	Above	68	1,345	83	1,173	151	1,250
None	Sign	Below	70	1,747	83	1,184	153	1,442
None	Sign	Within	70	1,500	84	1,059	154	1,260
Grand Total			**1,418**	**1,680**	**1685**	**1,274**	**3,103**	**1,459**

Note: Flash patterns are defined as follows: 100 = one 100-ms flash pattern; 2-5 = 2-5 flash pattern; wig-wag = wig-wag flash pattern; and sign = no active LEDs.

Table 15. Nighttime average detection time for set II and combined total for sets I and II.

Target Intensity (Candela)	Flash Pattern	Location of LED	Older Participants		Younger Participants		Combined Participants	
			Number of Participants	Average Detection Time (ms)	Number of Participants	Average Detection Time (ms)	Number of Participants	Average Detection Time (ms)
600	100	Within	70	1,227	72	1,257	142	1,242
600	125(2)	Above	69	1,167	72	1,192	141	1,179
600	125(2)	Below	66	1,195	72	1,246	138	1,221
600	125(2)	Within	69	1,132	76	1,311	145	1,226
600	2-5	Above	71	1,254	77	1,262	148	1,258
600	2-5	Below	61	1,558	76	1,383	137	1,461
1,400	100	Within	67	1,218	75	1,350	142	1,287
1,400	125(2)	Above	69	1,170	76	1,322	145	1,250
1,400	125(2)	Below	73	1,236	73	1,302	146	1,269
1,400	125(2)	Within	69	1,191	72	1,327	141	1,260
1,400	2-5	Above	68	1,249	78	1,303	146	1,278
1,400	2-5	Below	63	1,479	74	1,451	137	1,464
2,200	100	Within	71	1,202	74	1,242	145	1,222
2,200	125(2)	Above	72	1,191	79	1,312	151	1,255
2,200	125(2)	Below	68	1,394	71	1,343	139	1,368
2,200	125(2)	Within	67	1,320	74	1,470	141	1,399
2,200	2-5	Above	66	1,304	78	1,412	144	1,362
2,200	2-5	Below	50	1,390	75	1,481	125	1,445
None	Sign	Above	67	1,224	80	1,158	147	1,188
None	Sign	Below	67	1,385	76	1,214	143	1,294
None	Sign	Within	72	1,189	73	1,217	145	1,203
Total Set II			**1,415**	**1,265**	**1573**	**1,312**	**2,988**	**1,290**
Combined Total Sets I and II			**2,833**	**1,473**	**3258**	**1,292**	**6,091**	**1,376**

Note: Flash patterns are defined as follows: 100 = one 100-ms flash pattern; 125(2) = two 125-ms flashes; 2-5 = 2-5 flash pattern; and sign = no active LEDs.

Box plots were generated to demonstrate trends in the data before conducting the formal statistical analysis. The plots in figure 15 for daytime and figure 16 for nighttime demonstrate that detection time tended to be shorter for lower intensity and longer for higher intensity regardless of the location of the LEDs. This trend was more obvious at night (see figure 16). The trends held even when the data were sorted by pedestrian position rather than LED locations (see figure 17 for daytime and figure 18 for nighttime). The groups of boxes clearly tend to be higher to the right of the plot, which corresponds to higher intensities.

Figure 17 and figure 18 demonstrate a clear trend regarding the pedestrian position in the crosswalk. The time to correctly identify that there was no pedestrian in the crosswalk appears similar at different levels of LED intensity and at day and nighttime (i.e., the green boxes). The median detection time for that case was about 1,200 ms (i.e., the added horizontal line in the plots). In all other correct responses, it is clear that nighttime had longer times, but the relative trends appear constant; a pedestrian at the center of the crosswalk triggered faster detections than either pedestrian at the right or the left side of the crosswalk.

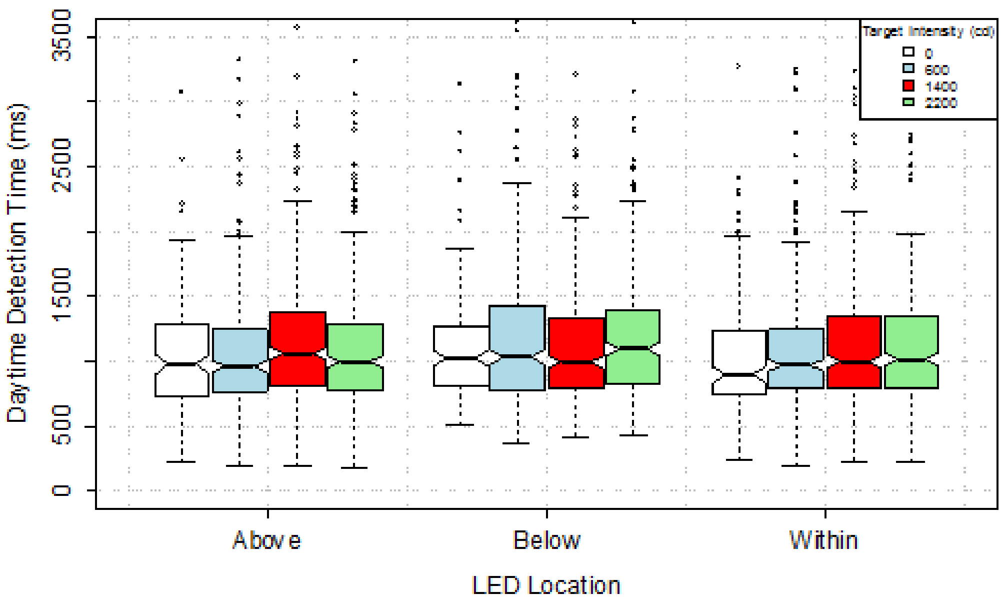


Figure 15. Graph. Daytime detection time by LED location and target intensity.

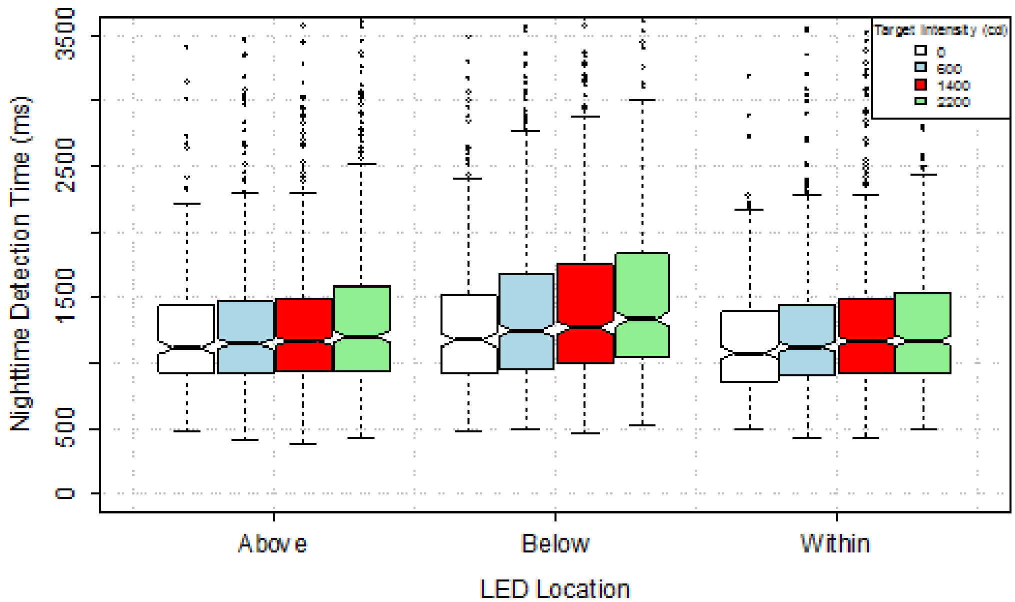
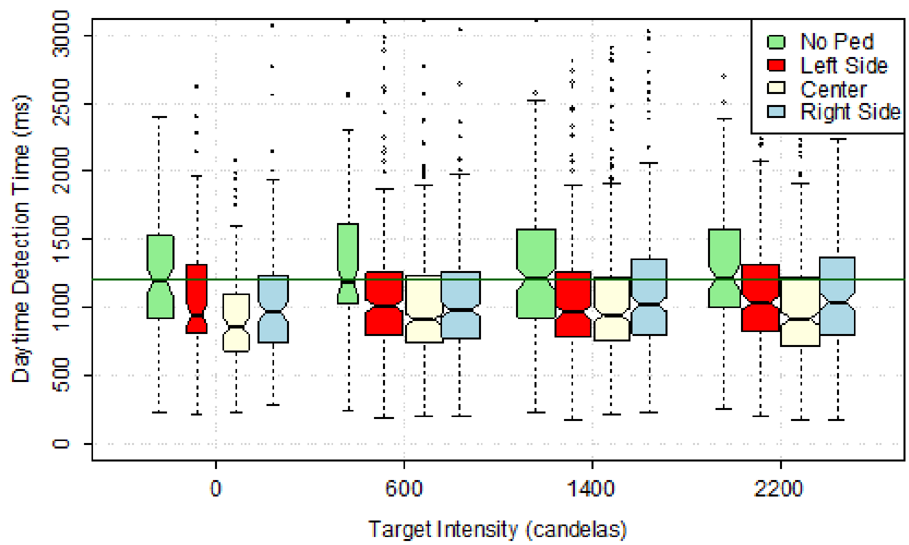
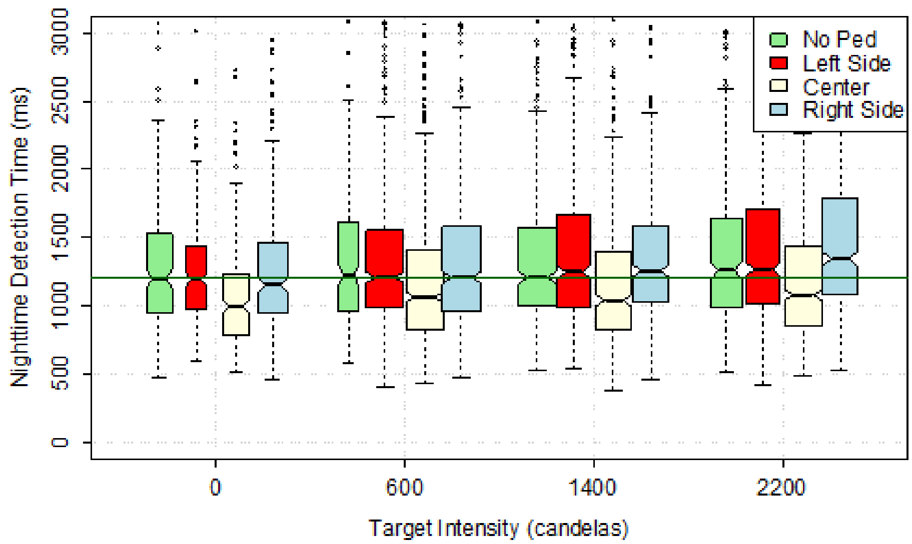


Figure 16. Graph. Nighttime detection time by LED location and target intensity.



Note: The horizontal line represents the median detection time.

Figure 17. Graph. Daytime detection time by pedestrian position and target intensity.



Note: The horizontal line represents the median detection time with no pedestrian present.

Figure 18. Graph. Nighttime detection time by pedestrian position and target intensity.

It should be noted that the plots make evident the fact that the data are heavily skewed toward longer detection times, especially at night. This means that the data are more disperse at values above the median than below the median. To control for this characteristic, the statistical analysis was performed using the natural logarithm of the detection time. This data transformation reduced the skewness while preserving the percentile ranks in the data. More details are provided in the Statistical Analysis section in this chapter.

Accuracy of Detecting Pedestrian Direction

Accuracy of detecting pedestrian direction was determined by the number of participants who correctly detected the direction of the cutout pedestrian to the number of participants for the given characteristics (e.g., flash pattern, etc.). Table 16 shows the accuracy rate for daytime, while table 17 shows similar data for nighttime. During the daytime, the average rate of correct detections of pedestrian direction was 98 percent from a sample of 3,053 detections. At night, the average detection rate was notably lower, 93 percent, from a sample of 6,515 detections.

Table 16. Daytime accuracy of correct detection for set I.

Target Intensity (Candela)	Flash Pattern	Location of LED	Older Participant Accuracy (Percent)	Younger Participant Accuracy (Percent)	All Participant Accuracy (Percent)	Sample Size
600	Five pulses	Within	99	98	99	140
600	Wig-wag	Above	93	100	96	150
600	Wig-wag	Below	95	98	97	149
600	100	Within	95	99	96	141
600	2-5	Above	97	100	99	143
600	2-5	Below	96	100	98	148
1,400	Five pulses	Within	99	100	99	141
1,400	Wig-wag	Above	96	100	98	148
1,400	Wig-wag	Below	98	100	99	146
1,400	100	Within	99	99	99	140
1,400	2-5	Above	97	100	99	148
1,400	2-5	Below	99	98	99	146
2,200	Five pulses	Within	100	100	100	142
2,200	Wig-wag	Above	100	100	100	147
2,200	Wig-wag	Below	95	97	96	149
2,200	100	Within	99	100	99	143
2,200	2-5	Above	99	99	99	150
2,200	2-5	Below	96	97	97	148
None	Sign	Above	96	100	98	143
None	Sign	Below	98	100	99	150
None	Sign	Within	99	100	99	141
Grand Total			**97**	**99**	**98**	**3,053**

Note: Flash patterns are defined as follows: wig-wag = wig-wag flash pattern; 100 = one 100-ms flash pattern; 2-5 = 2-5 flash pattern; and sign = no active LEDs.

Table 17. Nighttime accuracy of correct detection.

Target Intensity (Candela)	Flash Pattern	Location of LED	Set I		Set II		All Participant Accuracy (Percent)	Sample Size
			Older Participant Accuracy (Percent)	Younger Participant Accuracy (Percent)	Older Participant Accuracy (Percent)	Younger Participant Accuracy (Percent)		
600	Five pulses	Within	89	98	NS	NS	94	160
600	Wig-wag	Above	99	98	NS	NS	98	154
600	Wig-wag	Below	95	95	NS	NS	95	159
600	100	Within	93	98	93	91	94	312
600	125(2)	Above	NS	NS	92	92	92	153
600	125(2)	Below	NS	NS	90	92	91	151
600	125(2)	Within	NS	NS	92	96	94	154
600	2-5	Above	93	100	96	99	97	309
600	2-5	Below	87	95	84	95	90	311
1,400	Five pulses	Within	93	100	NS	NS	97	159
1,400	Wig-wag	Above	96	98	NS	NS	97	150
1,400	Wig-wag	Below	84	89	NS	NS	87	158
1,400	100	Within	92	98	92	96	94	308
1,400	125(2)	Above	NS	NS	92	96	94	154
1,400	125(2)	Below	NS	NS	99	94	96	152
1,400	125(2)	Within	NS	NS	92	96	94	150
1,400	2-5	Above	91	98	93	99	95	310
1,400	2-5	Below	91	94	85	93	91	313
2,200	Five pulses	Within	89	95	NS	NS	93	160
2,200	Wig-wag	Above	97	96	NS	NS	97	154
2,200	Wig-wag	Below	78	85	NS	NS	82	157
2,200	100	Within	93	100	95	95	96	313
2,200	125(2)	Above	NS	NS	96	99	97	155
2,200	125(2)	Below	NS	NS	92	92	92	151
2,200	125(2)	Within	NS	NS	89	95	92	153
2,200	2-5	Above	91	98	90	98	94	311

2,200	2-5	Below	82	89	71	94	85	308
None	Sign	Above	92	100	89	100	96	312
None	Sign	Below	95	100	92	95	95	310
None	Sign	Within	93	99	96	92	95	314
Grand Total			**91**	**96**	**91**	**95**	**93**	**6,515**

Note: Flash patterns are defined as follows: wig-wag = wig-wag flash pattern; 100 = one 100-ms flash pattern; 125(2) = two 125-ms flashes; 2-5 = 2-5 flash pattern; and sign = no active LEDs.
NS = Flash pattern was not studied within the set.

Mosaic plots were generated to demonstrate trends in the data before conducting a formal statistical analysis. The plots in figure 19 and figure 20 demonstrate that the percent of correct detections tends to be lower for higher target intensity at night. This trend is not seen in the daytime data.

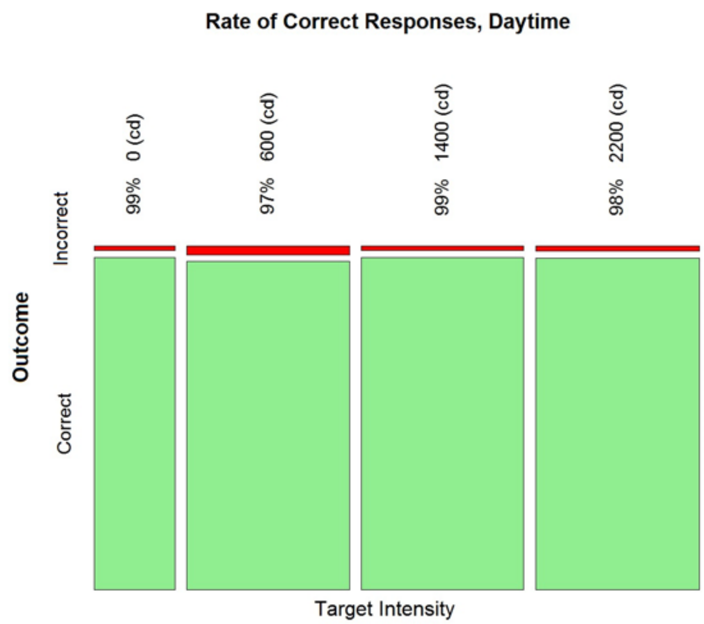


Figure 19. Graph. Daytime correct detection rate by target intensity.

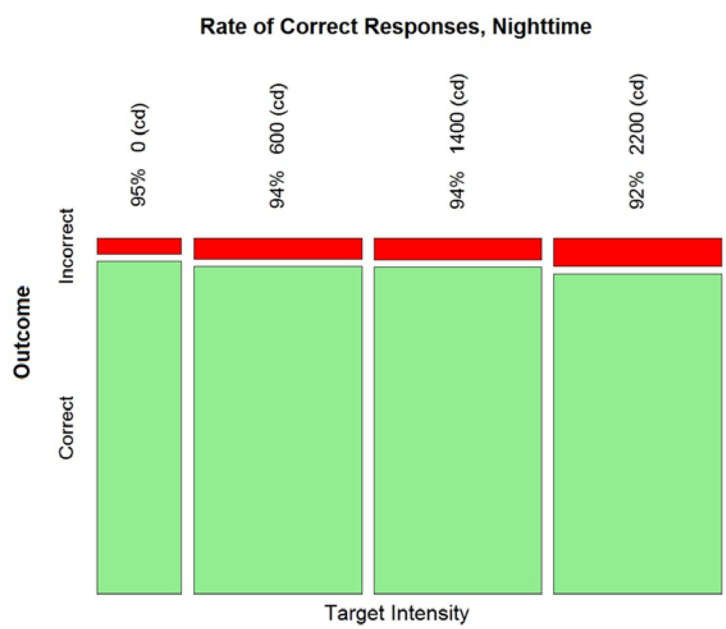


Figure 20. Graph. Nighttime correct detection rate by target intensity.

Figure 21 and figure 22 demonstrate that when subdividing the data by flash pattern, no trend appeared clear for daytime. It appears that the 2-5 (rapid) and wig-wag patterns tended to have slightly lower correct detection rates than the rest of patterns for nighttime condition.

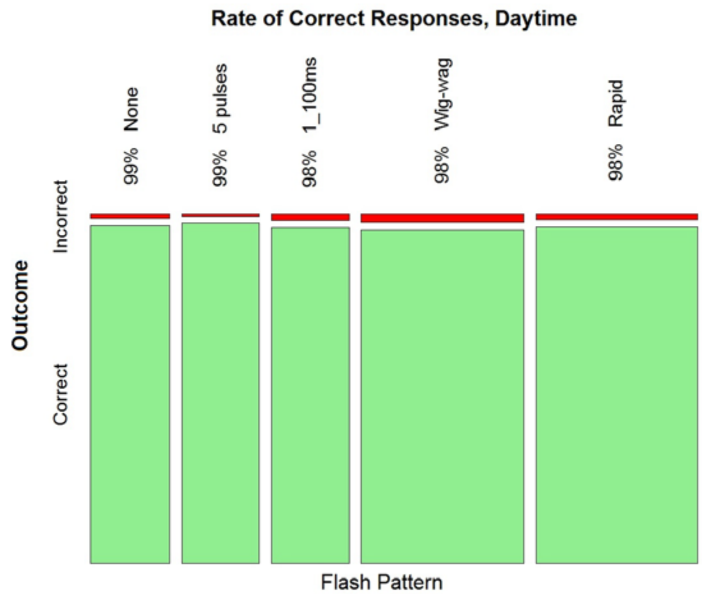


Figure 21. Graph. Daytime correct detection rate by flash pattern.

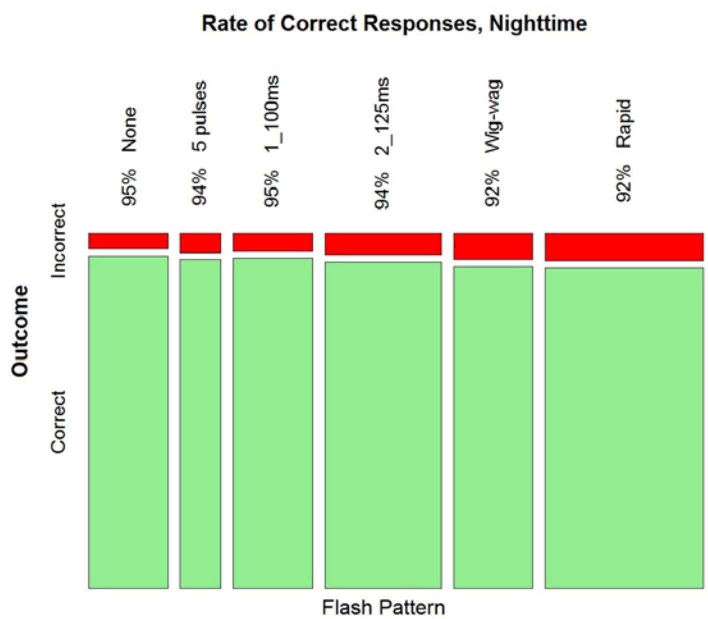


Figure 22. Graph. Nighttime correct detection rate by flash pattern.

Finally, the trends by age are demonstrated by figure 23 for daytime and figure 24 for nighttime. It seems clear the older participants tended to be less accurate than young participants.

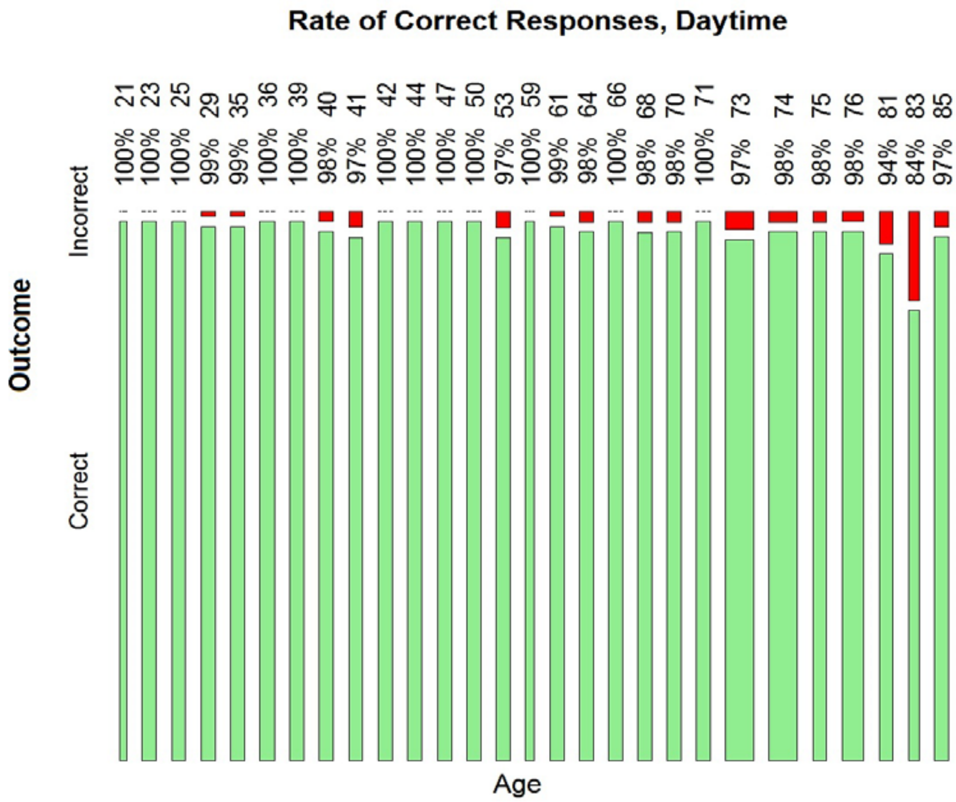


Figure 23. Graph. Daytime detection rate by age.

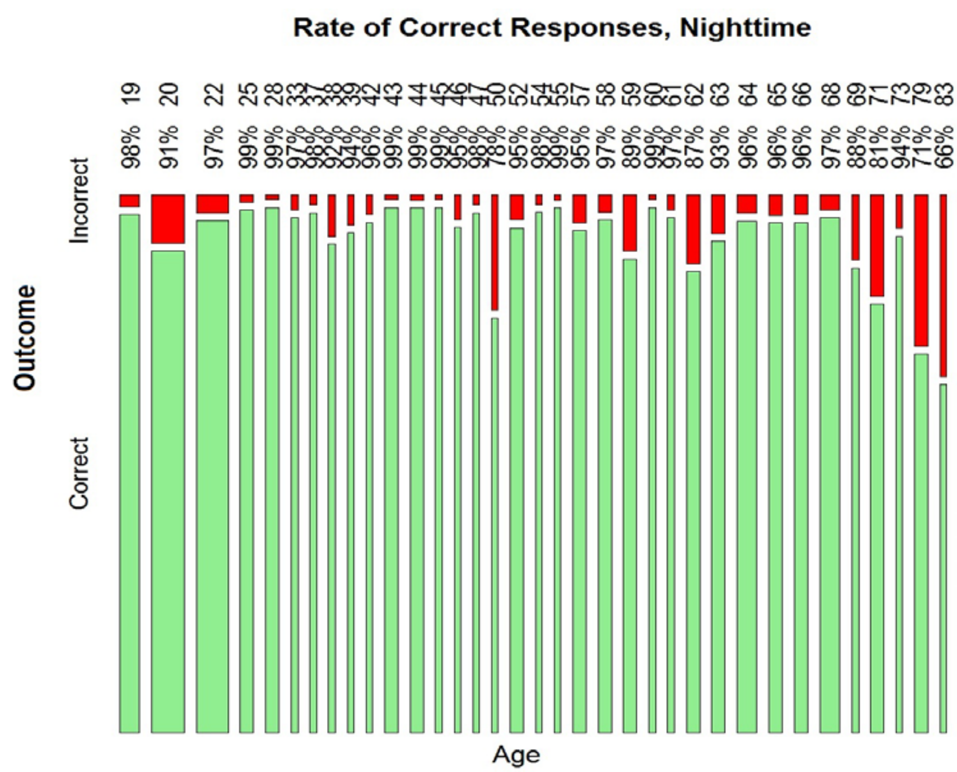


Figure 24. Graph. Nighttime detection rate by age.

Discomfort

After the participants indicated the direction the cutout pedestrian was traveling, they stated whether the intensity of the LEDs was comfortable, irritating, or unbearable. As expected, during the daytime, almost all of the participants were comfortable with the LEDs, as shown in figure 25 (older drivers) and figure 26 (younger drivers). Only the target intensity of 2,200 candelas was associated with more than a 10 percent level of irritating responses.

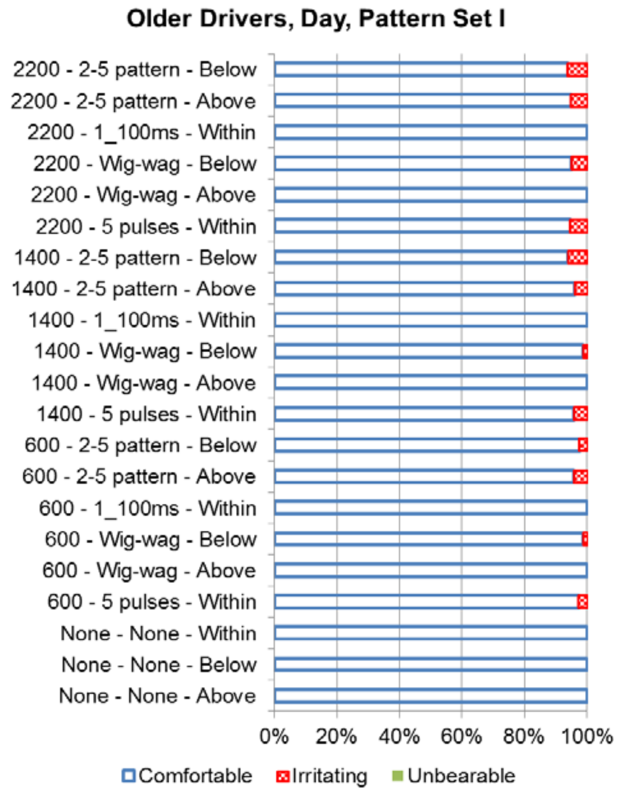


Figure 25. Graph. Older driver daytime discomfort rating for set I.

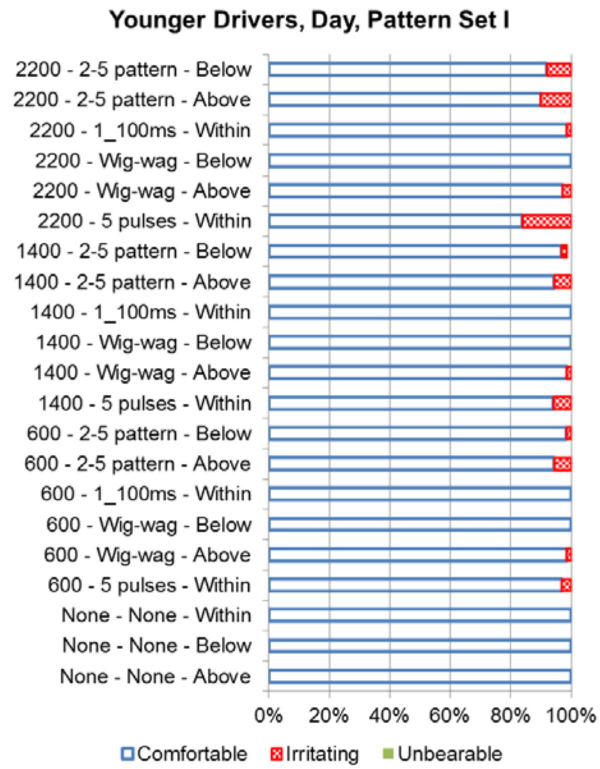


Figure 26. Graph. Younger driver daytime discomfort rating for set I.

During nighttime, more participants considered the LEDs to be unbearable, as illustrated in figure 27 and figure 28 for set I and figure 29 and figure 30 for set II. Trends in the data show that a larger proportion of the participants felt the flash patterns with the higher intensities were irritating or unbearable. Within set I, the wig-wag pattern with a target intensity of 2,200 candelas had the lowest number of participants, indicating it was comfortable for both older and younger drivers.

Reasons the participants gave an unbearable rating include the following:

- It was almost impossible to see the pedestrian.
- There was too much glare.
- Lights were too distracting.

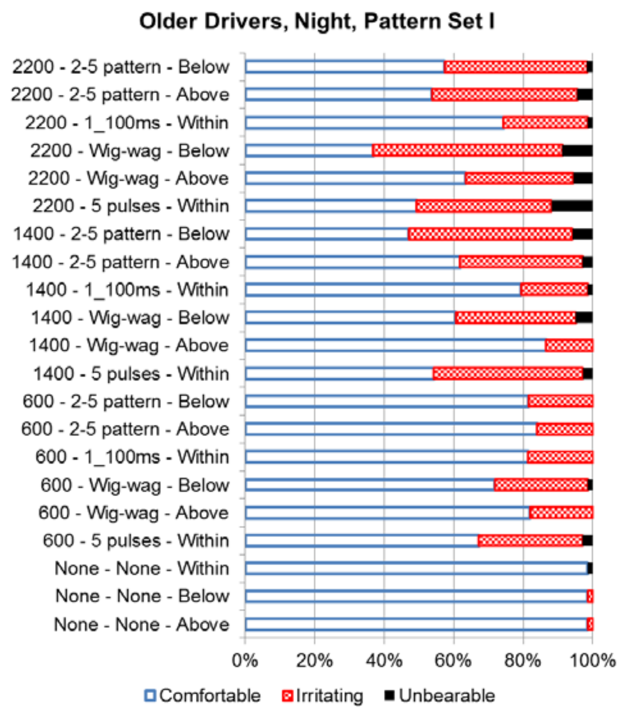


Figure 27. Graph. Older driver nighttime discomfort rating for set I.

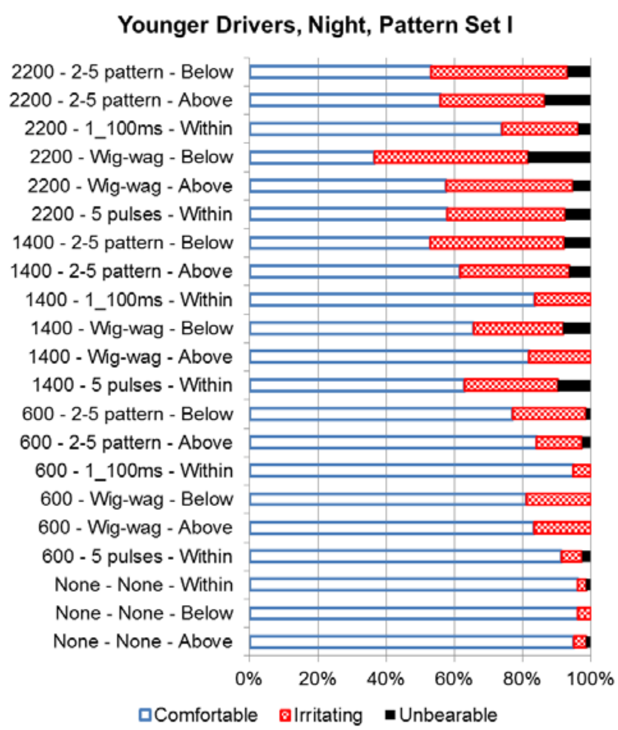


Figure 28. Graph. Younger driver nighttime discomfort rating for set I.

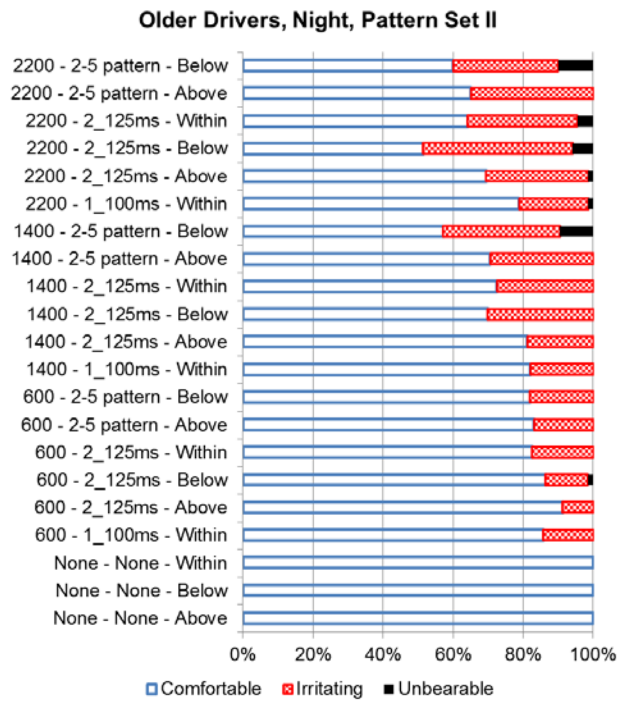


Figure 29. Graph. Older driver nighttime discomfort rating for set II.

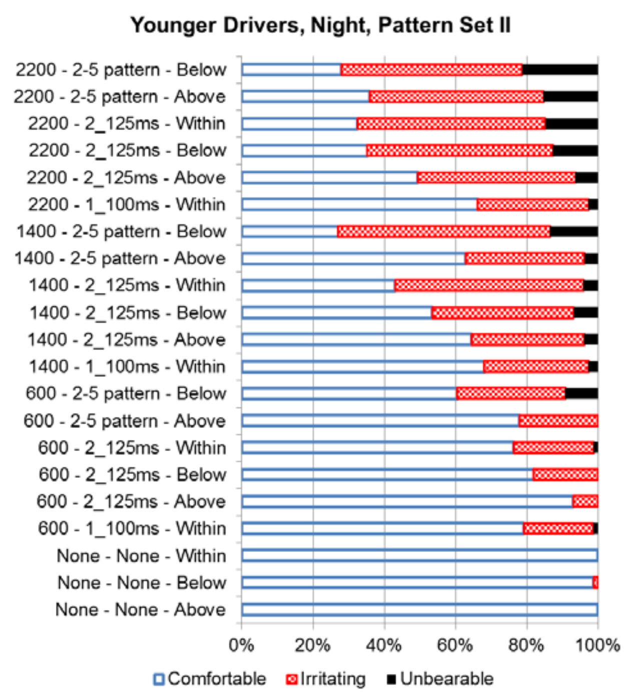


Figure 30. Graph. Younger driver nighttime discomfort rating for set II.

Concluding Survey

Queries 1 and 2—Driver Responses

The initial two queries asked the participants to indicate how the driver in the video would react to the pedestrian attempting to cross at the crosswalk. Table 18 highlights the number of participants who selected each of the potential responses for both queries 1 and 2 with the percent of participants shown in parentheses. Figure 31 shows a plot of the findings. For all of the devices studied, the answer selected by the majority of the participants was "stop." For two devices—the wig-wag pattern on the LEDs located below the sign and the sign without any active LEDs—had about one-third of the participants selecting the "confirm pedestrian is not crossing" answer while less than 17 percent selected that answer for the other two devices tested. Stated in another manner, the 2-5 below and the 100 ms within had more correct responses ("slow" or "stop" and "allow the pedestrian to cross") than the sign without LEDs or the sign with the LEDs below in a wig-wag pattern. The multiple flashes within a short time period, as is present with the 2-5 pattern, may be better at communicating the need to stop for a yellow device.

Table 18. Results for survey queries 1 and 2.

Flash Pattern	Number of Participants (Percent of Participants)				
	Slow[a]	Stop[b]	Confirm[c]	Continue[d]	Total
Within; 100	7 (22)	20 (63)	5 (16)	0 (0)	32 (100)
Below; wig-wag	3 (9)	18 (56)	11 (34)	0 (0)	32 (100)
Below; 2-5	5 (15)	23 (67)	6 (17)	0 (0)	34 (100)
Sign	23 (23)	44 (45)	29 (30)	2 (2)	98 (100)

[a]I would **slow** and allow the pedestrian to cross the roadway.
[b]I would **stop** and allow the pedestrian to cross the roadway.
[c]I would **confirm** the pedestrian is not crossing before proceeding.
[d]I would **continue driving** at the same speed.
Note: Flash patterns are defined as follows: 100 = one 100-ms flash pattern; wig-wag = wig-wag flash pattern; 2-5 = 2-5 flash pattern; and sign = no active LEDs.

Figure 31. Graph. Results for survey queries 1 and 2.

Queries 3 and 4—Flash Pattern and LED Location

Queries 3 and 4 explored whether certain flash patterns and LED locations affected the participants' sense of urgency in needing to yield to a pedestrian. Each participant saw two pairs of videos. The results for queries 3 and 4 were combined for this review along with whether the sign was shown on the left side or the right side of the screen. To facilitate review of the results, findings were repeated for each pair combination (e.g., the results were shown for both the comparison of the within LEDs being on for 100 ms to sign (i.e., no active beacons) as well as sign (i.e., no active beacons) to within LEDs being on for 100 ms). Table 19 and table 20 show the results.

Table 19 contains the comparisons between having a sign with no active LEDs and the other combinations. For all of these comparisons, the majority of the participants selected the device with an active LED as communicating more urgency for yielding. For the comparison between sign and either below LEDs with a 2-5 flash pattern or below LEDs with four 25-ms flashes and one 100-ms flash, all of the participants felt the flashing device communicated a greater urgency to yield than the sign without an active LED. A majority of the participants (60 percent) felt the within LEDs with two 125-ms flashes communicated a greater urgency; however, 30 percent felt that neither device communicated urgency.

Table 19 also shows the results for the comparisons with the devices when the LEDs below the sign were active. When the 2-5 flash pattern was used with the LEDs below the sign, the participants felt it communicated a greater urgency as compared to the three patterns tested with the LEDs within the sign. The 2-5 pattern below the sign was favored by 90 percent of participants compared to the single 100-ms flash within the sign, by 78 percent compared to two 125-ms flashes within the sign, and 78 percent compared to four 25-ms flashes and one 200-ms flash within the sign. The comparison of the 2-5 flash pattern to the flash pattern with four 25-ms flashes and one 200-ms flash used with the below LEDs showed that the majority of the participants felt both devices communicated similar urgency (66 percent). The flash pattern for the below LEDs with four 25-ms flashes and one 200-ms flash was a subset of the below 2-5 flash pattern in that it was the "5" portion of the 2-5 pattern. Perhaps it was the multiple pulses that helped to communicate the urgency. The comparison of the 2-5 flash pattern with the pattern that only had the two pulses (below LEDs with two 125-ms flashes) had fewer participants feeling that both of these devices communicated a similar urgency (only 33 percent). This result provides some support that the multiple pulses helped to communicate urgency. A total of 22 percent of the participants felt the below LEDs with two 125-ms flashes communicated greater urgency as compared to the below 2-5 flash pattern, which added caution to the observation that more flashes were associated with greater urgency. The location of the LEDs may be another factor.

The comparison of the same number of flashes being used at different LEDs locations shows that participants believed the LEDs below the sign demonstrated more urgency than LEDs within the sign. For example, when two 125-ms pulses were used, the participants felt the LEDs below communicated a greater urgency (70 percent). The results for the four 25-ms flashes and one 200-ms flash also revealed that more participants felt the LEDs below (78 percent) showed greater urgency.

Within the comparisons of different flash patterns used with the within LEDs (see table 20), almost all of the participants (80 percent) felt the two-pulse pattern (i.e., two 125-ms pulses) and the five-pulse pattern (i.e., four 25-ms pulses and one 200-ms pulse) communicated the same urgency. The participants indicated that the two-pulse pattern (56 percent) communicated greater urgency over the one-pulse pattern (i.e., within LEDs with one 100-ms flash), or they felt those two patterns communicated a similar urgency (33 percent).

Table 19. Percent of participants who felt a sense of urgency to yield for signs with no active LEDs and LEDs below the sign.

Device 1	Device 2	Device 1 More Urgent (Percent)	Device 2 More Urgent (Percent)	Similar Urgency Both Devices (Percent)	Neither Device Conveys Urgency (Percent)
Sign	Within; 100	11	56	22	11
Sign	Within; 125(2)	0	60	10	30
Sign	Within; 25(4)+200	11	56	33	0
Sign	Below; 2-5	0	100	0	0
Sign	Below; 125(2)	0	89	11	0
Sign	Below; 25(4)+200	0	100	0	0
Below; 2-5	Within; one 100	90	0	0	10
Below; 2-5	Within; 125(2)	78	0	22	0
Below; 2-5	Within; 25(4)+200	78	0	11	11
Below; 2-5	Below; 125(2)	44	22	33	0
Below; 2-5	Below; 25(4)+200	25	13	63	0
Below; 2-5	Sign	100	0	0	0
Below; 125(2)	Within; one 100	89	0	11	0
Below; 125(2)	Within; 125(2)	70	0	30	0
Below; 125(2)	Within; 25(4)+200	90	0	10	0
Below; 125(2)	Below; 2-5	22	44	33	0
Below; 125(2)	Below; 25(4)+200	20	40	40	0
Below; 125(2)	Sign	89	0	11	0
Below; 25(4)+200	Within; one 100	82	0	18	0
Below; 25(4)+200	Within; 125(2)	89	0	11	0
Below; 25(4)+200	Within; 25(4)+200	78	0	11	11
Below; 25(4)+200	Below; 2-5	13	25	63	0
Below; 25(4)+200	Below; 125(2)	40	20	40	0
Below; 25(4)+200	Sign	100	0	0	0

Note: Flash patterns are defined as follows: 100 = one 100-ms flash pattern; 125(2) = two 125-ms flashes; 25(4)+200 = four 25-ms flashes and one 200-ms flash; 2-5 = 2-5 flash pattern; and sign = no active LEDs.

Table 20. Percent of participant results for sense of urgency to yield for LEDs above the sign.

Device 1	Device 2	Device 1 More Urgent (Percent)	Device 2 More Urgent (Percent)	Similar Urgency Both Devices (Percent)	Neither Device Conveys Urgency (Percent)
Within; 100	Within; 125(2)	11	56	33	0
Within; 100	Within; 25(4)+200	0	22	78	0
Within; 100	Below; 2-5	0	90	0	10
Within; 100	Below; 125(2)	0	89	11	0
Within; 100	Below; 25(4)+200	0	82	18	0
Within; 100	Sign	56	11	22	11
Within; 125(2)	Within; 100	56	11	33	0
Within; 125(2)	Within; 25(4)+200	10	0	80	10
Within; 125(2)	Below; 2-5	0	78	22	0
Within; 125(2)	Below; 125(2)	0	70	30	0
Within; 125(2)	Below; 25(4)+200	0	89	11	0
Within; 125(2)	Sign	60	0	10	30
Within; 25(4)+200	Within; 100	22	0	78	0
Within; 25(4)+200	Within; 125(2)	0	10	80	10
Within; 25(4)+200	Below; 2-5	0	78	11	11
Within; 25(4)+200	Below; 125(2)	0	90	10	0
Within; 25(4)+200	Below; 25(4)+200	0	78	11	11
Within; 25(4)+200	Sign	56	11	33	0

Note: Flash patterns are defined as follows: 100 = one 100-ms flash pattern; 125(2) = two 125-ms flashes; 25(4)+200 = four 25-ms flashes and one 200-ms flash; 2-5 = 2-5 flash pattern; and sign = no active LEDs.

Queries 5 and 6—Number of Pulses

For queries 5 and 6, the participants were asked to indicate how many flashes they could see on the left side and the right side of an active light bar. The research team used the term “flashes” rather than “pulses” because it has more common usage for the participants. The correct term would be pulses because “A flash is a light pulse or a train of light pulses, where a dark interval of at least 160 ms separates the light pulse or the last pulse of the train of light pulses from the next pulse or the first pulse of the next train of light pulses.” (15)(pg. 4)

The 2-5 flash pattern was used and had five pulses on the left side of the light bar and two pulses on the right side of the light bar. The frequency and percent of the responses by number of pulses is listed in table 21. One participant said there were eight flashes on each side. The researcher who worked with that participant believed the participant was counting the number of unique LEDs within the beacon rather than counting the number of pulses.

The majority of the participants (77 percent) correctly counted two pulses. A few of the participants (four) correctly counted five pulses. The majority of the participants (55 percent) saw three pulses when five pulses were present.

Table 21. Number of pulses on light bar.

Number of Pulses	Response for Side with Five Pulses		Response for Side with Two Pulses	
	Frequency	Percent	Frequency	Percent
1	3	3	4	4
2	23	23	75	77
3	54	55	12	12
4	11	11	5	5
5	4	4	0	0
6	2	2	1	1
7	0	0	0	0
8	1	1	1	1
Total	**98**	**100**	**98**	**100**

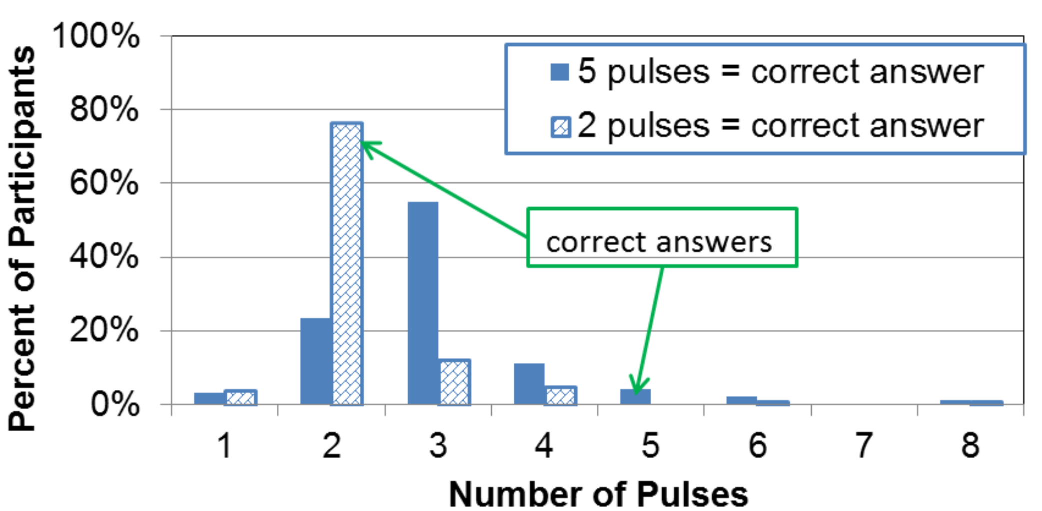


Figure 32. Graph. Number of pulses by percent of participants.

STATISTICAL ANALYSIS

The following subsections describe the statistical analyses performed on the data collected. It should be noted that when the term “significant” appears alone in these subsections, it indicates statistically significant (i.e., the differences found were unlikely to be a random variation but a systematic, measurable trend). Whenever appropriate, an explicit distinction is made to differentiate this term from “practical significance,” which refers to the scale of a difference. For example, a difference may be found statistically significant in one of the analyses, but its magnitude could be such that is too small to be considered practically significant.

Pedestrian Detection Time

The data were initially split by daytime and nighttime conditions. Each set was analyzed using linear mixed effects models (LMMs). These kinds of models combine characteristics from both linear regression and analysis of variance (ANOVA). The model was specified such that appropriate accounts were given to the data structure, known associations between variables, and systematic variation in the response variable. The analysis treated the codependency of data points from the same drivers including a random effect for each participant in the experiment.

The analysis incorporated fixed effects for other variables of interest. In the case of detection time, the fixed effect variables were age, intensity, flash pattern, pedestrian height, and pedestrian position. Estimates, confidence intervals, and conclusions were later extracted for these effects. Due to the heavy skewness of the data, the analysis was performed over the natural logarithm of the detection time (see figure 33).

$$ln\left(Detection\_Time_i\right) = X_i \times \beta + \alpha_j + \epsilon_{ij}$$

Figure 33. Equation. Natural logarithm of detection time.

Where:

$ln(Detection\_Time_i)$ = Natural logarithm of detection time for experiment *i*.
X_i = Vector of variable levels for experiment *i*.
β = Vector of coefficients for all variables in experiment (fixed effects, estimated).
α_j = Random effect for participant *j* (estimated).
ϵ_{ij} = Residual error for experiment *i* and subject *j*.

This statistical specification with a logged response allowed researchers to make inferences about the median detection time instead of the mean detection time. Because a logarithm transformation affects the distribution of the residual errors, the transformed mean is not equal to the original mean. However, an analysis on the transformed mean is equivalent to analyzing the median of the original scale (i.e., detection time) as long as normality or near-normality is achieved after the transformation. This is so because the normal distribution is symmetrical and also because the quartile distribution of the data is not affected by the log transformation. Therefore, each coefficient in the vector β can be interpreted (after exponentiation) as a multiplicative change on the median detection time per unit of explanatory variable.

All statistical analyses were performed using open-source statistical software. (See references 42–45.)

Daytime Time to Detect Pedestrian Direction

Table 22 shows the ANOVA on the variables in this analysis. These results indicate that target intensity had an impact on the detection time after accounting for the rest of variables in the table. In fact, except for two variables (LED location and lane) all of the experimental factors had a significant impact on detection time. The variables used in the following tables are defined as follows:

- **Target intensity**: Intensity of LEDs (0, 600, 1,400, or 2,200 candelas).
- **Flash pattern**: LED flash pattern (none, 2-5 flash pattern, wig-wag, one 100-ms flash, or five pulses).
- **LED location**: Location of LEDs in the assembly (above sign, below sign, or within sign).
- **Pedestrian height**: Height of the pedestrian when present (tall or short).

- **Pedestrian position**: Pedestrian position on crosswalk, when present (center, left, or right).

- **Lane**: Lane of vehicle with participant (left or right).

- **Age**: Age of participant (ranging from 19 to 85 years old).

Table 22. Daytime ANOVA for detection time fixed effects.

Variable	Numerator Degrees of Freedom (DF)	Denominator DF	*F*-value	*p*-value
Reference	1	2956	10730.10	< 0.0001
Target intensity	1	2956	22.44	< 0.0001
Flash pattern	4	2956	4.74	0.0008
LED location	2	2956	0.85	0.4270
Pedestrian height	1	2956	19.59	< 0.0001
Pedestrian position	3	2956	95.61	< 0.0001
Lane	1	28	2.11	0.1571
Age	1	28	7.37	0.0112

The coefficient estimates for daytime are shown in table 23. The comparison of flash patterns shows that 2-5 flash pattern produced longer detection times, though the *p*-values should be adjusted for multiple comparisons. The reference levels used for the base model in this study were no flash pattern, LED location is above, pedestrian height is tall, pedestrian position is none, and lane is left. The coefficient for target intensity in table 23 is small and statistically insignificant. The trend, however, is positive as is the trend at night (discussed in following subsection). Therefore, the no significance could be explained by the effect being smaller than the statistical power in the study. Indeed, examining the magnitude of the effect this coefficient implies, all other factors held equal (i.e. flash pattern, LED location in assembly, pedestrian height, pedestrian position, lane, and age of participant), the median response time increased by 0.00114 percent per additional candela of intensity (i.e., exp(0.0000114) = 1.0000114), which is about one-fourth of the magnitude of the same trend at night.

Table 23. Daytime detection time fixed effects coefficients.

Coefficient		Value	Standard Error	DF	*t*-value	*p*-value
Reference[a]		6.39000	0.21700	2956	29.5039	< 0.0001
Target intensity		0.00001	0.00001	2956	1.6846	0.0922
Flash pattern	2-5	0.05040	0.01800	2956	2.8054	0.0051 [b]
	100	0.04340	0.02380	2956	1.8231	0.0684 [b]
	Five flashes	0.04320	0.02380	2956	1.8135	0.0699 [b]
	Wig-wag	0.02260	0.01800	2956	1.2548	0.2097 [b]
LED location	Below	0.00686	0.01000	2956	0.6850	0.4934 [b]
	Within	-0.00422	0.02370	2956	-0.1783	0.8585 [b]
Pedestrian height—short		0.03850	0.00825	2956	4.6637	< 0.0001
Pedestrian position	Center	-0.22200	0.01320	2956	-16.8046	< 0.0001 [b]
	Left	-0.16700	0.01320	2956	-12.6137	< 0.0001 [b]
	Right	-0.16400	0.01330	2956	-12.3883	< 0.0001 [b]
Lane—right		0.17300	0.13400	28	1.2902	0.2075
Age		0.00947	0.00349	28	2.7139	0.0112

[a]Reference level used in model for each categorical variable base value: flash pattern = sign, LED location = above, pedestrian height = tall, pedestrian position = no pedestrian, and lane = left.
[b]*p*-values for discrete factors with three or more levels need a multiple comparison adjustment.
Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; 100 = one 100-ms flash pattern; and wig-wag = wig-wag flash pattern.

The adjusted comparisons, shown in table 24, constitute evidence of the 2-5 flash pattern being the only flash pattern with statistically significantly longer detection times than no LEDs flashing during daytime conditions.

Table 24. Daytime simultaneous tests for general linear hypothesis of detection time flash pattern effects.

Condition 1	Condition 2	Estimate[a]	Standard Error	*z*-value	*p*-value[b]	Significance[c]
2-5 flash pattern	None	0.05037	0.01796	2.805	0.0175	*
Wig-wag	None	0.02264	0.01805	1.254	0.5029	
One 100-ms flash	None	0.04337	0.02379	1.823	0.1952	
Five flashes	None	0.04323	0.02384	1.813	0.1986	

[a]Estimate is the difference between fixed effects coefficients corresponding to conditions 1 and 2.
[b]Adjusted *p*-values were reported using a single-step method.
[c]Significance values are as follows: blank cell = p > 0.10; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < .0.001.

Each row in in table 24 represents a scientific hypothesis being tested statistically from the model results. For example, the first row of this table corresponds to the hypothesis that the natural logarithm of the average detection time under the 2-5 flash pattern is no different from the natural logarithm of the detection time when no flashing is present. The estimate for the difference of natural logarithm of detection time under each of these conditions is shown under the column titled "Estimate." The last four columns provide the basis for the assessment of the statistical significance of said difference in natural logarithm of detection time.

For the four intensity levels used in the study, table 25 shows that the magnitude of the intensity effect on median detection time is negligible during the daytime.

Table 25. Daytime magnitude of detection time intensity effect.

Target Intensity (Candela)	Estimated Increase in Median Detection Time (Percent)
0	0 (reference level)
600	0.7
1,400	1.6
2,200	2.4

There was a moderate impact of pedestrian height in detection time. Using the corresponding coefficient in table 23, results indicate that there was a 3.9 percent increase in detection time when using a short pedestrian cutout instead of a tall pedestrian cutout.

Nighttime Time to Detect Pedestrian Direction

Table 26 shows the ANOVA on the variables of interest. The results indicate that at night, all of the experimental factors had a significant impact on detection time except for lane.

Regarding flash patterns, the 2-5 flash pattern is again the pattern that triggered longer detection times. For nighttime, wig-wag was also associated with longer detection times.

Table 26. Nighttime ANOVA for detection time fixed effects.

Variable	Numerator DF	Denominator DF	***F*-value**	***p*-value**
Reference	1	6,016	39772.22	< 0.0001
Target intensity	1	6,016	85.61	< 0.0001
Flash pattern	5	6,016	30.74	< 0.0001
LED location	2	6,016	73.12	< 0.0001
Pedestrian height	1	6,016	22.06	< 0.0001
Pedestrian position	3	6,016	149.86	< 0.0001
Lane	1	60	1.46	0.2322
Age	1	60	8.74	0.0045

The coefficient estimates for nighttime are shown in table 27.

Table 27. Nighttime fixed effects coefficients for detection time.

Coefficient		Value	Standard Error	DF	*t*-value	*p*-value
Reference[a]		6.6900	0.1060	6,016	63.2133	0.0000
Target intensity		0.0000	0.0000	6,016	5.9727	0.0000
Flash pattern	2-5	0.0580	0.0154	6,016	3.7787	< 0.00[b]
	100	-0.0328	0.0184	6,016	-1.7841	0.0745[b]
	125(2)	-0.0077	0.0162	6,016	-0.4770	0.6330[b]
	Five pulses	-0.0172	0.0213	6,016	-0.8106	0.4180[b]
	Wig-wag	0.1280	0.0175	6,016	7.3196	< 0.001[b]
LED location	Below	0.1160	0.0091	6,016	12.7706	< 0.001[b]
	Within	0.0582	0.0139	6,016	4.1920	< 0.001[b]
Pedestrian height—short		0.0357	0.0075	6,016	4.7693	0.0000
Pedestrian position	Center	-0.1310	0.0118	6,016	-11.1563	< 0.001[b]
	Left	0.0490	0.0119	6,016	4.1094	< 0.001[b]
	Right	0.0465	0.0119	6,016	3.9206	< 0.001[b]
Lane—right		0.0950	0.0717	60	1.3252	0.1900
Age		0.0056	0.0019	60	2.9558	0.0045

[a]Reference level used in model for each categorical variable base value: flash pattern = sign, LED location = above, pedestrian height = tall, pedestrian position = no pedestrian, and lane = left.
[b]*p*-values for discrete factors with three or more levels need a multiple comparison adjustment.
Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; 100 = one 100-ms flash pattern; 125(2) = two 125-ms flashes; and wig-wag = wig-wag flash pattern.

Table 28 shows the differences among flash patterns with statistical significance adjusted for multiple comparisons.

Table 28. Nighttime simultaneous tests for general linear hypothesis of flash patterns on detection time.

Condition 1	Condition 2	Estimate[a]	Standard Error	*z*-value	*p*-value[b]	Significance[c]
2-5 flash pattern	None	0.058007	0.015354	3.778	< 0.001	***
Wig-wag	None	0.12806	0.017492	7.321	< 0.001	***
One 100-ms flash	None	-0.03284	0.018403	-1.784	0.248	
Two 125-ms flashes	None	-0.00776	0.016156	-0.48	0.983	
Five pulses	None	-0.0172	0.021267	-0.809	0.871	

[a]Estimate is the difference between fixed effects coefficients corresponding to conditions 1 and 2.
[b]Adjusted *p*-values were reported using a single-step method.
[c]Significance values are as follows: blank cell = p > 0.10; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

There was statistical evidence of the 2-5 flash pattern delaying detection. The magnitude of this delay was very similar to the daytime delay (6 percent increase in median detection time at night versus 5.2 percent at daytime). However, at night, there was also evidence that the wig-wag flash pattern also delayed pedestrian detection. This delay is a substantial increase in detection time. Other variables being equal, median detection time was 13.7 percent longer for the wig-wag pattern than the median detection time with no LEDs active (i.e., 13.7 percent=[exp(0.12806) – 1.0] × 100 percent).

The coefficient for target intensity at night was highly significant as opposed to being insignificant during the daytime. This coefficient was also larger at night by a factor of about 3.7 compared to the daytime. It is estimated that the median response time increased by 0.00369 percent per additional candela of intensity (i.e., exp(0.0000369) = 1.0000369) after controlling for other experimental factors. Table 29 shows the magnitude of the estimated impact of LED intensity. These magnitudes were substantial increases in median detection time.

Table 29. Nighttime magnitude of intensity effect on detection time.

Target Intensity (Candela)	Estimated Increase in Median Detection Time (Percent)
0	0.0 (reference level)
600	2.2
1,400	5.3
2,200	8.5

There was a moderate impact of pedestrian height on detection time. Using the coefficient in table 27, results indicate that there was a 3.6 percent increase in detection time when using a short pedestrian cutout instead of a tall pedestrian cutout.

Table 30 shows the relative effects of LED location with statistical significance adjusted for simultaneous comparisons. The shortest nighttime detection times occurred when the LEDs were located above the sign. Using this position as a reference level, the median detection time was 6 percent longer when the LEDs were located within the sign and 12.3 percent longer when the LEDs were located below the sign as compared to above. Finally, a comparison between LEDs within the sign against LEDs below the sign indicated that the median detection time was 6 percent longer at LEDs below the sign. All three contrasts were statistically significant. Table 31 summarizes these findings.

Table 30. Nighttime simultaneous tests for effect of LED location on detection time.

Condition 1	Condition 2	Estimate[a]	Standard Error	*z*-value	*p*-value[b]	Significance[c]
Below	Above	0.116373	0.009112	12.771	< 0.001	***
Within	Above	0.058172	0.013877	4.192	< 0.001	***
Below	Within	0.058202	0.013906	4.185	< 0.001	***

[a]Estimate is the difference between fixed effects coefficients corresponding to conditions 1 and 2.
[b]Adjusted *p*-values were reported using a single-step method.
[c]Significance values are as follows: blank cell = p > 0.10; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Table 31. Nighttime magnitude of LED location effect on detection time.

LED Location	Estimated Increase in Median Detection Time (Percent)
Above	0.0 (reference level)
Within	6.0
Below	12.3

Key Findings Regarding Detection Time

For the analysis focusing on detection time, (i.e., the time it took participants to indicate the direction of the cutout pedestrian from the moment the occlusion glasses were cleared), results indicate the following:

- As expected, detection time was longer at night than during the day.

- The age of the participants had an impact on detection time, both during the day and at night. Detection time for younger participants was shorter than detection time for older participants. It is estimated that there was an increase of 1 percent in median detection time per year of age during the daytime. At night, age made less of a difference. The corresponding estimate for this effect was an increase of 0.5 percent in median detection time per year of age.

- Pedestrian height had a very similar impact on detection time during the day and at night. Detection time was longer when the pedestrian cutout was short rather than tall. Results indicate an increase in median detection time of 3.9 percent during the daytime and an increase of 3.6 percent at night for the short pedestrian cutout compared to a tall cutout.

- In the case of pedestrian position, trends were the same for daytime and nighttime: detection times were longer when the pedestrian cutout was located on either side of the crosswalk compared to when it was located at the center of the road.

- Flash pattern also had a significant impact on detection time, though most of the differences between the different flash patterns were not statistically significant. Only two flash patterns produced significantly longer detection times than the base level of no flash pattern: the 2-5 flash pattern (used above and below sign) used during the day and at night and the wig-wag pattern (used above and below sign) at night only. Compared to no active flash pattern, there was an increase in median detection time for the 2-5 flash pattern by 5.2 percent during the day and of 6 percent at night. The wig-wag pattern caused an increase in median detection time of 13.7 percent.

LED location had a significant impact at night but not during the day. At night, detection was fastest when the LEDs were above the signs after controlling for other factors. Compared to the above sign LED location, the median detection time increased by 6 percent when the LEDs were within the sign and increased by an additional 6 percent when the LEDs were below the sign for a total increase of 12.3 percent when the below location was compared to the above location.

Accuracy of Detecting Pedestrian Direction

Similar to the analysis of detection time, the data were split by daytime and nighttime conditions. In the detection time analysis, only data representing the correct responses by the participant were utilized. For the accuracy analysis; however, the dataset also included the instances when participants indicated the incorrect walking direction. This analysis used both subsets (i.e., correct and incorrect answers) to evaluate changes in the rate of correct to total answers due to the different variables considered in the experimental design.

The analysis of the resulting dataset was performed on the framework of generalized linear mixed effects models (GLMMs). Similarly to LMMs, these kinds of models combine characteristics from both generalized linear regression and analysis of deviance. The analysis treated the co-dependency of data points from the same drivers including a random effect for each participant in the experiment. In doing so, the model gave an appropriate account to the correlation structure in the data. The model also included a simultaneous parametric estimation for the variables of interest (i.e., as fixed effects).

Similar to the analysis of detection time, the fixed effect variables were age, intensity, flash pattern, pedestrian height, and pedestrian position. Estimates, confidence intervals, and conclusions were later extracted for these effects. The formal specification of the statistical model for accuracy analysis is shown in figure 34.

$$Logit(Accuracy\_Rate_{ij}) = X'_{ik} \times \beta + \alpha_j$$

Figure 34. Equation. Accuracy analysis.

Where:

$Logit$ = Logit transformation, such that $\text{Logit}(x) = \text{Ln}[x/(1 - x)]$.
$Accuracy\_Rate_{ij}$ = Accuracy rate at experiment i for participant j.
X'_{ik} = Vector of k variables whose levels are set for experiment i.

Since each experiment was only recorded once per participant, the best estimator for the accuracy rate was a binary variable, Z, representing the outcome of 1 if the response was correct, 0 otherwise. This variable was utilized as the response in the analysis. To make this a statistical model, an assumption that Z was binomially distributed was made, as shown in figure 35.

$$Z \sim \text{Binomial}(Accuracy\_Rate, n = 1)$$

Figure 35. Equation. Accuracy rate.

The accuracy rate in the equation shown in figure 30 was estimated in the model. The known parameter n is the number of valid data points for each experiment/participant combination, which equals 1 in this study. The experiment design was such that only one response was obtained per experiment/participant combination. The model is then as shown in figure 36.

$$Logit(Z) = X' \times \beta + \alpha$$

Figure 36. Equation. Logit model.

Where:

X' = Vector of explanatory variables.
α = Random effect, estimated for each participant.

The variables β and α in the equation shown in figure 36 were estimated by maximum likelihood.

Model Interpretation

The statistical specification linked the logit of the accuracy rate to a linear combination of the factors in the experiment design. Because the logit transformation is the natural logarithm of the odds of correct responses, inferences about the impact of changing experimental factors *X* to the accuracy rate should be made as follows: a marginal change of one variable in the linear predictor represents a multiplicative change in the odds of participant *j* correctly identifying the pedestrian direction. For experimental factor X_{i1}, with two levels, *A* and *B*, the equation in figure 37 defines the odds ratio that corresponds to coefficient, β_1.

$$\exp\left(\beta_1 \times (A - B)\right) = \frac{\omega_{x_{i1} = A}}{\omega_{x_{i1} = B}}$$

Figure 37. Equation. Odds ratio corresponding to levels *A* and *B* of factor X_{i1}.

Where:

$\omega_{x_{i1}} = A$ = Odds of level *A* of factor x_{i1}.
$\omega_{x_{i1}} = B$ = Odds of level *B* of factor x_{i1}.

The equation in figure 37 indicates that the odds ratio (i.e., the ratio of odds of correct answers at level *A* to odds of correct answers at level *B*) is the exponential of the difference between levels multiplied by the corresponding regression coefficient. All statistical analyses were performed using *R*, an open-source statistical software. (See references 42–45.)

Daytime Accuracy of Detecting Pedestrian Direction

Table 32 shows the proportion of deviance corresponding by each variable in the analysis (i.e., analogous to an ANOVA table). This table indicates that target intensity had little or no impact on accuracy after accounting for the rest of the variables in the experiment design. Similarly, flash pattern did not have any influence on the odds of correctly detecting the pedestrian cutout. In contrast, this table shows that pedestrian position and participant age were the only two variables that were influential to accuracy of pedestrian detection. Specific coefficient estimates for daytime are shown in table 33.

Table 32. Daytime analysis of deviance for accuracy fixed effects.

Variables	Numerator DF	Sum of Squares	Mean Squares	*F*-value	*p*-value[a]
Target intensity	1	0.812	0.812	0.812	0.367
Flash pattern	4	5.266	1.316	1.316	0.261
LED location	2	1.370	0.685	0.685	0.504
Pedestrian height	1	1.934	1.934	1.934	0.164
Pedestrian position	3	10.004	3.335	3.335	0.019
Lane	1	1.230	1.230	1.230	0.267
Age	1	12.130	12.130	12.130	< 0.001

[a]The statistics in this table are based on maximum likelihood estimates convergence to normality by virtue of the law of large numbers. Therefore, *p*-values were obtained from the limit case when DF in the denominator tends to infinity.

In table 33, only two coefficients were statistically significant: age of the participants and the position of the cutout when it faced to the right. The coefficient for age indicates that there was an inverse relationship between age and accuracy, as was expected. Except for the variables explicitly depicted, the rates in figure 38 correspond to the reference levels listed in table 33. From figure 38, it is evident that accuracy at daytime was high in general, with about 3 percent reduction in accuracy rates for the oldest participants when compared to the youngest participants in the study.

For the second statistically significant variable (i.e., pedestrian position to the right), the three *p*-values in table 33 should be adjusted for multiple comparisons. Table 34 shows multiple comparisons of interest and corresponding adjusted *p*-values. Although the trends are similar when comparing left and right sides with the center position, only the comparison between right side and center positions offers suggestive evidence of a real difference.

Table 33. Daytime accuracy fixed effects coefficients.

Daytime Coefficients		Value	Standard Error	*z*-value	*p*-value
Reference[a]		9.5480	1.3160	7.258	< 0.001
Target intensity		0.0004	0.0002	1.640	0.101
Flash pattern	2-5	-0.5800	0.6180	-0.938	0.34[b]
	100	-1.2440	1.1540	-1.079	0.281[b]
	Five flashes	-0.2500	1.2490	-0.200	0.841[b]
	Wig-wag	-0.9990	0.6120	-1.631	0.103[b]
LED location	Below	-0.3600	0.3320	-1.085	0.278[b]
	Within	0.2380	1.1790	0.202	0.840[b]
Pedestrian height—short		-0.4350	0.2990	-1.453	0.146
Pedestrian position	Center	-0.8780	0.8170	-1.075	0.282[b]
	Left	-1.5140	0.7840	-1.931	0.054[b]
	Right	-1.8500	0.7730	-2.391	0.017[b]
Lane—right		-0.3470	0.4520	-0.768	0.442
Age		-0.0490	0.0140	-3.483	< 0.001

[a]Reference level used in model for each categorical variable base value: flash pattern = sign, LED location = above, pedestrian height = tall, pedestrian position = no pedestrian, and lane = left.
[b]*p*-values for discrete factors with three or more levels need a multiple comparison adjustment.
Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; 100 = one 100-ms flash pattern; and wig-wag = wig-wag flash pattern.

Table 34. Daytime simultaneous tests for general linear hypothesis of flash pattern accuracy effects.

Condition 1	Condition 2	Estimate[a]	Standard Error	*z*-value	*Pr* (> |*z*|)[b]	Significance[c]	Odds Ratio
Center	No pedestrian	-0.878	0.817	-1.075	0.6516		0.416
Left Side	Center	-0.636	0.419	-1.520	0.3660		0.529
Right Side	Center	-0.972	0.399	-2.438	0.0534	~	0.378
Both Sides	Center	-0.804	0.3735	-2.153	0.1073		0.448
Left Side	Right Side	0.3355	0.3324	1.009	0.6948		1.399

[a]Estimate is the difference between fixed effects coefficients corresponding to conditions 1 and 2.
[b]Adjusted *p*-values were reported using a single-step method.
[c]Significance values are as follows: blank cell = p > 0.10; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Figure 38 and figure 39 show accuracy rates by pedestrian cutout position and age after accounting for other experimental factors. The extreme difference in accuracy curves when the pedestrian cutout is present is between the center and right-side positions as shown in figure 39. This difference was negligible for younger drivers and was a modest 3 percent for older drivers.

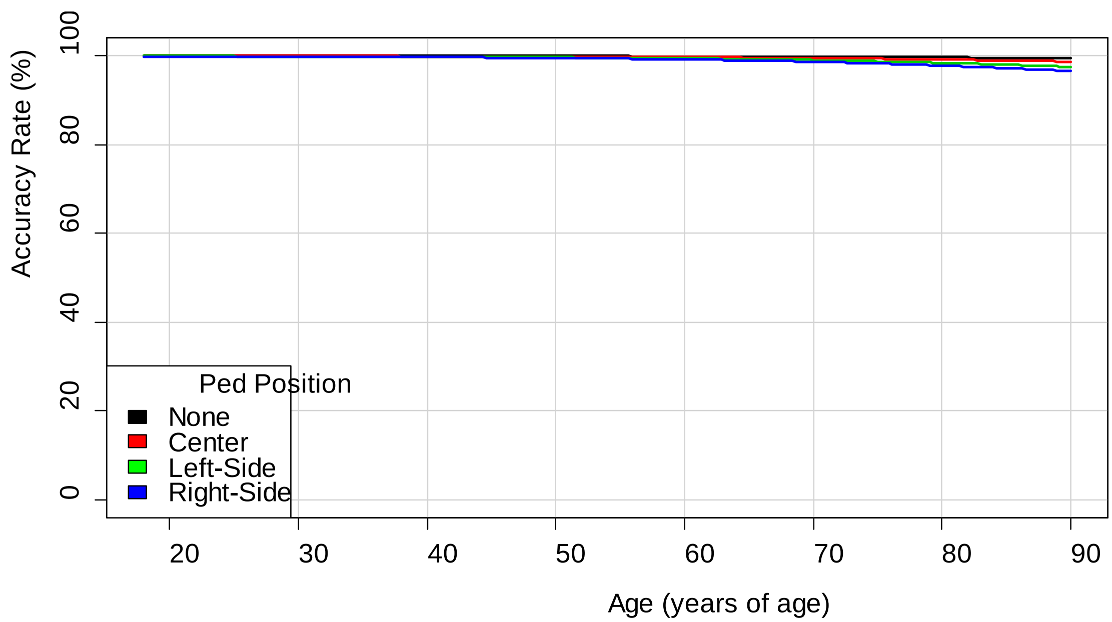


Figure 38. Graph. Daytime estimated accuracy rate by age and pedestrian position.

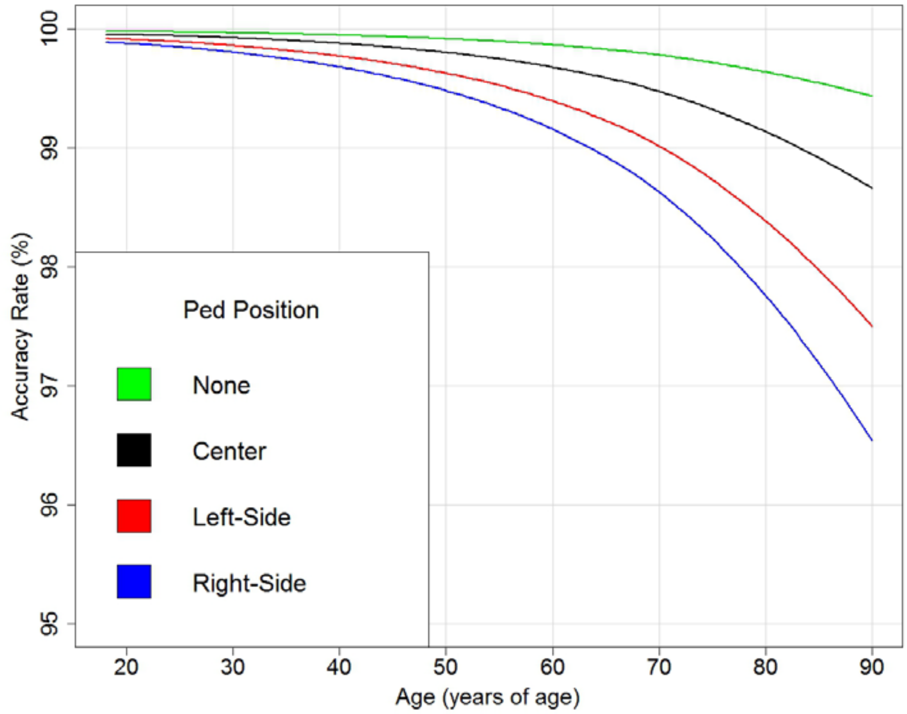


Figure 39. Graph. Close-up view of daytime estimated accuracy rate by age and pedestrian position.

Nighttime Accuracy of Detecting Pedestrian Direction

Table 35 shows the analysis of deviance of the model in this analysis. These results indicate that at night, all the experimental factors have a significant impact on the accuracy rate, except for lane. The coefficient estimates for nighttime are shown in table 36.

Table 35. Nighttime analysis of deviance for accuracy fixed effects.

Variables	Numerator DF	Sum of Squares	Mean Squares	*F*-value	*p*-value[a]
Target intensity	1	14.174	14.174	14.174	< 0.001
Flash pattern	5	13.470	2.694	2.694	0.019
LED location	2	50.289	25.145	25.145	< 0.001
Pedestrian height	1	15.686	15.686	15.686	< 0.001
Pedestrian position	3	95.724	31.908	31.908	< 0.001
Lane	1	1.363	1.363	1.363	0.243
Age	1	11.166	11.166	11.166	< 0.001

[a]The statistical quantifiers in this table are based on maximum likelihood estimates convergence to normality by virtue of the law of large numbers. Therefore, *p*-values were calculated in the limit when DF in the denominator tended to infinity.

Table 36. Nighttime accuracy fixed effects coefficients.

Nighttime Coefficients		Value	Standard Error	*t*-value	*p*-value
Reference[a]		8.2800	0.6580	12.575	< 0.0001
Target intensity		-0.0003	0.0001	-2.789	0.0053
Flash pattern	2-5	-0.2810	0.2440	-1.149	0.2506[b]
	100	0.3250	0.3020	1.073	0.2831[b]
	125(2)	0.2070	0.2590	0.802	0.4223[b]
	Five flashes	0.1160	0.3430	0.338	0.7357[b]
	Wig-wag	-0.4010	0.2750	-1.458	0.1447[b]
LED location	Below	-1.0900	0.1410	-7.762	< 0.0001[b]
	Within	-0.7780	0.2320	-3.349	0.0008[b]
Pedestrian height—short		-0.4540	0.1160	-3.918	0.0001
Pedestrian position	Center	-1.8900	0.4090	-4.625	< 0.0001[b]
	Left	-2.9200	0.4000	-7.305	0.0000[b]
	Right	-2.8400	0.4010	-7.101	0.0000[b]
Lane—right		0.3300	0.3200	1.031	0.3025
Age		-0.0283	0.0085	-3.342	0.0008

[a]Reference level used in model for each categorical variable base value: flash pattern = sign, LED location = above, pedestrian height = tall, pedestrian position = no pedestrian, and lane = left.
[b]*p*-values for discrete factors with three or more levels need a multiple comparison adjustment.
Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; 100 = one 100-ms flash pattern; 125(2) = two 125-ms flashes; and wig-wag = wig-wag flash pattern.

There was no evidence of a difference in accuracy of answers due to different flash patterns after accounting for other relevant factors. Compared to the no flash pattern, only the 2-5 and wig-wag flash patterns seemed to have hindered accuracy (i.e., negative coefficients), but the data did not offer statistical evidence that these differences in fact diverged from zero. However, it is interesting that these two flash patterns were the same for which the analysis of detection time found evidence of being counterproductive.

Also, similar to the results of the detection time analysis, the accuracy analysis found that intensity of the LEDs had an adverse effect. Using the base conditions from table 36, figure 40 and figure 41 demonstrate in absolute terms the impact of target intensity across the range of ages of participants. Also shown in figure 41 is the significant impact of participant age in accuracy of detection. Table 37 shows the odds ratios for the four intensity levels in this study. This table demonstrates that the odds of correct detections fell with increasing intensity.

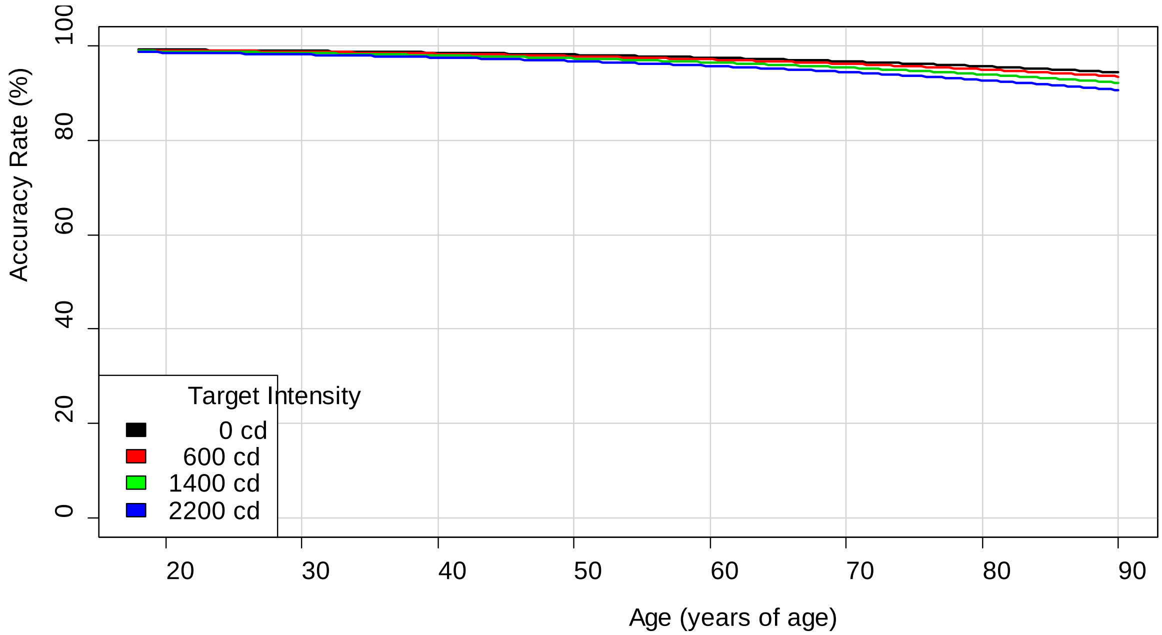


Figure 40. Graph. Nighttime estimated accuracy rate by age and LED intensity.

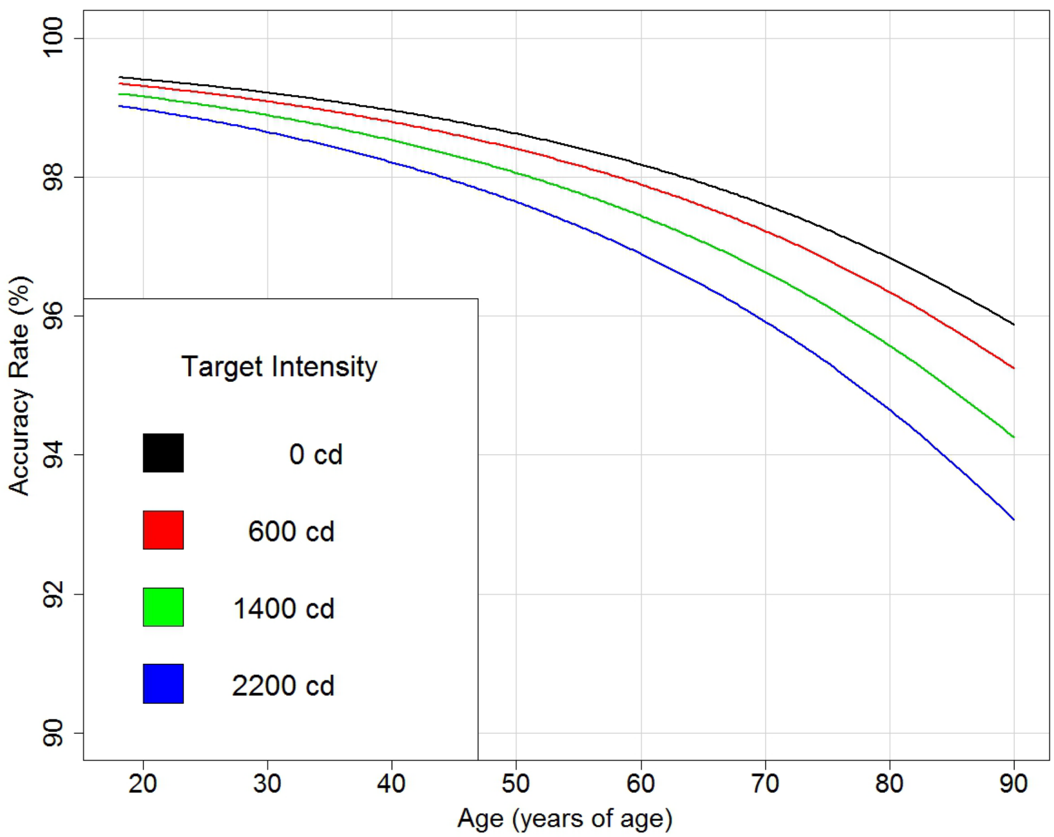


Figure 41. Graph. Close-up view of nighttime estimated accuracy rate by age and LED intensity.

Table 37. Nighttime odds ratio of correct detection intensity levels.

Target Intensity (Candela)	Odds Ratio (Correct Detections)
0	1.00 (reference level)
600	0.86
1,400	0.71
2,200	0.58

Table 38 shows the relative effects of pedestrian location with statistical significance adjusted for simultaneous comparisons. Compared to pedestrian in the center of the crosswalk, placing the pedestrian on either side caused a significant drop in the odds of accurate answers. The difference between left and right sides was found to be not significant.

Table 38. Nighttime simultaneous linear hypotheses for pedestrian position effect on accuracy.

Condition 1	Condition 2	Estimate[a]	Standard Error	*z*-value	*Pr*(>|z|)[b]	Significance[c]	Odds Ratio
Center	No pedestrian	-1.88952	0.40859	-4.625	< 0.001	***	0.151
Left side	Center	-1.03111	0.15249	-6.762	< 0.001	***	0.357
Right side	Center	-0.95434	0.15456	-6.175	< 0.001	***	0.385
Both sides	Center	-0.99272	0.13994	-7.094	< 0.001	***	0.371
Left side	Right side	-0.07677	0.12629	-0.608	0.914		0.926

[a]Estimate is the difference between fixed effects coefficients corresponding to conditions 1 and 2.
[b]Adjusted *p*-values were reported using a single-step method.
[c]Significance values are as follows: blank cell = p > 0.10; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Table 39 shows the relative effects of LED location with statistical significance adjusted for simultaneous comparisons. The most accurate detections at night occurred, as well as the shortest detection times, when the LEDs were located above the sign. Other variables kept equal, the odds of accurate detection with LEDs below the sign were about one-third of the odds with LEDs above sign. The data did not provide evidence supporting any significant difference in odds of accurate detection when comparing LEDs located below and within the sign.

Table 39. Nighttime simultaneous linear hypotheses on LED location effect on accuracy.

Condition 1	Condition 2	Estimate[a]	Standard Error	z-value	*Pr*(>|z|)[b]	Significance[c]	Odds Ratio
Below	Above	-1.0943	0.141	-7.762	< 0.001	***	0.335
Within	Above	-0.7783	0.2324	-3.349	0.00206		0.459
Below	Within	-0.316	0.2161	-1.462	0.30099		0.729

[a]Estimate is the difference between fixed effects coefficients corresponding to conditions 1 and 2.
[b]Adjusted *p*-values were reported using a single-step method.
[c]Significance values are as follows: blank cell = p > 0.10; ~ = p < 0.10; * = p < 0.05; ** = p < 0.01; and *** = p < 0.001.

Key Findings Regarding Accuracy of Detection

For the analysis focusing on accuracy of detection, results indicate the following:

- As expected, detection accuracy was higher during the daytime than at night.

- The age of participants had an impact on accuracy, both during the daytime and at night. Accuracy at daytime was high in general. The analysis indicated, however, a measurable but small reduction in accuracy by age. For example, it was estimated that there was a difference of about 3 percent in accuracy rate between the oldest participants (85 years old) and the youngest participants (19 years old) when they were presented with no flashing LEDs and the tall pedestrian was placed at either the right or the left side. Similarly, the age of the participant had a significantly larger effect under nighttime conditions compared to daytime conditions. For the same scenario described (i.e., no LED and the tall pedestrian cutout positioned at either the right or the left side of the crosswalk) the difference between accuracy rates of a participant 85 years old and another participant 19 years old was estimated at about 8 percent.

- Regarding pedestrian height, accuracy was higher when the pedestrian cutout was tall compared to when it was short.

- Pedestrian position had an impact on accuracy. The evidence for this effect was strong at night but only suggestive during the daytime. In general, locating the pedestrian at the center of the crosswalk had more accurate responses compared to when the cutout was located at either side of the crosswalk. In particular for daytime, only the difference between right-side and center position had a statistical significance, and it was minimal. For nighttime, however, the trends were the same, but the data provided convincing evidence of an impact of pedestrian position: lower accuracy could be attributed to placing the pedestrian cutout on either side of the crosswalk (i.e., closer to the LED assembly) compared to the center position. This finding suggests that being further away from the active LEDs makes accurately detecting pedestrian walking direction easier. As with daytime, no statistical difference was found between the left and right sides at night.

- No evidence was found of the flash pattern having a significant impact on accuracy during the day and at night.

- LED location had a significant impact on accuracy at night but not during the day. At night, detection was most accurate when the LEDs were above the signs after controlling for other factors. Placing the LEDs within the sign led to slightly better accuracy rates than the below location, which was similar to the trends observed for detection time across LED locations. However, this small difference in accuracy rates was not found statistically significant.

Discomfort Glare

The discomfort data obtained from participants' responses were categorized by daytime and nighttime conditions for the analysis. Similar to the analysis of detection times, the only discomfort data used in the analysis were those provided after a correct response was given on pedestrian direction. The discomfort analysis statistically evaluated the changes in the expressed discomfort that could be attributed to the different variables considered in the experimental design.

The analysis used GLMMs to account for repeated measures taken from the same participants. Similar to the previous two analyses, variables age, intensity, flash pattern, pedestrian height, and pedestrian position were coded as fixed effects, with their corresponding standard errors and confidence intervals. Random intercepts per participant were included as a random effect to induce the correlation expected between all responses from each participant.

The discomfort level expressed by the participants could be described as a discrete partition of a continuous non-observable variable that indicated true discomfort. In other words, the true discomfort experienced was ideally a continuous, monotonic function. The goal of the analysis was, in essence, to characterize the relationship between the unobserved real discomfort and the three-level, discrete variable corresponding to the question asked to participants after each experiment (where the only possible answers were comfortable, irritating, and unbearable). The relationship between the true and discrete discomfort variables can be idealized by the plot shown in figure 42 for a given level of an experimental factor:

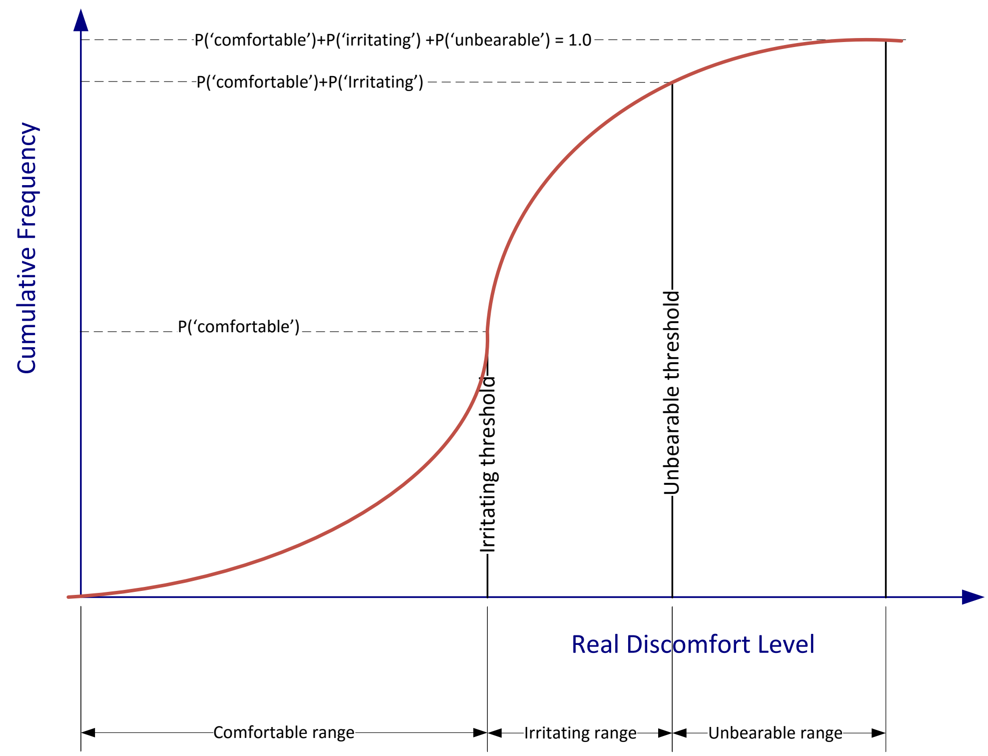


Figure 42. Graph. Idealized relationship between discrete and real discomfort scales.

It can be logically concluded from this graph that the cumulative frequency of answers from all participants defines incremental thresholds in the real discomfort level. Therefore, the statistical analysis quantified how the thresholds changed in response to the variability of the factors in the experiment design. These changes should directly correspond to changes in the idealized continuous discomfort scale.

Given that the odds corresponding to the cumulative frequency at any of the two thresholds are proportional to the odds corresponding to the cumulative frequency at the other threshold, then any of these cumulative frequencies can be related to the explanatory factors, as shown in figure 43.

$$Logit\left(Cumulative\_frequency_{dij}\right) = \theta_d - \left(X'_{ik} \times \beta + \alpha_j\right)$$

Figure 43**. Equation. Cumulative frequency.**

Where:

$Cumulative\_frequency_{dij}$ = Cumulative frequency of answers below threshold *d* in the discretized scale of discomfort at experiment *i* for participant *j*.
θ_d = Log-odds of the threshold for discomfort level *d* at base conditions (estimated).

Model Interpretation

The statistical specification linked the logit of the cumulative rate in the discomfort scale to a linear combination of the factors in the experiment design. Because the logit transformation is the natural logarithm of the odds, inferences about the impact of changing experimental factors *X* to the discomfort rate cannot be made in a linear fashion. Instead, inferences should be made similar to interpreting a logistic model as follows: for a given threshold *d*, a positive marginal change of one variable in the linear predictor represents a multiplicative increase in the odds of the participant indicating any higher level of discomfort compared to the odds of any lower level of discomfort. In other words, for a given threshold *d*, a positive coefficient indicates an increase in the odds of indicating any higher level of discomfort at that threshold. Similarly, a negative coefficient indicates a decrease in the odds of any higher level of discomfort at that threshold.

For experimental factor X_{i1} with two levels, *A* and *B*, the equation is shown in figure 44.

$$\exp\left(-\beta_1 \times [A - B]\right) = \left(\omega_{d \le 1, X_{i1} = A} / \omega_{d \le 1, X_{i1} = B}\right) = \left(\omega_{d \le 2, X_{i1} = A} / \omega_{d \le 2, X_{i1} = B}\right)$$

Figure 44. Equation. Odds ratio for levels *A* and *B* of variable X_{i1} at a maximum level of discomfort.

The quantities in parenthesis shown in figure 44 are odds ratios (i.e., the ratio of odds of level of discomfort *d* or below at $X_{i1} = A$ to odds of level of discomfort *d* or below at $X_{i1} = B$). This relationship implies that the odds ratio at both thresholds should be proportionally related to changes in all factors in the experimental design. Such condition is a critical assumption of the model. Re-expressing the last equality yields an equivalent form that can be used to verify the proportional odds assumption of the model, as shown in figure 45.

$$\left(\omega_{d \le 1, X_{i1} = A} / \omega_{d \le 2, X_{i1} = A}\right) = \left(\omega_{d \le 1, X_{i1} = B} / \omega_{d \le 2, X_{i1} = B}\right) \quad \forall X \text{ in the study}$$

Figure 45. Equation. Revised odds ratio.

The researchers verified that this equality reasonably held for various marginal odds obtained from partitioning the data by levels of the variables of interest (i.e., intensity and flash pattern) as well as by the age of participants. Therefore, the researchers found this model specification appropriate for analyzing the discomfort response. All statistical analyses were performed using *R*, an open-source statistical software. (See references 42–46.)

Daytime Discomfort

As an alternative to an analysis of deviance, Table 40 shows the likelihood ratio tests for models that incrementally add each experimental variable in the analysis.

Table 40. Daytime likelihood ratio tests for incremental discomfort fixed effects.

Variable	DF	Log Likelihood	Chi-Squared Statistic	*p*-value[a]
Reference	N/A	-248.5	N/A	N/A
Target intensity	1	-230.96	35.0783	< 0.001
Flash pattern	4	-193.54	74.8384	< 0.001
LED location	2	-193.5	0.0775	0.96198
Pedestrian height	1	-192.82	1.3694	0.24192
Pedestrian position	3	-189.57	6.5003	0.08965
Lane	1	-189.54	0.0463	0.82961
Age	1	-189.53	0.0165	0.89784

[a]The statistical quantifiers in this table were based on the expected convergence to normality of the log-likelihood function by virtue of the law of large numbers.
N/A = Not applicable.

Table 40 indicates that, after accounting for target intensity and flash pattern, little or no gains in explanatory power resulted from including additional variables. A notable exception in this table is the inclusion of pedestrian position; it showed a minor improvement that is barely statistically insignificant. However, the deviances should be taken as a preliminary assessment of the importance of variables in the analysis. To draw conclusions, specific coefficient estimates for a daytime model accounting for all variables simultaneously were obtained, as shown in table 41.

The only coefficient statistically significant in table 41 corresponds to LED target intensity. This is not surprising, given that the vast majority of discomfort answers during daytime were comfortable. This resulted in a problematic statistical estimation of the first two coefficients in the table (i.e., the discomfort thresholds). Even though the information about the thresholds of the discomfort scale is limited, there is strong evidence of the discomfort increasing with increasing intensity (per the target intensity coefficient in the table). All other factors held equal (i.e., flash pattern, LED location in assembly, pedestrian height, pedestrian position, lane, and age of participant), the odds of a higher level of discomfort increased by 0.089 percent per additional candela of intensity (i.e., $(1 - \exp(8.88\text{E-}04\ ) \times 100$ percent = 0.089 percent). Table 42 shows the odds ratios for increase discomfort level at the four intensity values included in this research.

Table 41. Daytime discomfort fixed effect coefficients.

Coefficient		Value	Standard Error	*z*-value	*p*-value
Intercept[a]	First threshold (comfortable | irritating)	39.87	451.2	0.088	0.930
	Second threshold (irritating | unbearable)	44.83	451.21	0.099	0.921
Target intensity		0.0009	0.0002	3.9340	0.0004
Flash pattern	2-5	27.6000	452.0000	0.0610	0.951[b]
	100	25.7000	696.0000	0.0370	0.971[b]
	Five flashes	29.7000	696.0000	0.0430	0.966[b]
	Wig-wag	25.7000	452.0000	0.0570	0.955[b]
LED location	Below	-0.0721	0.3330	-0.2170	0.829[b]
	Within	-1.8200	298.0000	-0.0060	0.995[b]
Pedestrian height—short		0.3120	0.2860	1.0900	0.2760
Pedestrian position	Center	-0.4310	0.4740	-0.9090	0.364[b]
	Left	-0.1780	0.4570	-0.3890	0.697[b]
	Right	0.4820	0.4580	1.0510	0.293[b]
Lane—right		-0.5840	2.7500	-0.2120	0.8320
Age		-0.0093	0.0718	-0.1290	0.8980

[a]Reference level used in model for each categorical variable base value: flash pattern = sign, LED location = above, pedestrian height = tall, pedestrian position = no pedestrian, and lane = left.
[b]*p*-values for discrete factors with three or more levels need a multiple comparison adjustment. Therefore, *p*-values in this table should not be used unless they correspond to a continuous variable or to a discrete factor of two levels.
Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; 100 = one 100-ms flash pattern; and wig-wag = wig-wag flash pattern.

Table 42. Daytime odds ratios for higher level of discomfort by target intensity level.

Target Intensity (Candela)	Odds Ratio
0	1.00 (reference level)
600	1.70
1,400	3.47
2,200	7.05

Nighttime Discomfort

Table 43 shows a preliminary assessment of the importance of experimental variables in the results based the deviance breakdown of the nighttime data. These results indicate that at night, all the experimental factors influenced the discomfort level.

Table 43. Nighttime likelihood ratio tests for incremental discomfort fixed effects.

Variable	DF	Log Likelihood	Chi-squared Statistic	*p*-value[a]
Reference	N/A	-3699.1	N/A	N/A
Target intensity	1	-3272.5	853.2187	< 0.001
Flash pattern	5	-3145.2	254.7609	< 0.001
LED location	2	-3104.0	82.2763	< 0.001
Pedestrian height	1	-3101.6	4.7844	0.02872
Pedestrian position	3	-3045.6	112.1452	< 0.001
Lane	1	-3043.2	4.6482	0.03109
Age	1	-3035.3	15.8501	< 0.001

[a]The statistical quantifiers in this table were based on the expected convergence to normality of the log-likelihood function by virtue of the law of large numbers.
N/A = Not applicable.

The coefficient estimates for nighttime are shown in table 44, which can be used to draw formal conclusions about the variables influencing discomfort at night. Results indicate that all factors had a bearing in the discomfort level expressed by participants, except for the lane (right or left) where the participant parked.

Table 44. Nighttime discomfort fixed effect coefficients.

Coefficient		Value	Standard Error	*z*-value	*p*-value
Intercept[a]	First threshold (comfortable | irritating)	4.2135	0.4709	8.9470	< 0.001
	Second threshold (irritating | unbearable)	6.8120	0.4763	14.3030	< 0.001
Target intensity (candela)		0.0010	0.0001	18.8520	< 0.001
Flash pattern	2-5	2.5600	0.2640	9.7190	< 0.001[b]
	100	1.2800	0.2820	4.5300	< 0.001[b]
	125(2)	2.1700	0.2660	8.1470	< 0.001[b]
	Five flashes	2.0600	0.2930	7.0460	< 0.001[b]
	Wig-wag	2.2400	0.2750	8.1720	< 0.001[b]
LED location	Below	0.6200	0.0802	7.7340	< 0.001[b]
	Within	0.6440	0.1390	4.6260	< 0.001[b]
Pedestrian height—short		-0.1490	0.0666	-2.2370	0.0253
Pedestrian position	Center	-0.1230	0.1080	-1.1350	0.2564[b]
	Left	0.5290	0.1060	4.9870	< 0.001[b]
	Right	0.4420	0.1080	4.0920	< 0.001[b]
Lane—right		0.2500	0.2660	0.9400	0.3471
Age		-0.0153	0.0070	-2.1790	0.0293

[a]Reference level used in model for each categorical variable base value: flash pattern = sign, LED location = above, pedestrian height = tall, pedestrian position = no pedestrian, and lane = left.
[b]*p*-values for discrete factors with three or more levels need a multiple comparison adjustment.
Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern; 100 = one 100-ms flash pattern; 125(2) = two 125-ms flashes; and wig-wag = wig-wag flash pattern.

Target Intensity

Not surprisingly, target intensity of the LEDs had a positive relationship with nighttime discomfort level. After accounting for all other factors, this analysis indicates that the odds of higher discomfort increased by 0.102 percent per additional candela of intensity. Table 45 shows the odds ratios corresponding to the target intensities used in the study. Similarly, there was convincing evidence of a reduction in discomfort levels associated with placing the short pedestrian in the crosswalk compared to placing the tall pedestrian.

Table 45. Nighttime odds ratios of higher discomfort by target intensity level.

Target Intensity (Candela)	Odds Ratio
0	1.00 (reference level)
600	1.84
1,400	4.17
2,200	9.43

Flash Pattern

There was also strong evidence of an increase in discomfort under all different flash patterns compared to no LEDs flashing after accounting for other relevant factors. Positive coefficients indicate that the odds of higher discomfort were statistically higher than the base condition of no flash pattern. It was of interest; however, to evaluate simultaneous comparisons to determine if there was any particularly flash pattern associated with a high risk of discomfort scores. Due to the particular statistical specification of this analysis, the researchers carried the multiple comparisons by computing the multivariate Hotelling's T^2 statistic in contrast with the previous two analyses. This is a single measure of significance for a set of independent simultaneous hypotheses that involve the coefficient estimates and their corresponding covariance. Since there were six different flash patterns, this methodology allowed up to five simultaneous comparisons for this factor. The researchers defined three comparisons that address the question of interest, shown in table 46. The unique and small *p*-value for this table (1.676E-05) indicates that the test rejected the prospect that all hypotheses were true simultaneously. The last two columns in this table show the expected range of variation in odds ratio for each hypothesis in an overall 95 percent confidence region associated with the simultaneous comparisons. From these columns, the results indicate the following:

- The odds ratio between the group of all the flash patterns to no flash pattern at all was statistically different from 1. The odds of a higher discomfort level were significantly larger for the group of all flash patterns.
- The odds ratio for higher discomfort was not different from 1 when comparing the 2-5 or wig-wag flash patterns to the rest of flash patterns (not including none).
- The odds ratio for higher discomfort was not different from 1 when comparing the 2-5 flash pattern to the wig-wag flash pattern.

Table 46. Nighttime simultaneous hypotheses for flash pattern discomfort effect.

Hypothesis on Odds Ratios	Minimum Estimate of Odds Ratio	Maximum Estimate of Odds Ratio
(All flashing) ÷ (None) = 1	2.10	29.42
(2-5 or wig-wag) ÷ (All others flashing) = 1	0.91	3.41
(2-5) ÷ (wig-wag) = 1	0.79	2.40

For this table, a multivariate T^2 statistic was computed to test the three hypotheses simultaneously. The corresponding T^2 statistic was 108.07; this statistic follows the *F*-distribution with 16 DF in the numerator and 6,075 DF in the denominator. The corresponding *F*-statistic is then $F(16; 6{,}075) = 6.738$. Because the corresponding critical *F*-statistic for a 95 percent confidence of simultaneous comparisons is 1.645, the result of this statistical test indicates that there is convincing evidence that at least one hypothesis in table 46 is such that it the confidence interval does not contain 1.0. From this table, it is clear that such hypothesis is the one comparing all flashing patters to none.

LED Location

Table 47 shows the relative effects of LED location with statistical significance adjusted for simultaneous comparisons. The T^2 statistic corresponding to this table indicates convincing evidence of higher discomfort when the LEDs were located below the sign compared to when they were located above the sign. In contrast, there was no sufficient evidence that locating LEDs within the sign resulted in higher discomfort as compared to above the sign. For this table, the resulting T^2 statistic was 64.9134; the corresponding *F*-statistic from a $F(16, 6{,}074)$ distribution was 4.047. The critical *F*-statistic for a 95 percent confidence of all simultaneous comparisons was 1.645, with a corresponding p-value of 9.033E-08 for a test on the two hypotheses simultaneously.

Table 47. Nighttime simultaneous hypotheses on LED location discomfort effect.

Hypothesis	Minimum Estimate of Odds Ratio	Maximum Estimate of Odds Ratio
(Below) ÷ (Above) = 1	1.23	2.81
(Within) ÷ (Above) = 1	0.93	3.89

Pedestrian Position

Table 48 shows the expected ranges for the relative effects of pedestrian position, given that they were compared simultaneously. There was convincing evidence of higher discomfort when the pedestrian was located at either side compared to when the pedestrian was located at the center of the crosswalk. In contrast, there was no sufficient evidence that having the pedestrian in the crosswalk resulted in higher discomfort compared to when no pedestrian was present. The T^2 statistic for this table was 73.225; the test statistic was $F(16, 6{,}074) = 4.565$. The critical *F*-statistic for a 95 percent confidence of all simultaneous comparisons was 1.645, with corresponding *p*-value of 3.353E-09.

Table 48. Nighttime tests for simultaneous hypotheses on discomfort effect of pedestrian location.

Hypothesis	Minimum Estimate for Odds Ratio	Maximum Estimate for Odds Ratio
(Pedestrian) ÷ (No pedestrian) = 1	0.81	2.16
(Either side) ÷ (Center) = 1	1.24	2.73
(Left side) ÷ (Right side) = 1	0.59	1.42

Age

Finally, this analysis found that driver age influenced the odds of higher discomfort after controlling for other factors in the experimental design. This decreasing discomfort trend is shown in figure 46 when no pedestrian was in the crosswalk and the LEDs were set at 2,200 candelas using the 2-5 flash pattern.

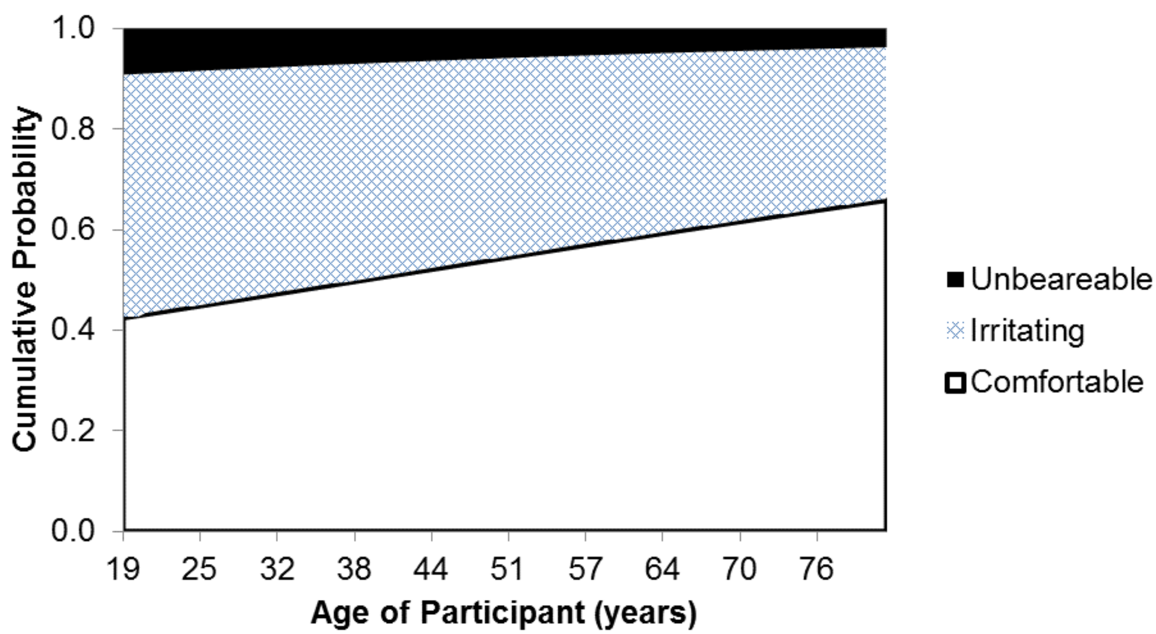


Figure 46. Graph. Estimated cumulative probabilities by age of participant for the discrete scale of discomfort when using 2,200 candelas of intensity and the 2-5 flash pattern.

Key Findings Regarding Discomfort of Detection

For the analysis focusing on discomfort, results indicate the following:

- There were clear differences in discomfort between daytime and nighttime. It was estimated that the odds of increasing discomfort were only influenced by LED intensity during the day, whereas almost all experimental factors had an impact at night.
- LED intensity had a significant impact on discomfort levels during the nighttime only.
- The age of participants had an impact on discomfort levels during the nighttime only. Discomfort tended to decrease with increasing participant age.

- Pedestrian position had an impact on discomfort level during the nighttime only. There was no evidence for increasing discomfort levels when the pedestrian was present compared to when the pedestrian was absent. However, locating the pedestrian at any side of the crosswalk yielded higher discomfort compared to when the pedestrian was located at the center of the crosswalk. This effect is probably associated with the proximity to the active LEDs. No evidence of higher discomfort was found when the pedestrian cutout was placed on the right side compared to when it was placed on the left side.

- For nighttime only, there was convincing evidence of the flash pattern having an impact on discomfort levels. Not surprisingly, this analysis found a significant increase of discomfort associated with any flash pattern compared to no flash pattern at all.

- For nighttime only, LED location had a significant impact on discomfort levels. This analysis found evidence of higher discomfort levels when the LEDs were located below the sign compared to LEDs above the signs after controlling for other factors. Although the trend is similar when comparing LEDs within the sign to LEDs above the sign, this analysis did not find this difference statistically significant.

CHAPTER 4. DRIVER-YIELDING RESULTS FOR BEACONS PLACED ABOVE OR BELOW CROSSING SIGN IN AN OPEN-ROAD SETTING

INTRODUCTION

For the open-road study, the test conditions were set to determine driver yielding when the beacons were located above or below the warning sign. Both placements were studied at all sites so that a similar driver population would see both treatments. This chapter describes the methodology and results from the open-road study that investigated the effects of the placement of yellow rapid-flashing beacons above or below the pedestrian crossing sign.

Due to the findings documented in this report, FHWA issued another interpretation: Official Interpretation #4(09)-58 (I)—*Placement of RRFBs Units Above Sign.*(3) This permits the placement of the beacons either above or below the crossing warning sign.

Study Overview

When IA-11 was issued in July 2008 for the RRFB, the only position of the beacons described in the document was below the crossing warning sign and above the supplemental downward diagonal arrow plaque.(4) As described in chapter 3 of this report, the position of the beacons had an effect on drivers' time to detect the presence and direction of crossing pedestrians as well as discomfort glare during nighttime conditions on a closed course. Prior to developing the proposed provisions for incorporating a rapid-flashing beacon traffic control device into the MUTCD, it is important to determine which beacon position is most beneficial from a driver yielding perspective.(1) This study sought to determine if mounting the beacons above the pedestrian crossing sign was more effective in terms of driver yielding than the traditional position below the sign.

Study Objective

The objective of this study discussed in this chapter was to determine benefits of different positions for the RRFBs used with pedestrian crossing signs in an open-road setting. Because the closed-course study presented in chapter 3 indicated that benefits may exist for placing the beacons above the sign, the open-road study investigated if drivers yielded differently to RRFBs placed above versus below the pedestrian crossing sign.

STUDY DEVELOPMENT

Study Sites

Near the conclusion of the closed-course study described in chapter 3, the researchers talked to agency representatives and made requests during professional society meetings, seeking agencies that would be willing to participate in the open-road research. Four agencies volunteered: Aurora, IL; Douglas County, CO; Marshall, TX; and Phoenix, AZ. As a minimum, the agencies were asked to identify at least two locations that either had existing RRFBs below the pedestrian crossing sign that could be moved to the position above the sign or that would allow the beacons to be installed in one position and then moved to the other position after the initial data collection. Table 49 lists the 13 sites included in the study. The average daily traffic (ADT) values were provided by the agencies in Arizona, Colorado, and Texas. Researchers estimated the ADT for the Illinois sites based on 1-h counts made from the video recordings.

Table 49. Study site characteristics for above-below study.

Site	Posted Speed Limit (mi/h)	Total Crossing Distance (ft)	Crossing Distance to Refuge (ft)	ADT	Crosswalk Marking Pattern	Presence of Advanced Stop or Yield Lines	Number of Through or Left-Turn Lanes Crossed by Pedestrians	Median Type	Intersection Geometry[a]	Pedestrians Crossing per Hour[b]
AZ-PH-04	35	61	20	23,700	Ladder	Yes	5	Raised	Midblock with median jog (50)	25
AZ-PH-05	35	49	NR	8,700	Ladder	Yes	3	TWLTL	Three legs	288
CO-DC-02	45 and 50[c,d]	63	25	7,900	Ladder	No	4	Raised	Three legs	20
CO-DC-03	30	35	NR	2,600	Ladder	No	2	None	Four legs	15
CO-DC-04	30	35	NR	4,900	Ladder	No	2	None	Four legs	19
CO-DC-05	45[d]	78	32	16,100	Ladder	Yes	4	Raised	Three legs	16
CO-DC-06	35 and 45[c]	63	28	19,800	Ladder	Yes	4	Raised	Midblock (50)	36
CO-DC-07	45[d]	78	34	18,800	Ladder	Yes	4	Raised	Midblock (50)	18
IL-AU-02	35	56	NR	30,800	Diagonal	No	4	TWLTL	Midblock (30)	17
IL-AU-03	35	30	NR	8,900	Diagonal	No	2	None	Midblock (360)	19
IL-AU-04	35	94	50	9,400	Transverse	Yes	5	Raised	Four legs	18
TX-MA-01	30	40	NR	1,400	Diagonal	No	2	None	Midblock (300)	137
TX-MA-02	30	30	NR	4,900	Diagonal	No	2	None	Three legs	17

Note: Sites are labeled as XX-YY-##, where XX represents the two-letter State code; YY represents the two-letter city code, and ## represents the site number within the city.
NR = No refuge; TWLTL = Two-way left-turn lane.
[a]The distance (ft) to nearest intersection or major driveway is shown in parentheses (measured from the center of the crossing to the center of the nearest driveway/intersection).
[b]This indicates the number of pedestrian crossings per hour during the daytime data collection period when the beacons were located below the crossing sign.
[c]Speed limit varied by approach.
[d]Site also includes the following two advance traffic control assemblies: pedestrian crossing (W11-2) warning sign with AHEAD (W16-9P) plaque, and SPEED LIMIT 25 (R2-1) regulatory sign with WHEN FLASHING (S4-4P) plaque and a 12-inch circular beacon that is activated when the pedestrian pushes the pushbutton at the crossing.

Study Assemblies

Examples of the study assemblies are shown in figure 47 and figure 48. The beacons were mounted on a roadside pole to supplement either a W11-2 (pedestrian) or W11-15 (trail) crossing warning sign with a diagonal downward arrow (W16-7p) plaque and located at or immediately adjacent to a marked crosswalk. The flash pattern used at the study sites was the 2-5 flash pattern. Table 50 provides information on installation order along with the dates of the data collection.

Figure 47. Photo. Example of RRFB placed above the sign.

Figure 48. Photo. Example of RRFB placed below the sign.

Table 50. Installation and data collection dates.

Site	Existing Beacons on Assembly	Initial Position	Date Above Installed	Date Above Data Collection	Date Below Installed	Date Below Data Collection
AZ-PH-04	RRFB	Below	2/20/2015	2/26/2015	Existing	2/17/2015
AZ-PH-05	RRFB	Below	2/20/2015	2/27/2015	Existing	2/16/2015
CO-DC-02	Activated	Above	3/18/2015	4/14/2015	4/27/2015	5/13/2015
CO-DC-03	Activated	Above	3/18/2015	4/14/2015	4/27/2015	5/14/2015
CO-DC-04	Activated	Above	3/18/2015	4/15/2015	4/27/2015	5/14/2015
CO-DC-05	Activated	Below	4/27/2015	5/14/2015	3/27/2015	4/13/2015
CO-DC-06	Activated	Below	4/27/2015	5/13/2015	3/27/2015	4/13/2015
CO-DC-07	Activated	Below	4/27/2015	5/13/2015	3/18/2015	4/14/2015
IL-AU-02	RRFB	Below	10/16/2014	10/28/2014	Existing	10/10/2014
IL-AU-03	RRFB	Below	10/16/2014	10/28/2014	Existing	10/10/2014
IL-AU-04	RRFB	Below	10/16/2014	10/29/2014	Existing	10/11/2014
TX-MA-01	RRFB	Below	3/25/2015	4/9/2015	Existing	2/12/2015
TX-MA-02	RRFB	Below	3/25/2015	4/10/2015	Existing	2/13/2015

Existing = RRFB was installed below the sign at site prior to the study.
Activated = Pedestrian-activated yellow circular 12-inch flashing beacons were activated.

Rotation

To account for the possibility that device installation order could affect the results, the RRFB was installed above the sign first in some locations and second in other locations. For the 13 study sites, the RRFB was installed initially above the sign in 3 of the sites and was previously installed or initially installed below the sign at the remaining sites.

DATA COLLECTION AND REDUCTION

Study Periods

The study was conducted between October 2014 and May 2015. Following installation of the device in its initial position, the research team collected after data. Once the after data were obtained, the research team requested that the device be installed in the second position (i.e., RRFBs above the sign were moved below the sign and vice versa). After receiving confirmation that the devices had been moved, the research team collected after data for the second position.

Data were collected primarily during the daytime when vehicles were free-flowing. Because few studies have collected data at night, the research team wanted to obtain some data for nighttime conditions. The characteristics of the beacons and the site may have different impacts on driver yielding during night conditions as compared to daytime conditions. Therefore, nighttime data were collected for one site within each city.

Staged Pedestrian Protocol

The research team used a staged pedestrian protocol to collect driver yielding data to ensure that oncoming drivers received a consistent presentation of approaching pedestrians. Under this protocol, a member of the research team acted as a pedestrian using the crosswalk to stage the conditions under which driver yielding would be observed. Each staged pedestrian wore similar clothing (gray t-shirt, blue jeans, and gray tennis shoes) and followed specific instructions in crossing the roadway. The staged pedestrian was accompanied by a second researcher, who observed and recorded the yielding data on pre-printed datasheets.

Prior to the staged crossing maneuvers, researchers placed markers (either small contractor flags or cones) at the edge of the traveled way at a distance corresponding to the AASHTO SSD value for the posted speed limit at that site; one marker was placed in each direction approaching the crosswalk.[38] SSD is 200 ft for 30 mi/h, 305 ft for 40 mi/h, and 360 ft for 45 mi/h. After the study site had been prepared, the researchers followed the predetermined staged pedestrian protocol, which was defined as follows:

1. The staged pedestrian approached the crosswalk as oncoming vehicles approached the SSD marker activating the RRFB.

2. The staged pedestrian reached the edge of the crosswalk in time to place one foot in the crosswalk (e.g., off the edge of the curb or curb ramp) within approximately 1 s of the approaching driver(s) reaching the SSD marker.

3. The staged pedestrian waited to cross until approaching drivers yielded or until all approaching drivers had traveled through the crosswalk.

4. The observer recorded how many motorists did/did not yield as well as how many were in a position to yield for each crossing maneuver. Drivers were considered to be in position to yield if they were upstream of the SSD marker when the staged pedestrian was positioned at the edge of the crosswalk. Each such vehicle that did not yield was counted as was each yielding vehicle. Of the vehicles in a position to yield, a vehicle was considered to be yielding if the driver slowed or stopped for the purpose of allowing the waiting pedestrian to cross. Any vehicles traveling in a platoon behind yielding vehicles were not counted because those drivers did not have the opportunity to make a decision on whether to yield to the pedestrian; therefore, the maximum number of yielding vehicles possible for each crossing maneuver was equal to the number of travel lanes through which the crosswalk passed.

5. Yielding was observed separately for each direction of vehicular travel because Arizona, Colorado, Illinois, and Texas law is written such that drivers must yield to pedestrians in or approaching their half of the roadway.

6. The observer noted any unusual events or noteworthy comments for each crossing.

7. Once the crosswalk was clear (i.e., the approaching vehicle had either stopped or passed through the crossing), the staged pedestrian crossed the street and waited on the sidewalk or roadside until all vehicles visible during that crossing traveled through the crosswalk. After

all such vehicles had left the study site, the staged pedestrian prepared for the next crossing maneuver.

The protocol called for the completion of a minimum of 20 staged crossing maneuvers in each direction of travel for a total of 40 crossings. Observation periods were chosen such that vehicle traffic was heavy enough to create frequent yielding situations but not heavy enough for congestion to affect speeds. Data were always collected during daylight and in good weather, avoiding rain, wet pavement, dusk or dawn, or other conditions that could affect a driver's ability to see and react to a waiting staged pedestrian.

A minimum of 40 (and a desired 60) staged pedestrian crossings were collected at each site within each time period during daytime. Because of the length of time needed to collect the crossing, a minimum of 40 staged pedestrians were collected at night.

Driver Yielding

After completing the data collection, researchers entered the crossing data and the site characteristics data from the field worksheets into an electronic database. The average yielding rate for a site was calculated, as shown in figure 49; however, data for individual crossings were used in the statistical evaluation.

$$\textit{Yielding rate} = \frac{\textit{Number of yielding vehicles}}{\textit{Number of yielding vehicles} + \textit{Number of non-yielding vehicles}}$$

Figure 49. Equation. Driver yielding rate.

Table 51 lists the driver yielding rates for each site and beacon position along with the number of staged pedestrian crossings for the nighttime data collection periods. Driver yielding to staged pedestrians at night averaged 68 percent for the above position and 65 percent for the below position.

Table 51. Nighttime driver yielding rate by site and beacons position.

Site	Number of Staged Crossings for Above Position	Driver Yielding for Above Position (Percent)	Number of Staged Crossings for Below Position	Driver Yielding for Below Position (Percent)
AZ-PH-05	44	81	60	85
CO-DC-06	41	80	40	73
IL-AU-03	60	50	62	46
TX-MA-01	60	73	39	74
Total	**205**	**68**	**201**	**65**

Table 52 shows similar results for the daytime data collection periods. During the daytime, driver yielding to staged pedestrians averaged 64 percent for the above position and 61 percent for the below position. For several sites, neither beacon position showed a large increase in driver yielding as compared to the other. The range of driver yielding to staged pedestrians at these sites ranged from 19 to 98 percent.

Table 52. Daytime driver yielding rate by site and beacon position.

Site	Number of Staged Crossings for Above Position	Driver Yielding for Above Position (Percent)	Number of Staged Crossings for Below Position	Driver Yielding for Below Position (Percent)
AZ-PH-04	60	47	60	54
AZ-PH-05	60	88	43	94
CO-DC-02	61	93	58	98
CO-DC-03	60	82	41	66
CO-DC-04	58	90	60	86
CO-DC-05	60	92	60	79
CO-DC-06	60	82	56	93
CO-DC-07	60	89	60	87
IL-AU-02	59	20	58	19
IL-AU-03	61	42	64	59
IL-AU-04	60	67	60	32
TX-MA-01	42	93	63	87
TX-MA-02	61	85	62	77
Total	**762**	**64**	**745**	**61**

RESULTS

When a driver approaches a pedestrian crossing, the driver either yields and stops (or slows) the vehicle or does not yield to the waiting pedestrian. This binary behavior (yield or no yield) can be modeled using logistic regression. A significant advantage of using logistic regression is it permits consideration of individual crossing data rather than reducing all the data at a site to only one value. For the dataset available within this study, that means that over 1,900 data points could be available (i.e., all the unique staged crossings recorded) rather than only 34 data points (i.e., the number of study sites by number of assemblies and by day or night). For the analyses that focused on comparing the below position to the above position, that means 1,507 data points rather than 26 data points were available. These larger sample sizes could result in finding significant relationships that would not be apparent with a smaller dataset. Additionally, it is possible to utilize random effects to account for site-specific differences since such differences induce a correlation structure in the dataset.

Using logistic regression to model the relationships assumes that the logit transformation of the outcome variable (i.e., yielding rate) has a linear relationship with the predictor variables, which results in challenges in interpreting the regression coefficients. The interpretation of such coefficients is not on the yield rate changes directly but a change in the odds of motorists yielding (*odds* are defined as the ratio of the number of yielding motorists to the number of non-yielding motorists). The regression coefficients can be transformed and interpreted as odds ratios of different levels of the corresponding independent variable. In other words, a unit change of the independent variable corresponds to a change in the odds of motorists yielding, which is an alternative way to express a change in yielding rate. More details on these types of models can be found in the literature.(47) All the statistical analyses were performed using *R*, an open-source statistical language and environment, and two open-source packages for fitting GLMMs.(48,44,45)

COMPARISON OF BELOW TO ABOVE

Because a previous study that included RRFBs found posted speed limit, crossing distance, and city influenced driver yielding, the initial analyses were also conducted with those variables.[35] In addition, a variable to reflect the intersection configuration was included, as preliminary reviews indicated that the number of approach legs may be related to yielding results.

Preliminary modeling revealed a correlation between road type (e.g., number of lanes and median treatment) and speed limit present in the dataset; therefore, only posted speed limit was included in the final model. Models were examined that included other variables, such as total crossing distance; however, the best results were found when the variables shown in table 53 were included. The reference level for a driver yielding in the model was estimated for the following conditions: an above sign during the daytime in Arizona with a three-leg intersection.

From the preliminary review of the results in table 52, it appears that there were only minor, if any, differences between the above and below position for the RRFBs. The results from the GLMM are shown in table 53, and these results support that observation. The results indicate that there were no significant differences between the two beacon locations (p-value = 0.1611).

The day/night variable was significant (p-value = 0.0005), which indicates that there were day/night differences for this dataset regarding driver yielding. It appears that Illinois had notably lower driver yielding as compared to the base State, Arizona. An adjusted p-value for multiple comparisons is required to make a formal assessment. Texas and Colorado were not different from Arizona. The model also indicates that the driver yielding at the midblock offset configuration was statistically different from the driver yielding at the three-legged intersections. A caution with this finding is offered since there was only one site with a midblock offset configuration in the dataset.

Table 53. GLMM results comparing below to above.

Variable		Estimate	Standard Error	*t*-value	*p*-value	Significance[c]
Reference[a]		0.10770	1.04333	0.103	0.917783	
Below		-0.09931	0.07087	-1.401	0.161107	
Night		-0.41899	0.12048	-3.478	0.000506	***
Posted speed limit		0.05858	0.02718	2.155	0.031185	*
State	Colorado	-0.26452	0.56242	-0.470	0.638119[b]	
	Illinois	-2.18731	0.64555	-3.388	0.000703[b]	***
	Texas	0.02124	0.60734	0.035	0.972104[b]	
Intersection configuration	Four legs	-0.07459	0.47508	-0.157	0.875249[b]	
	Midblock	-0.49582	0.44650	-1.110	0.266803[b]	
	Offset midblock	-2.11671	0.57363	-3.690	0.000224[b]	***

Estimate = Natural logarithm of the ratio = Odds (coefficient level)/Odds (reference level). In the case of reference level, estimate is the log-odds of the average yielding rate at the reference level.

t-value = Conservative estimate of the *z*-value, which is the standard normal score for the estimate, given the hypothesis that the actual odds ratio equals 1.

p-value: Probability that the observed log-odds ratio is at least as extreme as the estimate, given the hypothesis that the actual odds ratio equals 1.

[a]Reference level driver yielding in the model is estimated for the following conditions: above, day, Arizona, and three-legged intersection.

[b]These *p*-values require an adjustment for multiple comparisons if inferences about different yielding rates among States or among configuration are intended.

[c]Significance values are as follows: blank cell = $p > 0.10$; ~ = $p < 0.10$; * = $p < 0.05$; ** = $p < 0.01$; and *** = $p < 0.001$.

CHAPTER 5. DRIVER-YIELDING RESULTS FOR THREE RRFB PATTERNS IN AN OPEN-ROAD SETTING

INTRODUCTION

This chapter describes the methodology and results from an open-road study that examined different flash patterns for use with yellow RRFBs.

Study Overview

When IA-11 was issued in July 2008 for the RRFBs, the only flash pattern that had been tested was the 2-5 flash pattern.(4) Because the 2-5 flash pattern appears be a 2-3 flash pattern according to the human eye, several devices were installed with the 2-3 flash pattern rather than the 2-5 flash pattern. Only after looking at the flash pattern using an oscilloscope were transportation professionals able to determine that the original devices had a 2-5 flash pattern, which is why FHWA changed the flash pattern from a 2-3 flash pattern to a 2-5 flash pattern in Official Interpretation 4(09)-21.(9)

An inability to accurately determine the number of pulses within the 2-5 RRFB flash pattern was later confirmed in the closed-course study (see chapter 3). The same study found that certain flash patterns (i.e., those that could be characterized as having limited or no dark periods within the flash pattern) negatively influenced the amount of time participants needed to identify a pedestrian's direction of travel. Prior to developing the proposed provisions for incorporating the RRFB a rapid-flashing beacon traffic control device into the MUTCD, it is important to determine which flash patterns are acceptable from the perspectives of effectiveness and simplicity.(1) This study sought to determine if less complicated flash patterns and flash pattern with different proportions of dark and light periods could be as or more effective than the 2-5 flash pattern.

Study Objective

The objective of this study was to determine if the use of simpler flash patterns or flash patterns with a greater proportion of dark periods resulted in different driver yielding rates at uncontrolled crosswalks in an open-road setting. This study's measure of effectiveness (MOE) was the number of drivers who did and did not yield at crosswalks during staged pedestrian crossings.

STUDY DEVELOPMENT

Study Sites

The cities of College Station, TX, and Garland, TX, along with TAMU agreed to participate in the study by providing locations where the research team could install temporary equipment. Table 54 lists the sites included in the study. A goal was to try to match the distribution of site characteristics used in the original FHWA study on RRFBs.(16) For example, the research team preferred locations on multilane roads so that yielding behavior associated with the multiple threats issue could be observed. Because of limited ability to mount temporary beacons on overhead mast arms, the research team did not consider locations where the RRFB had been installed on mast arms over the roadway.

Table 54. List of sites for rapid flash pattern study.

Site ID	Posted Speed Limit (mi/h)	Number of Lanes	Median	Crossing Distance (ft)
CS-02	40	4	Flush	56
CS-03	30	2	Flush	37
GA-02	40	4	Flush	58
GA-06	40	4	Raised	80
GA-07	45	4	Raised	82
GA-10	40	4	Raised	62
GA-11	40	4	Raised	62
GA-13	40	4	Raised	55

Temporary Light Bar

To conduct an in-field evaluation of multiple flash patterns, the research team needed to be able to set the flash pattern and brightness of the beacons at the study sites in a quick, reliable, and consistent manner. Because of the difficulties with working with different equipment in different cities and unknown characteristics for the beacons at these locations (such as brightness), the research team designed temporary controllers to be used with temporary light bars. In the field, the temporary light bars were mounted in front of existing RRFB light bars.

The temporary light bar setup was designed such that it was not obvious that the beacons being observed during the staged pedestrian crossings were any different from the permanent RRFB equipment. Figure 50 shows an example of TTI personnel installing the temporary light bar at a site, and figure 51 shows an example of the installed light bar being used by a staged pedestrian. The staged pedestrian had a remote control to activate the light bars and activated the device if a non-staged pedestrian approached the crossing while the temporary light bars were installed.

Figure 50. Photo. Installation of the light bar in field.

Figure 51. Photo. CS-02 study site with installed temporary light bars and staged pedestrian crossing.

Flash Patterns

The study budget and parameters made it possible to test four different conditions at each study site. One of the four conditions was reserved for collecting driver yielding data with the existing equipment. Data were collected with the existing equipment in order to control for differences between the existing equipment and the temporary equipment. The other three conditions used the temporary equipment. Of the three remaining conditions, one condition was reserved for the 2-5 flash pattern.

To determine flash patterns for the other two conditions, a flash pattern workshop was held at TTI. The workshop included a selection of licensed transportation engineering professionals, representatives of FHWA, and TTI research staff. The patterns were initially reviewed using a mockup of a rectangular beacon light bar and a controller in a conference room. Several pre-developed patterns were shown to the participants. Based on participant comments, new patterns were developed. For example, some flash patterns were changed to have more dark periods or to have periods where both beacons were on. A reason for wanting increased dark periods for some of the flash patterns for this study was a preliminary finding from a closed-course research study (see chapter 3) that indicated drivers could determine the direction a pedestrian was walking in a crosswalk more quickly when the flashing traffic control devices had larger dark periods.

After identifying a short list of potential patterns during the meeting in the conference room, the meeting moved to a TTI closed-course location to look at the potential patterns in the field during the nighttime setting. The participants parked the vehicle 200 ft from a crosswalk on a two-lane approach with RRFB assemblies located on both sides of the roadway. The patterns developed during the conference room meeting were demonstrated to the meeting participants in the field. Based on the meeting participants' comments, two potential patterns were selected. These two patterns were demonstrated to FHWA representatives, and final approval was given to use these two flash patterns as the two remaining conditions for the open-road study.

Figure 52 illustrates the three patterns selected for testing in the field using the temporary light bars. The patterns considered in this study included the following:

- Temporary light bar and pattern using a combination of long and short flashes (i.e., blocks).
- Temporary light bar and a pattern using a combination of wig-wag and simultaneous flashes.
- Temporary light bar and the 2-5 flash pattern.
- Existing equipment and the 2-5 flash pattern or 2-3 pattern (whichever was present at the site). Because of when the cities installed the existing RRFBs, some of the sites may have had the 2-3 flash pattern rather than the 2-5 flash pattern with the existing equipment.

Pattern	Blocks		WW+S		2-5	
Cumulative Time in Milliseconds (ms)	Left [a] (ms)	Right [b] (ms)	Left [a] (ms)	Right [b] (ms)	Left [a] (ms)	Right [b] (ms)
25	25		25		25	
50	25		25		25	
75	25				25	
100	25	25			25	
125	25	25		25	25	
150	25	25		25		
175	25					
200	25					
225	25		25		25	
250			25		25	
275					25	
300					25	
325		25		25	25	
350		25		25		
375		25				
400	25	25				
425	25	25	25	25		25
450	25	25	25	25		
475		25				25
500		25				
525		25	25	25		25
550			25	25		
575						25
600						
625						25
650						25
675						25
700						25
725						25
750						25
775						25
800						25
On time (ms)	300	300	200	200	250	300
Percent of cycle for a given beacon with the beacon on	38%	38%	25%	25%	31%	38%
On ratio = percent of cycle where at least one of the beacons is on	56%		37%		69%	
Off ratio = percent of cycle where both beacons are dark	44%		63%		31%	

Yellow cell = beacon is on for 25 ms

Gray cell = beacon is off

[a] **Left—time left beacon is on (ms),** [b] **Right—time right beacon is on (ms)**

Figure 52. Illustration. Flash patterns studied.[49]

Brightness of LEDs

Preliminary findings from the closed-course study (see chapter 3) indicate that brightness of the beacons can influence how quickly a participant can detect a pedestrian within a crosswalk. Therefore, the same brightness level was used for the three flash patterns tested with the temporary light bars. Table 55 shows the target and measured intensity for the beacons when measured at horizontal and vertical angles of 0 degrees. The table also shows the measured optical power along with the on and off ratios (i.e., percent of the cycle where at least one of the beacons was on or where both beacons were dark, respectively).

Table 55. Brightness measurements.

Flash Pattern with Temporary Equipment	Target Intensity (Candela)	Measured Target Intensity (Candela)	Optical Power (Candela-s/min)	On Ratio (Percent)	Off Ratio (Percent)
2-5	1,400	1,414	58,300	69	31
Blocks	1,400	1,415	63,700	56	44
Wig-wag and simultaneous (WW+S)	1,400	1,418	42,500	37	63

Sample Size

Based on a statistical analysis of past driver yielding data at RRFB locations in Texas, the research team estimated it would take between 7 and 13 sites to obtain a sufficient sample of data to permit detection of at least a 5 percent difference in driver yielding.[(36)] With available resources for the study, a total of eight sites were selected for testing. Based on previous experience, the minimum number of staged pedestrian crossings for each condition was set at 40.

Flash Pattern Order

The order that treatments were presented could have had an effect on results; therefore, flash pattern order for the sites was randomized. Table 56 lists the order that the flash patterns were installed at each site.

Table 56. Flash pattern order by test site location.

Site ID	Initial Flash Pattern	Second Flash Pattern	Third Flash Pattern	Fourth Flash Pattern
GA-02	Temporary; 2-5	Existing; 2-5 or 2-3	Temporary; blocks	Temporary; WW+S
CS-02	Existing; 2-5 or 2-3	Temporary; blocks	Temporary; WW+S	Temporary; 2-5
CS-03	Temporary; blocks	Temporary; WW+S	Temporary; 2-5	Existing; 2-5 or 2-3
GA-06	Temporary; WW+S	Temporary; 2-5	Existing; 2-5 or 2-3	Temporary; blocks
GA-07	Temporary; 2-5 flash	Existing; 2-5 or 2-3	Temporary; blocks	Temporary; WW+S
GA-10	Existing; 2-5 or 2-3	Temporary; blocks	Temporary; WW+S	Temporary; 2-5
GA-11	Temporary; blocks	Temporary; WW+S	Temporary; 2-5	Existing; 2-5 or 2-3
GA-13	Temporary; WW+S	Temporary; 2-5	Existing; 2-5 or 2-3	Temporary; blocks

Note: Flash patterns are defined as follows: 2-5 = 2-5 flash pattern and 2-3 = 2-3 flash pattern.

DATA COLLECTION AND REDUCTION

Study Periods

The data were collected during daytime conditions in February and March 2014. The research team avoided Monday mornings and Friday afternoons along with weekends because travel patterns for those time periods can be different from travel patterns associated with a typical weekday.

Staged Pedestrian Protocol

The research team used a staged pedestrian protocol to collect driver yielding data to ensure that oncoming drivers received a consistent presentation of approaching pedestrians. Under this protocol, a member of the research team acted as a pedestrian using the crosswalk to stage the conditions under which driver yielding would be observed. Each staged pedestrian wore similar clothing (gray t-shirt, blue jeans, and gray tennis shoes) and followed specific instructions in crossing the roadway. The staged pedestrian was accompanied by a second researcher, who observed and recorded the yielding data on pre-printed datasheets. Additional information on the staged pedestrian protocol followed is available in chapter 4 of this report or in “Driver Yielding to Traffic Control Signals, Pedestrian Hybrid Beacons, and Rectangular Rapid-Flashing Beacons in Texas.”[36]

DATA REDUCTION

After completing the data collection, researchers entered the crossing data and the site characteristics data from the field worksheets into an electronic database. The average yielding rate for a site was calculated; however, data for individual crossings were used in the statistical evaluation. Table 57 lists the driver yielding rates for each site, type of light bar, and flash pattern. As shown in the final row of the table, the three flash patterns used with the temporary light bar had similar average driver yielding rates—between 78 and 80 percent. When comparing the results for the individual sites, some sites did have larger differences between the different flash patterns.

Table 57. Driver yielding rate by site and pattern.

Site	Temporary Light Bars with WW+S (Percent)	Temporary Light Bars with Blocks (Percent)	Temporary Light Bars with 2-5 Flash Pattern (Percent)	Existing Light Bars with 2-5 or 2-3 Flash Patterns (Percent)
CS-02	63	50	61	44
CS-03	84	94	87	76
GA-02	76	75	67	98
GA-06	96	81	85	96
GA-07	78	92	84	92
GA-10	90	94	89	94
GA-11	87	90	82	92
GA-13	80	84	84	95
Total	**80**	**80**	**78**	**81**

RESULTS

When a driver approaches a crossing, the driver either yields and stops the vehicle or does not yield to the waiting staged pedestrian. This binary behavior (yield or no yield) can be modeled using logistic regression. A significant advantage of using logistic regression is it permits consideration of individual crossing data rather than reducing all the data at a site to only one value. For the dataset available within this study, that means over 1,100 data points could be available (i.e., all the unique staged crossings recorded) rather than only 32 data points (i.e., the number of study sites by number of flash patterns). The larger sample size provides more detailed data and could result in finding significant relationships that would not be apparent with a smaller dataset.

Using logistic regression to model the relationships assumes that the logit transformation of the outcome variable (i.e., yielding rate) has a linear relationship with the predictor variables, which results in challenges in interpreting the regression coefficients. Odds ratios can be used to illustrate how to interpret the logistic regression results. The interpretation of such coefficients is not on the yield rate changes directly but a change in the odds of motorists yielding (*odds* are defined as the ratio of the number of yielding motorists to the number of non-yielding motorists). The regression coefficients can be transformed and interpreted as odds ratios of different levels of the corresponding independent variable. In other words, the odds ratio is the expected change in the odds of motorists yielding per unit change of the independent variable. More details on these types of models can be found in the literature.[47] All the statistical analyses were performed using *R*, an open-source statistical language, and environment and two open-source packages for fitting GLMMs.[48,45]

Patterns Used with Temporary Light Bars

From the preliminary review of the results in table 57, it appears that there were only minor, if any, differences between the tested flash patterns. The results from the GLMM are shown in table 58. Statistical significance of coefficients was obtained from comparing the coefficient (i.e., parameter estimate) to a value of zero. If an estimate is found to be statistically different from zero, then the variable has a statistically significant effect on the odds of driver yielding.

Additionally, if the coefficient is different from zero, then the odds ratio is different from 1. Conversely, coefficients without statistical significance indicate an odds ratio indistinguishable from one, thus indicating that the variable has no bearing on driver yielding rate. In this study, the reference level for a driver yielding in the model was estimated as follows: temporary light bar with a 2-5 flash pattern in College Station, TX.

Table 58. Linear mixed-effects model results for flash patterns used with temporary light bars.

Variable	Estimate	Standard Error	DF	*t*-value	*p*-value
Reference[a]	1.3864637	0.9582977	941	1.4467986	0.1483
Temporary; blocks	0.1662325	0.1503383	941	1.1057233	0.2691
Temporary; WW+S	0.1164097	0.1452238	941	0.8015884	0.4230
Garland, TX	0.8213472	0.5663119	5	1.4503443	0.2067
Crossing distance (ft)	-0.0090980	0.0184713	5	-0.4925464	0.6432

Estimate = Natural logarithm of the ratio = odds (coefficient level)/odds (reference level). In the case of reference level, estimate is the log-odds of the average yielding rate at the reference level.
t-value = Conservative estimate of the *z*-value, which is the standard normal score for the estimate, given the hypothesis that the actual odds ratio equals 1.
p-value = Probability that the observed log-odds ratio is at least as extreme as the estimate, given the hypothesis that the actual odds ratio equals 1.
[a]Reference level driver yielding in the model is estimated for the following conditions: 2-5 flash pattern used with temporary light bars in College Station, TX.

Because a previous study on RRFBs found that posted speed limit, crossing distance, and city influenced driver yielding, the analysis considered those variables initially. However, for this set of sites, posted speed limit and crossing distance were correlated; therefore, posted speed limit was removed. Site selection was heavily influenced by whether four lanes were present and whether the beacons were located on the roadside rather than overhead. In other words, site selection was not a function of the posted speed limit and crossing distance, and a high number of sites had one posted speed limit (40 mi/h for six of the eight sites), which did not provide a sufficient range for parameter estimation on that variable. The city (Garland, TX, or College Station, TX) was included as a fixed effect, with the results shown in table 59. Both city and crossing distance were found to be not significant for this dataset.

The *p*-values from table 58 were adjusted to allow multiple comparisons, as shown in table 59. The table indicates that there were no significant differences between the 2-5 flash pattern and the WW+S flash pattern (*p*-value = 0.707), between the 2-5 flash pattern and the blocks flash pattern (*p*-value = 0.517), between the blocks flash pattern and WW+S flash pattern (*p*-value = 0.941), or between blocks, WW+S, or the 2-5 flash pattern (*p*-value = 0.516).

Table 59. Simultaneous comparisons on flash pattern differences.

Hypothesis	Estimate	Standard Error	*z*-value	*Pr*(>|z|)[a]
Temporary; blocks – Temporary 2-5 flash pattern = 0	0.16623	0.14994	1.109	0.517
Temporary; WW+S – Temporary; 2-5 flash pattern = 0	0.11641	0.14484	0.804	0.707
Temporary; blocks – Temporary; WW+S = 0	0.04982	0.14872	0.335	0.941
(Temporary; blocks and Temporary; WW+S) – (Temporary; 2-5 flash pattern) = 0	0.14132	0.12728	1.11	0.516

[a]Adjusted *p*-values were reported using a single-step method.

2-5 Flash Pattern

The previous evaluation kept the temporary light bar constant, while this evaluation kept the 2-5 flash pattern constant. Comparing the results between the 2-5 flash pattern used with the temporary light bars and the results when the 2-5 flash pattern was used with the existing equipment indicates that a difference may exist. As shown in table 57, the average yielding for the 2-5 flash pattern with temporary light bars was 78 percent, while the average yielding for the existing equipment was slightly higher at 81 percent. Overall, the driver yielding rates were higher for the existing light bars for the Garland, TX, sites, and the driver yielding rates were lower for the existing light bars for the College Station, TX, sites.

Table 60 shows the results for the LMM, which found that the equipment (*p*-value = 0.0010) and the city (*p*-value = 0.0205) were both significant. Because these statistical significant differences existed, they indicate that characteristics of the city, the roadway, and the beacons other than flash pattern had an effect on driver yielding. Even with accounting for crossing distance and city, a statistical significant difference was found between the existing and temporary light bars. Therefore, other characteristics that were not measured (i.e., brightness) are possibly influencing a driver's decision to yield or not yield. The reference level driver yielding in the model was estimated as having existing light bars in College Station, TX.

Table 60. LMM results comparing the 2-5 flash pattern with temporary and existing equipment.

Variable	Estimate	Standard Error	DF	*t*-value	*p*-value
Reference[a]	1.4748929	0.8625094	644	1.71002	0.0877
Temporary beacons	-0.5002792	0.1516542	644	-3.298814	0.0010
Garland, TX	1.6766262	0.5014311	5	3.343682	0.0205
Crossing distance (ft)	-0.0131371	0.0166508	5	-0.788978	0.4659

Estimate = Natural logarithm of the ratio = odds (coefficient level)/odds (reference level). In the case of reference level, estimate is the log-odds of the average yielding rate at the reference level.
t-value = Conservative estimate of the *z*-value, which is the standard normal score for the estimate, given the hypothesis that the actual odds ratio equals 1.
p-value = Probability that the observed log-odds ratio is at least as extreme as the estimate, given the hypothesis that the actual odds ratio equals 1.
[a]Reference level driver yielding in the model is estimated for the following conditions: existing light bars in College Station, TX.

CHAPTER 6. PHB STUDY

INTRODUCTION

This chapter describes the methodology and results from a study that examined driver and pedestrian behavior at PHBs. The PHB, or HAWK as it is known in Tucson, AZ, is a traffic control device used at pedestrian crossings. The crossing typically has the crosswalk across only one of the major road approaches. The PHB's vehicular display faces are typically located on mast arms over the major approaches to an intersection and in some locations on the roadside. An example is shown in figure 53 for an installation in Tucson, AZ, and in figure 54 for an installation in Austin, TX. The face of the PHB consists of two red indications above a single yellow indication. It rests in a dark mode, but when activated by a pedestrian, it first displays a few seconds of flashing yellow followed by a steady yellow change interval and then displays a steady red indication to drivers, which creates a gap for pedestrians to cross the major roadway. During the flashing pedestrian clearance interval, the PHB displays an alternating flashing red indication to allow drivers to proceed after stopping if the pedestrians have cleared their half of the roadway, thereby reducing vehicle delays.

Figure 53. Photo. Example of PHB installation in Tucson, AZ.

Figure 54. Photo. Example of PHBs being used in Austin, TX.

The PHB has shown great potential for improving pedestrian safety; however, questions remain regarding under what roadway conditions—such as crossing distance (i.e., number of lanes) and posted speed limit—should it be considered for use.[26,27] In addition, there are questions about the device's operations. For example, a current topic of discussion within the profession is the way drivers treat a PHB when it is dark. PHBs dwell in a dark mode for drivers until activated by a pedestrian. A concern among some is that drivers will see a dark PHB and treat it as a Stop sign, similar to the required behavior for a dark traffic signal that has experienced a power outage.

The STC of the NCUTCD assists in developing language for chapter 4 of the MUTCD.[1] It is interested in research and/or assistance in refining material on the PHB. The PHB was first included in the 2009 MUTCD, which discusses the design and operations of the device along with guidance for installation categorized by low speed (roadways where speeds are 35 mi/h or less) and high speed (roadways where speeds are more than 35 mi/h).[1] The 2009 MUTCD also indicates that the PHB "…should be installed at least 100 ft from side streets or driveways that are controlled by Stop or Yield signs"[1](pg. 449) In 2011, the STC recommended to remove that statement because it was a significant change from what was reviewed and approved by the National Committee in 2007 and what was proposed in the Notice of Proposed Amendment (NPA) for the 2009 MUTCD.[50] The statement was added to the PHB 2009 MUTCD discussion just prior to publication. The STC provided the following concerns with the 100-ft distance (with additional details added by this study's research team based on reviewer comments):

- The result of the added 100-ft guidance, if followed, is that these beacons could not be used at unsignalized intersections or driveways. The NPA language did not include any limitations (either standard or guidance) on the locations for use of the PHB; therefore, the 100-ft change was not subject to public review and comment.

- The 100-ft offset listed in the guidance is not supported by research or experimentation with this device. Most sites used for experimentation when the PHB was being tested were intersection or driveway locations which were the natural crossing locations.

Therefore, the typical use of the device as tested, which ultimately proved to be successful, is recommended against in the 2009 MUTCD.

- All of the sites included in the FHWA study that evaluated the safety effectiveness of these devices were at stop-controlled intersections or major driveways.(27) The study was performed just prior to the publication of the 2009 MUTCD.

- The 100-ft guidance, if followed, causes increased mobility difficulties and discomfort for pedestrians with disabilities and forces all pedestrians to experience increased inconvenience if they must divert away from their desired crossing location at an intersection or driveway to a different crossing point located 100 ft or more away which would likely lead to 200 ft or more out-of-way travel. If the PHB is not placed at the natural crossing locations, it is likely it will not be used by most pedestrians, and their value as a safety device could be compromised.

Because of the questions being asked regarding driver and pedestrian behaviors with PHBs, FHWA sponsored a study to record behaviors at existing sites.

Study Objective

The objective of this study was to determine actual driver and pedestrian behaviors at locations with a PHB.

STUDY SITES

Through existing contacts and research team knowledge along with responses to requests, the research team compiled a preliminary list of PHB locations. Data for key variables (posted speed limit, number of through lanes, and the type of median treatment) were gathered and added to the list for the PHBs in communities with multiple installations. Pedestrian crossings on higher speed roadways and with wider crossings have historically experienced lower driver yielding, so posted speed limit and crossing distance (as reflected by number of lanes) were selected as key variables. The goal was to have at least eight sites with higher posted speed limits (defined for this study as being 40 mi/h or higher) and four sites with lower posted speed limits (defined for this study as being 35 mi/h or lower). The presence of a median can provide refuge for a crossing, which may affect the measures of effectiveness considered for this study, so it was also included in the original study matrix. Because of efficiencies in data collection, data were collected for a total of 20 sites. Roadway and traffic characteristics for the sites are listed in table 61.

Table 61. Site characteristics.

Site Name[a]	Roadway Configuration	Number of Approach Legs	Posted Speed Limit (mi/h)	ADT	Pedsetrians/ Hour[b]	Number of Through Lanes	Park Lane/ Bike Lane Width (ft)	Median Type	Median Width (ft)	Total Crossing Distance (ft)
TU-003	Intersection	4	35	7,400	4.8	4	NA/6	TWLTL	13	69
TU-004	Intersection	3	40	7,600	9.3	4	NA/6	TWLTL	13	82
TU-007	Intersection	3	40	8,700	8.9	4	NA/6	TWLTL	13	69
TU-021	Intersection	4	40	31,000	8.2	4	NA/5	TWLTL	12	83
TU-037	Intersection	4	35	27,500	11.1	4	NA/5	TWLTL	11	75
TU-042	Intersection	4	30	5,100	14.2	4	NA/NA	Raised	8	88
TU-059	Intersection	4	40	28,400	3.1	4	NA/4	Raised	8	89
TU-070	Intersection	3	40	29,900	3.6	4	NA/4	Raised	7	80
TU-072[c]	Intersection	4	40	41,300	7.6	6	NA/6	Raised	10	119
TU-073	Intersection	4	40	13,800	13.3	6	NA/6	Raised	8	93
TU-090	Intersection	4	40	10,100	1.1	4	NA/7	Raised	8	92
TU-091	Intersection	3	35	5,200	2.5	4	13/5	Raised	11	112
AU-04	Intersection	4	35	26,600	11.5	4	NA/NA	Raised	10	50
AU-07[c]	Midblock (50)[d]	2	35	24,600	23.3	4	NA/NA	Raised	8	57
AU-11	Intersection	3	40	26,900	6.4	4	8/NA	TWLTL	12	90
AU-16	Intersection	4	35	28,500	18.5	4	NA/NA	TWLTL	12	60
AU-21	Midblock (60)[d]	2	35	27,100	20.0	4	NA/NA	None	NA	40
AU-22	Midblock (70)[d]	2	45	19,600	38.3	4	NA/6	TWLTL	12	68
AU-24	Intersection	4	35	14,100	20.7	4	NA/NA	Raised	6	68
AU-27	Midblock (80)[d]	2	35	21,200	10.7	4	NA/6	Raised	6	80

NA = Not applicable.
[a]Site name is denoted as AA-XXX, where AA represents the two-letter city code and XXX represents the number assigned to the site.
[b]Number of pedestrians per hour did not include any research team member crossings. They were observed during data collection (typically over a 4-h daytime period).
[c]PHB is located within coordinated corridor where the timing of when the PHB is active is influenced by the nearby coordinated corridor.
[d]For midblock roadway configuration, the number in parentheses shows the distance (ft) measured from center of crossing to center of nearest driveway/intersection to the nearest intersection or major driveway.

The cities of Tucson, AZ and, Austin, TX, had the greatest variety in site characteristics of interest to this project and were selected for the study. Differences in practices between the two cities include the following:

- The Tucson, AZ, PHB faces had back plates with yellow reflective borders (see figure 53), while the Austin, TX, PHB faces did not have back plates (see figure 54).
- The signs used at most of the Tucson, AZ, sites included the CROSSWALK STOP ON RED (symbolic circular red) (R10-23) sign (see figure 55) and an internally illuminated PEDESTRIAN CROSSING or CROSSWALK sign (see figure 56). The sign used at the crossing for the Austin, TX, sites is shown in figure 57. This sign was selected to help educate drivers regarding appropriate behavior during the flashing red. Recently, FHWA has received numerous inquiries regarding how to address comprehension issues with the flashing red phase and is now recommending that if an alternative legend to the R10-23 sign is used, that it be the sign shown in figure 58.
- In advance of the crossing, Tucson, AZ, frequently installed a pedestrian crossing warning sign (W11-2) (see figure 59). School crossing signs were used at school sites.
- Austin, TX, included the STOP HERE ON RED (R10-6, R10-6a) sign at the stop line.
- The red clearance time (i.e., the elapsed time between start of the vehicular steady red indication and start of the pedestrian walk indication) was 1 s at the Tucson, AZ, sites and 2 s at the Austin, TX, sites.
- The steady red interval was 8 s for Tucson, AZ, sites and ranged between 9 and 12 s for the Austin, TX, sites.
- When the Tucson, AZ, sites had a median, a PHB face and a CROSSWALK STOP ON RED (symbolic circular red) (R10-23) sign was frequently included on a post in the median.

Figure 55. Photo. Example of sign used in Tucson, AZ.

Figure 56. Photo. Example of internally illuminated sign used in Tucson, AZ.

Figure 57. Photo. Sign used in Austin, TX.

The currently preferred format for the type of sign shown in figure 57 is shown in figure 58.

Figure 58. Photo. Sign recommended by FHWA to address comprehension issues with the flashing red phase.

Figure 59. Photo. Example of advance warning sign used in Tucson, AZ.

The crosswalk markings were always located on only one side of the intersection. The PHBs had between 3 and 4 s of flashing yellow and between 3 and 4 s of steady yellow, consistent with city policies regarding clearance intervals at signalized intersections. For both cities, the flashing red duration varied based on the site's crossing width and ranged from 15 to 29 s.

DATA COLLECTION AND REDUCTION

Data using a multiple video camera setup were collected in November 2014 for the Austin, TX, sites and in February 2015 for the Tucson, AZ, sites. All observations were collected during daytime dry weather conditions between 6:30 a.m. and 6:30 p.m. The observers and the video recording device were placed to be inconspicuous from the pedestrians, bicyclists, and motorists. The goal was to record a minimum of 50 pedestrian crossing events or 4 h of data (the smaller of the two) at each location, where each crossing event consisted of one or more pedestrian(s) crossing the entire width of the street. If it appeared that fewer than 50 pedestrian crossing events would occur within the 4-h block, research team members would cross the street to increase the sample size of pedestrian crossings. Additional information on the staged pedestrian protocol is available in *Characteristics of Texas Pedestrian Crashes and Evaluation of Driver Yielding at Pedestrian Treatments*.(35) The research team members sought to complete data collection efforts at two sites per day, accounting for travel time between sites and the need to notify local stakeholders (e.g., school personnel) of their activity. Hence, the periods of peak vehicle and pedestrian volumes were not necessarily observed.

The video footage was reviewed in several rounds to extract the required observations for analysis. After the first two rounds, a list of vehicle arrivals, pedestrian arrivals, pedestrian departures, and PHB actuations was assembled and sorted by site and time. The beacons and pedestrian signal indications were determined for each event in this list through a series of computations using the timestamps and the known timing parameters for each PHB.

In the next rounds of video footage review, the computed beacon indications were verified, and additional detailed observations were extracted including the following:

- Vehicle position relative to the pedestrian for vehicles arriving on a steady or flashing red beacon indication.
- Driver yielding behavior during steady or flashing red beacon indication.
- Button presses by arriving pedestrians.
- Categorization of pedestrians as staged or non-staged.
- Conflict occurrences.
- Recording whether each driver arriving on steady or flashing red stopped before proceeding through the crosswalk.
- Recording whether drivers stayed stopped throughout the flashing red indication.

Additional efforts were also undertaken to record any instances of major street vehicles stopping while the beacon indication was dark as well as to identify minor road driver behaviors during a beacon actuation. The final dataset reflected over 78 h of video data and included 1,149 PHB actuations and 1,979 pedestrians who crossed the street.

DRIVER BEHAVIOR FINDINGS

Driver Behavior During Dark Indication

Selected videos were reviewed to identify each occurrence when a vehicle stopped at the crossing when the PHB was displaying a dark indication. There were several events; however, in almost all cases, it was because of congestion. There were a few cases where the driver stopped because of a bus or truck loading/unloading or because a pedestrian was in the crosswalk. Therefore, none of the drivers who stopped at the crossing when the PHB was dark appeared to be confused regarding the device.

Driver Position Relative to Pedestrian Position During Steady or Flashing Red Indications When the Driver Drove Across the Crosswalk

The position of the driver and the pedestrian for each driver that drove across the crosswalk during a steady or flashing red indication was identified. Figure 60 provides an illustration of driver and pedestrian positions for a crossing. For each cycle and for each approach, the number of cycles by approach where a given pedestrian-vehicle position combination occurred was counted. Table 62 summarizes the findings for the 1,252 cycle approaches (1,149 cycles plus 103 cycles where pedestrians were crossing in both directions) for the 20 sites included in the study. The pedestrian positions were (1) edge of the street clearly indicating the desire to cross, (2) within the crosswalk on the initial approach (or first half of the crossing), or (3) within the crosswalk on the second approach (or second half of the crossing). The vehicle was either on the same approach as the pedestrian or the other approach relative to the pedestrian.

As an example, if a pedestrian was crossing a street that was oriented north and south and was on the initial approach (say the southbound approach), and if the vehicle was on the other approach, then the vehicle would be on the northbound approach. In this example, the northbound vehicle can legally enter the crosswalk during the flashing red portion of the cycle while the pedestrian is walking eastbound and crossing the southbound approach. Both Arizona and Texas State laws indicate that vehicles must yield the right-of-way to pedestrians within a crosswalk that are in the same half of the roadway as the vehicle. So drivers in cases A to F in table 62 would be considered as not yielding to the pedestrian. Both States also indicate that vehicles are to yield right-of-way if a pedestrian is approaching closely enough from the opposite side of the roadway to constitute a danger. Cases G and H in table 62 could possibly fit this situation; however, in the opinion of those reducing the data, these observations did not have the pedestrian that close to the vehicle approaching from the other approach. For all those observations, the vehicle on the other approach entered the crosswalk shortly after the steady red indication had started and the pedestrian had recently left the curb. A driver entering the intersection during the steady red indication would be in violation of the beacon indication. Cases A, C, E, G, and I reflect combinations when the driver would be in violation of the beacon.

For those cases when the driver should yield, the combination with the most yielding violations was when the pedestrian was at the edge of the street and the drivers entered the crosswalk on the steady red indication. Case A occurred for 7.7 percent of the observed cycle approaches (96 of 1,252). Most of these non-yielding (and violation) events occurred soon after the beacon changed to steady red. While it could be argued that a vehicle was not required to yield to the pedestrian in this situation since the pedestrian was not on the pavement, in the research team's opinion the pedestrians in these situation were clearly communicating the intent to cross and were not on the pavement due to safety concerns. Of course, these drivers were clearly in violation of the steady red indication. While the research team included cases A and B in the non-yielding counts, the counts are shown in table 62 so readers can draw their own conclusions. Few, but not zero as preferred, cycles had a driver entering the crosswalk when the pedestrian was on the same approach (see cases B to F). Reviewing the situations when a vehicle enters the crosswalk when the pedestrian is in the second half of their crossing (see cases E and F) revealed several occurrences when the vehicles entered the crosswalk soon after the pedestrian departed the lane.

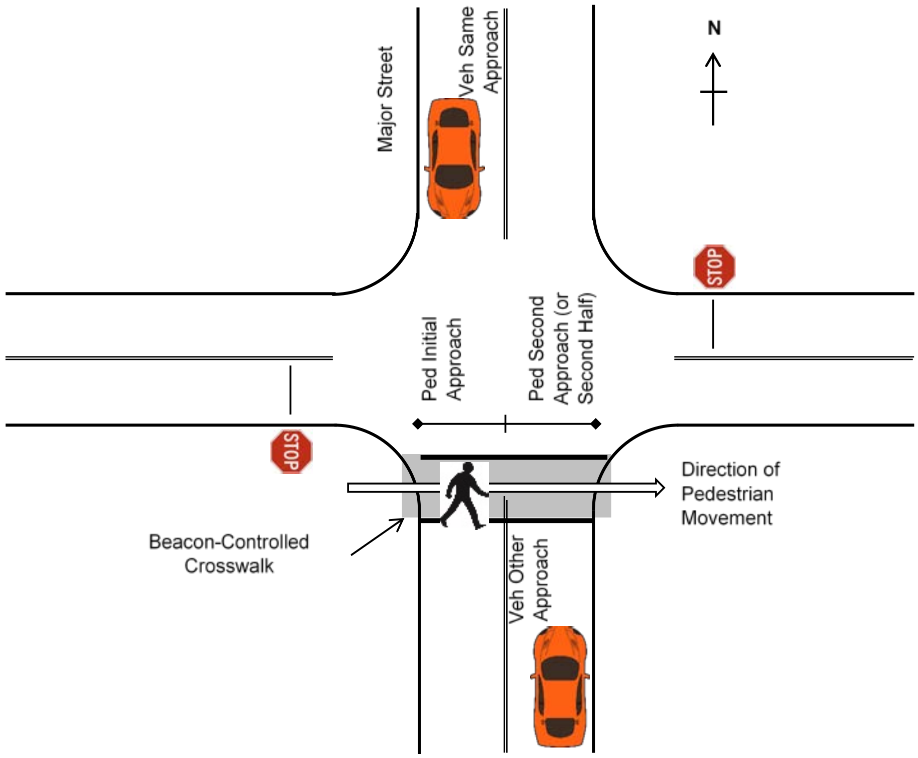


Figure 60. Illustration. Pedestrian and driver positions when the pedestrian is on the initial approach and vehicles are present on the same approach and on the other approach.

Table 62. Pedestrian position and vehicle approach during steady or flashing red indications.

Case	Pedestrian Position	Vehicle Approach[a]	Beacon Indication	Percent of Cycles Approaches[b]	Non-Yielding and/or Violation
A	Initial approach, edge of street	Same	Steady red	7.7	Non-yielding[d]; violation
B	Initial approach, edge of street	Same	Flashing red	0.0	Non-yielding
C	Initial approach, moving within crosswalk	Same	Steady red	0.4	Non-yielding; violation
D	Initial approach, moving within crosswalk	Same	Flashing red	0.2	Non-yielding
E	Second approach, moving within crosswalk	Same	Steady red	0.2	Non-yielding; violation
F	Second approach, moving within crosswalk	Same	Flashing red	1.7	Non-yielding
G	Initial approach, moving within crosswalk	Other	Steady red	8.8	Violation
H	Initial approach, moving within crosswalk	Other	Flashing red	0.2	Neither
I	Second approach, moving within crosswalk	Other	Steady red	1.0	Violation
J	Second approach, moving within crosswalk	Other	Flashing red	23.6	Neither

[a]Pedestrian and vehicle positions are relative to where the pedestrian started the crossing (see figure 60 for an example).
[b]Results reflect the percent of the 1,252 cycle approaches when the combination of pedestrian and vehicle position occurred. The total number of cycle approaches (1,252) reflect 1,149 cycles plus 103 cycles when pedestrians were crossing in both directions for the 20 sites included in the study.
[c]Demonstrates whether this case reflects a non-yielding driver and/or a violation of the red indication.
[d]While it could be argued that a vehicle is not required to yield to the pedestrian in this situation since the pedestrian was not "on the pavement," the pedestrians in these situation were clearly communicating the intent to cross and remained on the curb rather than on the pavement due to safety concerns. These drivers were in violation of the steady red indication.

Driver Yielding Behavior During Steady or Flashing Red Indications

For each pedestrian crossing when the PHB was showing steady or flashing red, the number of drivers that yielded and did not yield was determined. The driver yielding rates reflected all available pedestrian crossings regardless of whether the pedestrian was a member of the research team. A driver was considered to have not yielded to the pedestrian if the driver crossed the crosswalk markings when the PHB was in either the steady red or flashing red indications and the pedestrian was at the edge of the street clearly communicating to drivers the intent to cross or was walking on the same approach as the driver. When the crossing pedestrian was a member of the research team, the team member would place a foot on the pavement to clearly communicate the intent to cross. Using only staged pedestrian crossings would have required a much longer data collection period per site because of the large number of pedestrians crossing at the intersections. Therefore, the study included non-staged pedestrians. If it appeared that the non-staged pedestrian was not clearly communicating the intent to cross, perhaps by not standing near the edge of the sidewalk, the pedestrian crossing was not included in the study.

Counting the number of vehicles that did or did not yield to a crossing pedestrian was easier with video data when compared to gathering the data in the field. The video could be replayed to determine the exact position of a vehicle when the signal indication changed. In addition, the video allowed for greater consistency between data collectors, as an event could be reviewed by more than one person. Table 63 provides the driver yielding values for the 20 sites. Overall, driver yielding for these 20 sites averaged 96 percent. In almost all of the crossings, drivers appropriately yielded to the crossing pedestrians.

Table 63. Driver yielding values for all 20 sites.

Site	Number of PHB Actuations	Number of Drivers Yielding	Number of Drivers Not Yielding	Driver Yielding (Percent)[a]
TU-003	19	54	3	95
TU-004	49	162	4	98
TU-007	60	183	5	97
TU-021	52	131	7	95
TU-037	74	248	8	97
TU-042	71	187	6	97
TU-059	55	151	0	100
TU-070	52	159	4	98
TU-072	51	230	5	98
TU-073	70	368	19	95
TU-090	28	61	0	100
TU-091	30	67	4	94
AU-04	62	147	9	94
AU-07	95	256	11	96
AU-11	60	169	26	87
AU-16	71	195	6	97
AU-21	52	139	5	97
AU-22	70	171	4	98
AU-24	97	182	9	95
AU-27	31	99	10	91
Total	**1,149**	**3,359**	**145**	**96**

[a]Driver yielding = Percent of approaching drivers who should have yielded and did so.

When reviewing the results by city, Tucson, AZ, had an average yielding rate of 97 percent while Austin, TX, had an average yielding rate of 94 percent. Affecting the average result for Austin, TX, were two sites: AU-11 and AU-27. Almost all of the non-yielding vehicles at AU-11 were northbound vehicles that crossed the crosswalk very soon after the PHB turned steady red and frequently moved at lower speeds due to high vehicle volumes present or due to an active reduced speed limit for the school zone. At AU-27, about half of the non-yielding vehicles entered the crosswalk very soon after the PHB turned to steady red (six vehicles), with the remaining non-yielding vehicles (four vehicles) entering the crosswalk before the pedestrian completely cleared that half of the roadway. Other potential differences between Austin, TX, and Tucson, AZ, that could affect yielding rates could be the length of time the PHB treatment has been used in the city (they have been in Tucson, AZ, for many more years than Austin, TX), the use of back plates (common in Tucson, AZ, not in Austin, TX), beacon face mounting locations (Tucson, AZ, typically mounted one face over the approach, one to the right of the approach, and one in the median if a raised median was present, while Austin, TX, typically mounted two faces over the approach), and the use of supplemental signs on the mast arm (Tucson, AZ, sites typically included a CROSSWALK or PEDESTRIAN CROSSWALK sign in addition to the regulatory CROSSWALK STOP ON RED (symbolic circular red) (R10-23) sign while Austin, TX, used a combination sign that provided the additional information of STOP ON FLASHING RED (symbolic flashing circular red) THEN PROCEED IF CLEAR).

There were different driver behaviors within those situations when drivers did not yield to the pedestrians. Reviewing the conditions when drivers were non-compliant revealed that several of the non-compliant drivers entered the crossing just after the PHB changed from steady yellow to steady red and the pedestrian was at the edge of the street. Given that these drivers were provided with at least 7 to 8 s of warning by way of the flashing and steady yellow indications, and based on the posted speed limits for these sites (30 to 45 mi/h), the drivers did have sufficient warning to stop upstream of the crossing but decided not to stop. In a few of the cases, the driver proceeded through the crosswalk just after the pedestrian had cleared the lane.

Driver Behavior During Flashing Red Indication

For about 20 percent of the observed PHB actuations, vehicles were not present during the flashing red indication. When a queue of vehicles was present during the flashing red indication, about half of the crossing actuations included at least one driver who did not completely stop prior to entering the crosswalk. About 5 percent of the actuations included at least one driver who stopped on the flashing red indication and remained stopped until the dark indication. This behavior was observed at about the same frequency in both cities. In some cases, these drivers might not have realized that they could proceed after stopping if their half of the crosswalk was clear of pedestrians. However, there were many cases where the stopped drivers could not proceed for one or more of the following reasons:

- The driver arrived in the last few seconds of the flashing red indication.
- The driver’s half of the crosswalk was continually occupied by pedestrians, some of whom may have been slow or may have started their crossing after the start of the flashing red indication (i.e., during their flashing do not walk indication).
- Minor movement drivers were proceeding without complying with their requirements to stop.

Impact of PHB Actuation on Minor Movement Drivers

Interested practitioners have raised questions about how PHBs affect minor movements that do not pass through the beacon-controlled crosswalk. These movements may include one left-turn movement originating from the major street (LT), up to two through movements on the minor-street approaches (TH1 and TH2), a left-turn movement originating from the minor street (LT1), and a right-turn movement originating from the minor street (RT2). These movements are illustrated in figure 61. Specifically, the following questions have been asked:

- When the PHB is active, do minor movement drivers take advantage of the gaps that have been created in the major street traffic and complete their movements more easily?
- When the PHB is showing the flashing red indication, does the intersection function like a four-way stop-controlled intersection?

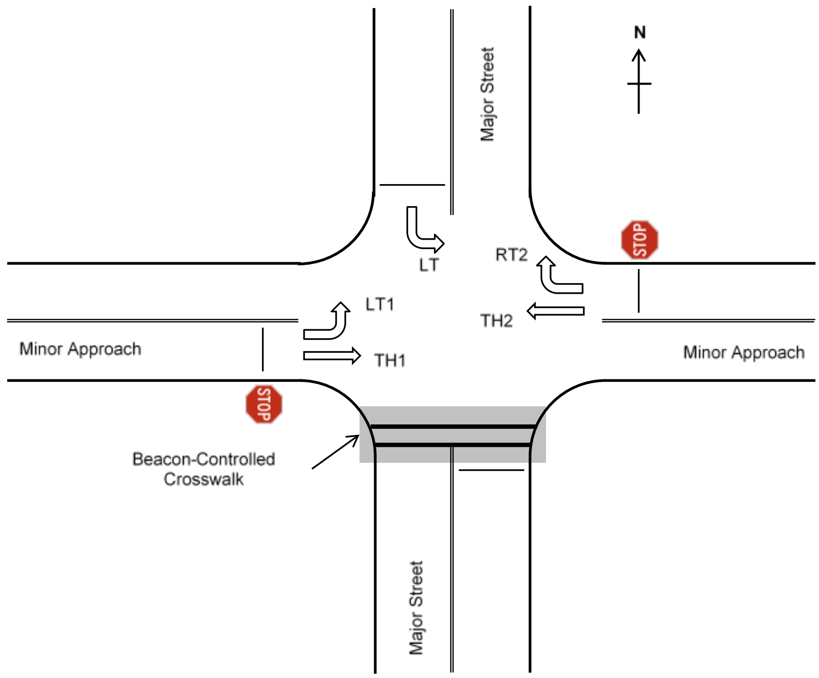


Figure 61. Illustration. Minor movements at a PHB-controlled crosswalk.

The research team conducted a review of the video footage to answer these questions. The review included 17 of the 20 PHB sites. Sites TU-091, AU-07, and AU-27 were excluded because they lacked the relevant movements due to site layout (midblock crossing, stop line located well downstream of the movement, or the movement is prohibited) or the movements existed but were negligible in volume. Not all minor movements were present at every site because some of the sites were three-legged intersections or the fourth leg was a driveway with minimal traffic (e.g., TU-070). The minor movements permitted at the sites are listed in table 64.

Table 64. Minor movements permitted at the sites.

Movements Present	Sites
LT, LT1, TH1, TH2, and RT2 (four-legged intersection)	TU-003, TU-021, TU-037, TU-042, TU-059, TU-072, TU-073, TU-090, AU-04, AU-16, and AU-24
LT and LT1 (three-legged intersection)	TU-004, TU-070, and AU-11
LT and RT2 (midblock site with nearby driveway)	AU-21 and AU-22

A total of 850 minor movement vehicles were observed. This set of vehicles includes only those that arrived and/or departed while the PHB was active (i.e., not displaying the dark indication). The vehicle distribution by site and movement code is provided in table 65. Note that the pairing of the LT and RT2 movements represents a significant portion of the sample size, particularly at sites TU-042, TU-072, TU-073, AU-21, and AU-22. These movements at these sites represent about 62 percent of the sample size (525 of 850 vehicles). Additional turning movements were possible but not included in the minor movement analysis. Turning vehicles that originated from the minor approaches and passed through the crosswalk are included in the other analyses documented in this chapter.

Table 65. Minor movement vehicle distribution by site.

	Movement Code					
Site	**LT**	**LT1**	**RT2**	**TH1**	**TH2**	**Total**
TU-003	2	1	0	0	0	3
TU-004	10	0	7	0	0	17
TU-007	3	0	3	0	0	6
TU-021	3	13	8	4	6	34
TU-037	4	7	10	4	1	26
TU-042	154	2	116	11	0	283
TU-059	9	34	3	6	3	55
TU-070	0	10	0	0	0	10
TU-072	30	7	18	5	3	63
TU-073	27	3	46	1	0	77
TU-090	0	13	1	2	0	16
AU-04	8	17	9	2	0	36
AU-11	0	21	0	0	0	21
AU-16	0	8	0	0	0	8
AU-21	13	0	42	0	0	55
AU-22	28	0	51	0	0	79
AU-24	12	42	2	2	3	61
Grand Total	**303**	**178**	**316**	**37**	**16**	**850**

The vehicle distribution by movement code and PHB indication on vehicle arrival is provided in table 66. *Arrival* is defined as the time that the vehicle stopped at the stop line on its approach or the time that the vehicle crossed the stop line if it did not stop. The vehicle distribution by movement code and PHB indication on its departure is provided in table 67. *Departure* is defined as the time that the vehicle exited the intersection.

Table 66. Minor movement vehicle distribution upon vehicle arrival.

Movement Code	PHB Indication					
	Dark	Flashing Yellow	Steady Yellow	Steady Red	Flashing Red	Total
LT	31	1	14	85	172	303
LT1	41	3	12	54	68	178
RT2	32	4	15	79	186	316
TH1	14	1	2	8	12	37
TH2	7	0	1	3	5	16
Grand Total	**125**	**9**	**44**	**229**	**443**	**850**

Table 67. Minor movement vehicle distribution upon vehicle departure.

Movement Code	PHB Indication					
	Dark	Flashing Yellow	Steady Yellow	Steady Red	Flashing Red	Total
LT	33	0	3	107	160	303
LT1	22	0	0	89	67	178
RT2	39	0	1	111	165	316
TH1	4	0	0	22	11	37
TH2	1	0	0	11	4	16
Grand Total	**99**	**0**	**4**	**340**	**407**	**850**

As shown by the total count numbers in the rightmost columns of table 66 and table 67, the turning movements were the most commonly observed movements, especially movements LT and RT2, which were complementary. The through movements were less common, partly because these movements did not exist at the three-legged intersection sites.

The total count numbers in the bottom rows of table 66 and table 67 generally reflect the proportion of time that the PHB was active. The number of vehicles arriving or departing on the dark indication is small because vehicles that both arrived and departed on the dark indication were excluded from this analysis.

The distribution of minor movement vehicles by PHB indication upon arrival and PHB indication upon departure is shown in table 68. As shown, most vehicles departed on either steady red or flashing red regardless of when they arrived. However, a small number of vehicles experienced notable delay because they arrived while the PHB was active but could not depart until the next dark indication. Specifically, nine vehicles arrived during flashing red but did not depart until the steady yellow or steady red indication during the next PHB actuation. These long delays occurred during periods when the major street volume was sufficiently high enough that no acceptable turning or crossing gaps were available during the dark indication, and the major street drivers were aggressive during the flashing red indication such that they either did not stop consistently or stopped briefly and proceeded without waiting for other drivers' movements to proceed.

Table 68. Minor movement vehicle distribution by PHB indication.

PHB Indication Upon Arrival	PHB Indication Upon Departure					
	Dark	Flashing Yellow	Steady Yellow	Steady Red	Flashing Red	Total
Dark	0	0	0	108	17	125
Flashing yellow	0	0	0	8	1	9
Steady yellow	0	0	0	39	5	44
Steady red	5	0	0	180	44	229
Flashing red	94	0	4	5	340	443
Grand Total	**99**	**0**	**4**	**340**	**407**	**850**

To examine stop compliance, drivers were classified as violators under the following conditions:

- The driver was making the LT movement, arrived during a steady or flashing red indication, and did not stop. At all sites, the stop line was marked across all through and left-turn lanes, such that these drivers were required to stop even though they do not pass through the crosswalk.

- The driver was making the LT1, TH1, TH2, or RT2 movement and did not stop. In other words, the driver failed to stop at the STOP sign.

Each driver in the database was thus classified as a violator or non-violator, and violation rates were computed for each site based on the amount of video footage that was collected at the site (i.e., violations per hour). These findings are shown in table 69. The percentage of drivers not stopping varied widely, from 30.8 to 89.9 percent. Many of these percentages were computed based on the small number of minor movement vehicles that were observed while the PHBs were active. In terms of rate, violations at most sites were less common than five violations/h (or one violation every 12 min).

Table 69. Minor-movement violation rates by site.

Site	Number of Vehicles	Percent Not Stopping	Violation Rate (Violations/h)
TU-003	3	33	0.4
TU-004	17	65	2.6
TU-007	6	33	0.5
TU-021	34	32	2.2
TU-037	26	31	1.9
TU-042	283	72	46.7
TU-059	55	60	7.2
TU-070	10	60	1.5
TU-072	63	33	3.9
TU-073	77	42	7.5
TU-090	16	44	1.6
AU-04	36	64	6.3
AU-11	21	52	3.0
AU-16	8	38	0.8
AU-21	55	49	10.2
AU-22	79	90	40.6
AU-24	61	39	5.4

The following seven sites were found to have violation rates in excess of five violations/h: TU-042, TU-059, TU-073, AU-04, AU-21, AU-22, and AU-24. A more focused examination of these sites was conducted by computing violation rates for each movement. The results of this examination are shown in table 70. Similar computations were performed for all movements at all sites, but none of the movements omitted from table 70 had violation rates higher than four violations/h.

Table 70. Selected minor-movement violation rates by site and movement code.

Site	Movement Code	Number of Vehicles	Percent Not Stopping	Violation Rate (Violations/h)	Notes
TU-042	LT	154	72	25.4	Entering a collector near a high school campus
	RT2	116	77	20.4	Exiting a collector near a high school campus
TU-059	LT1	34	56	4.2	Exiting a residential neighborhood with a nearby elementary school campus
TU-073	RT2	46	46	4.9	Exiting a residential neighborhood with a nearby high school campus
AU-04	LT1	17	88	4.1	Exiting a collector near a supermarket
AU-21	RT2	42	48	7.8	Exiting a supermarket
AU-22	LT	28	96	15.4	Entering a supermarket
	RT2	51	86	25.2	Exiting a supermarket
AU-24	LT1	42	43	4.1	Exiting a supermarket

All of the movements listed in table 70 were located close to major traffic generators such as schools or supermarkets. In fact, the majority of the violations observed at site TU-042 occurred in the morning period before classes began for the day. Violations were also frequent at site AU-22; however, it should be noted that the LT movement at this site occurred from a TWLTL, and the stop line for the PHB was marked in the adjacent through lanes but not in the TWLTL, suggesting that the stopping requirement might not have been intended for this movement. This marking practice differed from the practice at other Austin, TX, sites, where stop lines were extended through all approach lanes. Sites AU-21 and AU-22 were similar in that their LT and RT2 movements went into or out of supermarkets, but the LT movement at site AU-22 did not have a high violation rate. The major street at this site was a four-lane undivided city arterial, so left-turning drivers did not have a turn bay and were often blocked from completing the LT movement while the PHB was active.

Based on the preceding information, the following observations could be made:

- Minor movement drivers took advantage of gaps that were created in the major street traffic while the PHBs were active.
- PHB sites did not necessarily operate like four-way stops while the flashing red indication was shown. At sites near major traffic generators, movements entering or exiting the traffic generator tended to dominate the operation of the intersection, and stop compliance for these movements tended to be low.

These trends may occur at any type of unsignalized pedestrian crossing treatment while pedestrians are present. They are likely not unique to PHB-controlled crossings.

PEDESTRIAN BEHAVIORS FINDINGS

Pedestrian Departures by Indication

Of the 1,979 pedestrians crossing the street, 290 were research team members who always crossed when the beacons showed steady or flashing red to the motorists. Most of the remaining 1,689 general public pedestrians departed when the beacon showed a steady red indication to the drivers. As shown in table 71, 80 percent departed during the steady red or flashing red indications. Approximately 13 percent of the pedestrians departed while the PHB was still in the vehicle clearance intervals.

Table 71. Pedestrian departures by indication.

Site	Dark	Flashing Yellow	Steady Yellow	Steady Red	Flashing Red	Total
TU-003	0	1	1	11	1	14
TU-004	0	1	13	58	5	77
TU-007	1	0	5	47	3	56
TU-021	3	1	6	53	1	64
TU-037	6	0	5	66	5	82
TU-042	22	2	18	101	12	155
TU-059	0	1	4	21	4	30
TU-070	3	0	2	18	3	26
TU-072*	16	0	9	57	0	82
TU-073	1	1	0	77	12	91
TU-090	2	0	3	3	0	8
TU-091	4	0	0	10	0	14
AU-04	6	4	4	44	5	63
AU-07[a]	20	6	22	132	18	198
AU-11	0	0	2	47	22	71
AU-16	1	2	2	86	3	94
AU-21	1	3	20	73	7	104
AU-22	7	10	28	123	22	190
AU-24	28	10	16	130	25	209
AU-27	3	1	3	46	8	61
Grand Total (Percent)	**124 (7)**	**43 (3)**	**163 (10)**	**1,203 (71)**	**156 (9)**	**1,689 (100)**

[a]The PHB was located within the coordinated corridor where the timing of when the PHB was active was influenced by the nearby coordinated signals.

For the pedestrian crossings observed that did not include the research team member crossings, only 124 pedestrians (7 percent) left during the dark indication. For the majority of these pedestrians, the roadway volume was such that the pedestrian was able to find sufficient gaps to cross. The volume per minute per lane was less than four vehicles/min/lane for the majority of these crossings. Figure 62 shows the cumulative distributions of the 1 min/lane volume for those pedestrians that departed during the dark indication (i.e., blue dashed line) and those that departed during an active indication (i.e., red solid line). Pedestrians were more likely to wait for the PHB to be active before starting to cross at the higher roadway volumes, as shown by the location of the red solid line to the right of the blue dashed line. For example, the cumulative distributions reached the value of 80 percent at volumes of about six vehicles/min/lane for the blue dashed line and about eight vehicles/min/lane for the red solid line. This trend shows that only 20 percent of non-compliant pedestrians were still willing to cross if the roadway volume exceeded six vehicles/min/lane (i.e., 1,440 vehicles/h at a four-lane site). Less than 5 percent of non-compliant pedestrians crossed when the roadway volume exceeded 10 vehicles/min/lane. Conversely, roughly half of the compliant pedestrians crossed at roadway volumes exceeding six vehicles/min/lane.

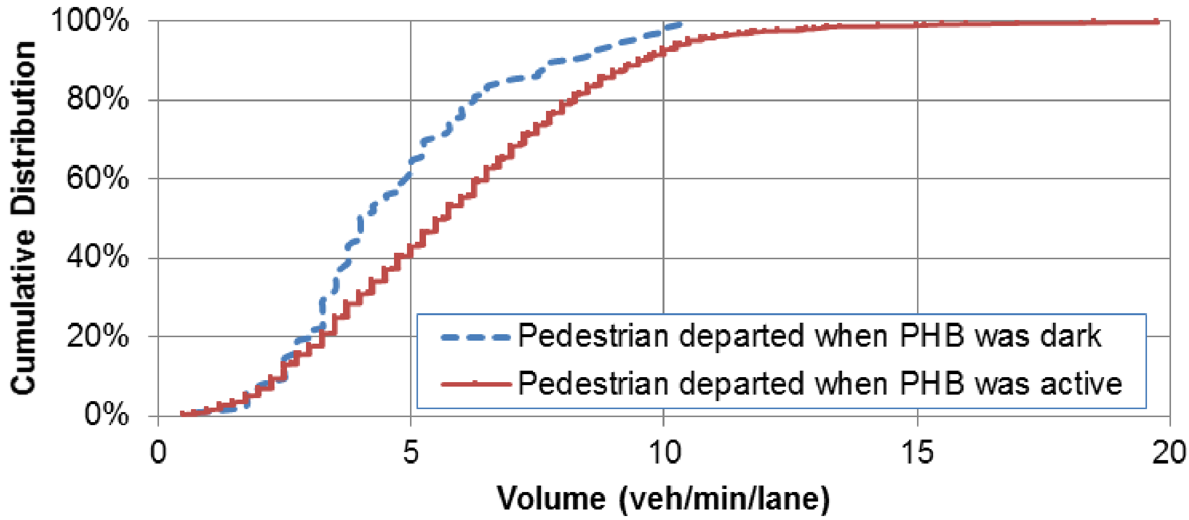


Figure 62. Graph. Volume cumulative distribution when pedestrian started the crossing.

Two of the PHB sites were located within coordinated corridors where the timing of PHB activation was influenced by the nearby coordinated signals. The other 18 sites were at "hot button" sites, where the PHB sequence starts following the push of the pushbutton. About one-third of the pedestrians (36 of 124) who departed during the dark indication were at the sites where the PHB is coordinated with nearby signals. While a large value, there were other sites with more pedestrians departing during the dark indication, both in terms of number of pedestrians and proportion of pedestrians observed at the site. The percentage of pedestrians departing during the dark indication was 13 percent at the coordinated sites and 6 percent at the hot button sites. Departures on dark were much less frequent at the coordinated site that had pedestrian pushbuttons with red lights that illuminate when the button is pressed. The coordinated site with the red-lighted buttons had 10 percent of pedestrians departing on dark, while the coordinated site with the non-lighted buttons had 20 percent of pedestrians departing on dark.

Pedestrian Actuation of the PHB

Of the 1,979 pedestrians crossing the street, 290 were research team members who crossed using a staged pedestrian protocol and always activated the PHB. The remaining 1,689 general public pedestrians were coded by whether they pushed the pedestrian pushbutton or did not push the pushbutton subdivided by whether the PHB was already active or not active when they arrived to the crossing. Table 72 shows the number of pedestrians by action. Overall, most pedestrians (average of 91 percent) who could have activated the PHB did. As can be seen in table 72, there were some sites with lower percent actuations (e.g., AU-04) and other sites where every pedestrian crossed with an activated PHB (e.g., TU-03, TU-04, and AU-11).

Table 72. Number of pedestrians by site who pushed, did not push, or did not push because PHB was active.

Site	Pushed	Did Not Push	Did Not Push; Already Active	Total Number of Pedestrians	Percent[a]
TU-003	13	0	1	14	100
TU-004	73	0	4	77	100
TU-007	55	1	0	56	98
TU-021	61	2	1	64	97
TU-037	75	6	1	82	93
TU-042	116	21	18	155	85
TU-059	29	1	0	30	97
TU-070	21	3	2	26	88
TU-072[b]	66	14	2	82	83
TU-073	62	13	16	91	83
TU-090	6	2	0	8	75
TU-091	12	2	0	14	86
AU-04	43	14	6	63	75
AU-07[b]	165	14	19	198	92
AU-11	49	0	22	71	100
AU-16	90	1	3	94	99
AU-21	97	2	5	104	98
AU-22	147	11	32	190	93
AU-24	162	25	22	209	87
AU-27	55	3	3	61	95
Grand Total	**1,397**	**135**	**157**	**1,689**	**91**

[a]Percent = Percentage reflecting the ratio of the number of pedestrians that pushed the button to the number of pedestrians that if they would have pushed the button would have triggered a change in the device (i.e., those that pushed and those that did not when the device was dark). In other words, this column does not include those pedestrians who arrived when the PHB was active.
[b]The PHB was located within coordinated corridor where the timing of when the PHB was active was influenced by the nearby coordinated signals.

A plot of the percentage of pedestrians who activated the PHB when arriving to the crossing when the PHB was not already active is shown by posted speed limit in figure 63, by crossing distance in figure 64, and by hourly volume in figure 65 . A review of these plots shows trends for the highest values. A high number of pedestrians (93 percent) activated the device on the 45-mi/h posted speed limit road. For the 40-mi/h or less roads, a large range of actuation was observed—between 75 and 100 percent. The percentage of pedestrians pushing the button was always greater than 83 percent for the longer crossing distances (i.e., longer than 110 ft).

The 1-min volume count nearest to the arrival time of the pedestrian was determined. The number of pedestrians by their action was summed for each 1-min count value for all 20 sites. The 1-min counts with less than 20 pedestrians crossing were omitted for the plot shown in figure 65. The 1-min count was adjusted to an hourly equivalent value by multiplying the 1-min count by 60. When the hourly volume for both approaches was 1,500 vehicles/h or more, the percent of pedestrians activating the PHB was always 92 percent or more.

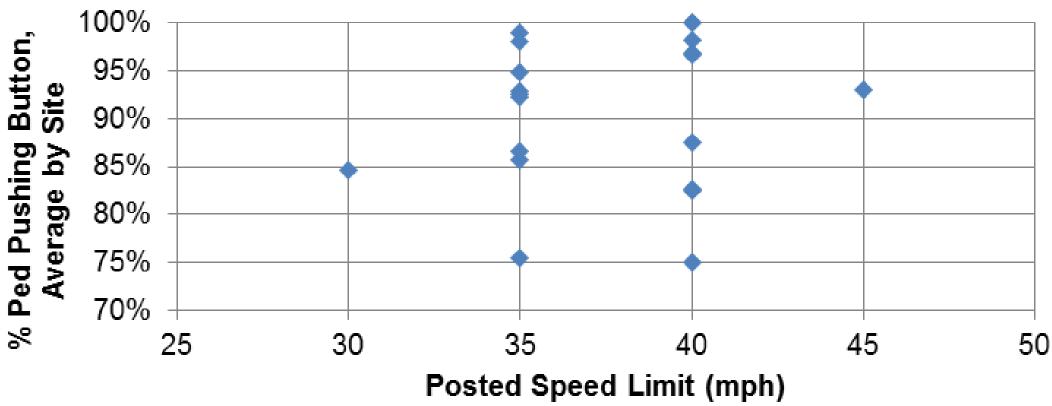


Figure 63. Graph. Percentage of pedestrians pushing the button, by posted speed limit.

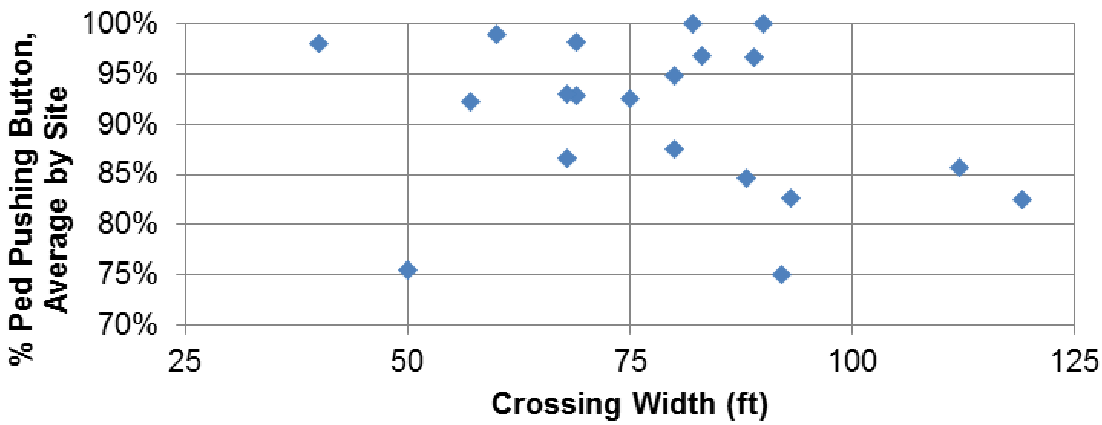


Figure 64. Graph. Percentage of pedestrians pushing the button, by crossing distance.

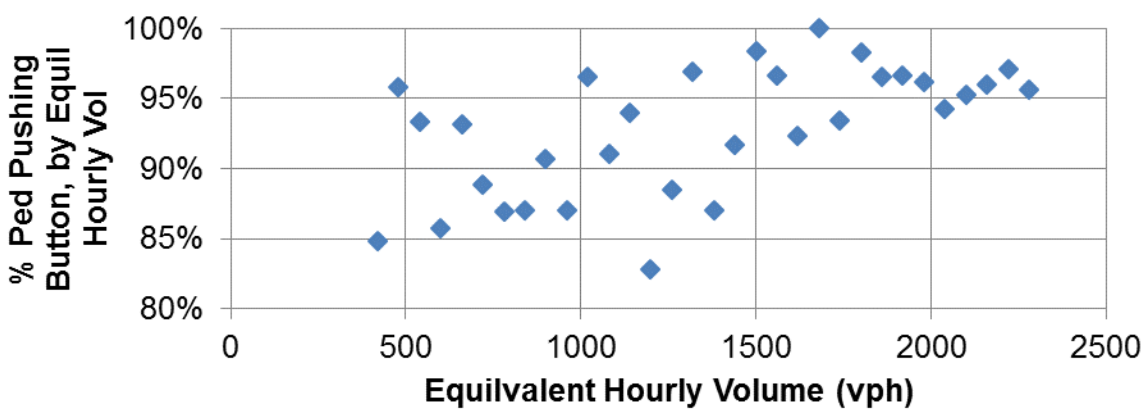


Figure 65. Graph. Percentage of pedestrians pushing the button, by 1-min volume counts adjusted to hourly counts.

Some of the pedestrians who activated the PHB departed prior to the walk indication. The beacon indication when the pedestrian departed is shown in table 73. Most of the pedestrians who departed after pushing the pushbutton either left during the steady red (82 percent) or the flashing red (2 percent). About 1 percent of those who activated the device left while the device was still dark, with most occurring at the two locations where the PHB was within a coordinated corridor (sites TU-072 and AU-07).

Table 73. Indication when pedestrian departed for those that activated the PHB.

Site	Dark	Flashing Yellow	Steady Yellow	Steady Red	Flashing Red	Total
TU-003	0	1	1	11	0	13
TU-004	0	1	13	58	1	73
TU-007	0	0	5	47	3	55
TU-021	0	1	6	54	0	61
TU-037	0	0	5	66	4	75
TU-042	0	2	18	96	0	116
TU-059	0	1	4	21	3	29
TU-070	0	0	2	18	1	21
TU-072[a]	5	0	8	53	0	66
TU-073	0	1	0	60	1	62
TU-090	0	0	3	3	0	6
TU-091	2	0	0	10	0	12
AU-04	0	4	4	35	0	43
AU-07[a]	6	6	22	129	2	165
AU-11	0	0	2	47	0	49
AU-16	0	2	2	86	0	90
AU-21	0	3	20	70	4	97
AU-22	1	9	28	109	0	147
AU-24	3	10	16	129	4	162
AU-27	0	1	3	46	5	55
Grand Total (Percent)	**17 (1.2)**	**42 (3.0)**	**162 (11.6)**	**1,148 (82.2)**	**28 (2.0)**	**1,397 (100)**

[a]The PHB was located within coordinated corridor where the timing of when the PHB was active was influenced by the nearby coordinated signals.

CONFLICTS FINDINGS

All occurrences of pedestrian/vehicle conflicts and erratic maneuvers were noted when observed in the video footage. A *conflict* is defined based on the following criteria:

- The vehicle suddenly changes path, speed, or both.
- The vehicle's brake lights illuminate unexpectedly during a turning maneuver.
- The pedestrian exhibits one or more of the following behaviors:
    - Slows down due to vehicle presence.

- Stops and waits for the vehicle to pass through the crosswalk.
- Steps sideways to avoid a vehicle.
- Runs or speeds up to avoid a vehicle.
- Turns back to origin curb to avoid a vehicle.
- Makes another sudden change in path or speed in response to an approaching vehicle.

In the 78 h of video footage, 54 conflicts were observed. The distribution of the conflicts categorized by vehicle maneuver was 38 for through vehicles, 10 for left-turning vehicles, and 6 for right-turning vehicles. Distribution by vehicle maneuver was analyzed because of concerns about turning traffic operations while the PHB was serving pedestrians. While major street through vehicles were stopped by the PHB, turning drivers originating from the minor approaches could see significant gaps form on the major street and may have taken this opportunity to turn, possibly leading to conflicts with pedestrians in the crosswalk.

The conflicts were tabulated by vehicular beacon indication and vehicle maneuver, as shown in table 74. Beacon indication can be used to classify pedestrians as compliant (i.e., they departed the corner on a steady red indication while the walk indication was displayed) or non-compliant (i.e., they departed on one of the other beacon indications while the flashing or steady do not walk indication was displayed). Slightly less than half of the observed conflicts occurred during the dark beacon indication and involved a through vehicle. These conflicts usually involved pedestrians who either crossed without pushing the button or pushed the button but did not wait for the walk indication and then paused in the raised curb median while crossing. The latter case occurred most frequently at site TU-072 (14 conflicts), which had 6 lanes and operated in coordinated mode.

Table 74. Vehicle and pedestrian conflicts by beacon indication and vehicle maneuver.

Beacon Indication	Vehicle Maneuver			
	Through	**Left Turn**	**Right Turn**	**Total**
Dark[a]	25	2	0	27
Flashing yellow[a]	0	0	0	0
Steady yellow[a]	0	1	0	1
Steady red	8	7	6	21
Flashing red[a]	5	0	0	5
Total	**38**	**10**	**6**	**54**

[a]Indicates pedestrians who were not in compliance with signal indication.

A notable number of conflicts involving left-turning vehicles was observed at site AU-21. This site was located near a well-patronized supermarket and a bus stop, with a driveway located about 45 ft away from the crosswalk. At that distance, drivers making left turns out of the supermarket parking lot would be able to turn onto the major street but would still be oriented diagonally when encountering the crosswalk. Many of these drivers encroached on the crosswalk while attempting to complete their turning maneuvers, leading to conflicts if pedestrians were present. A similar geometric layout was present at site AU-22, but this site did not exhibit conflicts because the driveway was located farther away from the crosswalk (about 60 ft) and afforded left-turning drivers more room to complete their turning maneuvers and wait for pedestrians to clear.

To account for exposure differences across the sites, conflict rates were computed using three conflict rate measures, as provided in table 75. The measure of conflicts per pedestrian-vehicle accounted for the influence of both pedestrian and vehicle exposure. For all three rate measures, the conflict rate was found to be higher for non-compliant pedestrians than for compliant pedestrians. These rates were interpreted in terms of total exposure (pedestrians or vehicles or pedestrian and vehicles). That is, at a site that experiences 100 pedestrians crossing per hour, it is expected that 2.73 conflicts would be observed per hour, of which 1.06 would involve compliant pedestrians and 1.67 would involve non-compliant pedestrians.

Table 75. Pedestrian-vehicle conflict rates.

Pedestrian Group	Conflicts per 100 Observed Pedestrians	Conflicts per 10,000 Vehicles
All	2.73	4.15
Compliant	1.06	1.61
Non-compliant	1.67	2.54

Notable conflict rates were observed at site TU-072 because of the high number of non-compliant pedestrians. This site operated in coordinated mode with buttons that did not provide audible or visual cues indicating that the button press had been registered. As a result, many pedestrians pushed the button but may have believed that the PHB was malfunctioning or may have grown impatient while waiting for service and crossed the major street before the walk indication was displayed. Similar behavior was not observed at site AU-07, which operated in coordinated mode but with buttons that had small red lights that illuminated when the button was pressed.

Notable conflict rates for both compliant and non-compliant pedestrians were also observed at several sites where the PHBs were located near supermarkets and multiple bus stops. At these sites, many bus riders walked through the supermarket parking lots or ran across the major street while transferring between bus lines. The presence of bus stops near an access point with significant turning vehicle volumes tended to result in higher conflict rates.

CHAPTER 7. SUMMARY/CONCLUSIONS, DISCUSSION, AND FUTURE RESEARCH NEEDS

OVERVIEW

This chapter provides summaries and conclusions along with a discussion of the implications of the findings or each of the studies. The chapter concludes with a list of future research needs.

CLOSED-COURSE STUDY

Summary/Conclusions

The closed-course study was designed to quantify drivers' ability to detect pedestrians within and around a crosswalk (a measure of disability glare) and quantify discomfort glare ratings associated with LEDs in traffic control devices. Participants drove the study vehicle to the starting location where they parked the vehicle 200 ft from sign assemblies that consisted of a pedestrian crossing sign with LEDs within the sign face and LEDs in rectangular beacons above and below the sign. After the driver placed the vehicle into park, they were asked to set occlusion glasses on their faces. The occlusion glasses obscured the participants' vision by going opaque when there was no power supplied to them and going clear when power was supplied.

Once the participants' vision was occluded, technicians placed a static cutout photo of a pedestrian (either 54 inches tall to represent a child or 70 inches tall to represent an adult) within the crosswalk located near the sign assemblies. An experimenter then restored the participants' vision, and the participants were asked to identify the direction the pedestrian was traveling (to the left, to the right, or not present) as quickly as possible using a button box. When the participants pressed the button on the button box, the glasses turned opaque again. Following the participants' identification of the pedestrian's direction, the researcher asked the participants to rate the intensity of the LED (comfortable, irritating, or unbearable) before asking the field crew to set up the next condition. This process was repeated for various combinations of LED brightness, LED locations, pedestrian positions, and flash patterns. This portion of the study was stationary, and after completion, the participants drove to the check-in location and completed a laptop survey that asked a series of questions to obtain the participants' opinions regarding flash patterns for LEDs used with signs.

To increase the number of flash patterns tested in the study but to keep within a reasonable testing period, data were collected within two sets. Within each set, two flash patterns were tested for the LEDs in rectangular beacons and two flash patterns for the LEDs within sign. For set I, the study was conducted during both daytime and nighttime. For set II, the study was only conducted during the nighttime. During the testing of set I, it was determined that night was the more critical condition, which is why only nighttime data were collected during set II.

A summary of the findings for LED intensity and location along with flash pattern is provided in table 76. Table 77 summarizes the findings for pedestrian height, pedestrian position, and participant age. Following is an overview of the key findings from this research study.

Table 76. Summary of results for LED intensity and location along with flash pattern.

Variable	LED Intensity	Flash Pattern	LED Location
Detection time	• **Night: Detection time was longer when intensity was higher—8.5 percent greater for 2,200 candelas compared to when the LEDs were off.** • Day: 2.4 percent greater for 2,200 candelas compared to when LEDs were off.	• **Night: 2-5 flash pattern when used above or below sign yielded detection time 6 percent longer than no flash pattern at all. Using the wig-wag pattern above or below sign resulted in a 13.7 percent increase in detection time compared to no flash pattern at all.** • **Day: 2-5 flash pattern when used above or below sign caused a 5.2 percent increase in detection time compared to no flash pattern at all.**	• **Night: Detection time was fastest when LEDs were above the signs. In comparison, there was a 6 percent increase in detection time when LEDs were within the sign and 12 percent increase when LEDs were below the sign.** • Day: Not statistically significant.
Detection accuracy	• **Night: Accuracy was lower when intensity was higher. Odds of accurate detection for 2,200 candelas reduced to 0.58 times the odds for 0 candelas.** • Day: Not statistically significant.	• Night: Not statistically significant. • Day: Not statistically significant.	• **Night: Higher accuracy when LEDs were above the sign. In comparison, odds of accurate responses for LEDs below were 0.54 times the odds for LEDs above.** • Day: Not statistically significant.
Discomfort	• **Night: Discomfort was higher when intensity was higher. Odds of increased discomfort for 2,200 candelas was 9.43 times the odds when LEDs were off.** • **Day: Discomfort was higher when intensity was higher. Odds of increased discomfort for 2,200 candelas was 7.05 times the odds when LEDs were off.**	• **Night: When LEDs were active, the odds of increased discomfort were about 8 times the odds for no LEDs flashing (statistically significant).** No difference between either 2-5 or wig-wag patterns compared to the rest of patterns. No difference between 2-5 and wig-wag patterns. • Day: Not statistically significant.	• **Night: Odds of higher discomfort when the LEDs were below 1.86 times the odds when LEDs were above.** No difference between within and above locations. • Day: Not statistically significant.

Note: Bold text indicates the results were statistically significant.

Table 77. Summary of results for pedestrian height and position and participant age.

Variable	Ped Height	Pedestrian Position	Participant Age
Detection time	• **Night: Detection time was longer when the pedestrian was short rather than tall. There was a 3.6 percent detection time increase for the short pedestrian.** • **Day: Detection time was longer when the pedestrian was short rather than tall. There was a 3.9 percent increase for the short pedestrian.**	• **Night: Detection time shorter for center position as compared to either side.** • **Day: Detection time shorter for center position as compared to either side.**	• **Night: 0.5 percent increase in detection time per additional year of driver age.** • **Day: 1 percent increase in detection time per year of driver age.**
Detection accuracy	• **Night: Detection accuracy was higher when the pedestrian was tall compared to short. Odds of accurate detection for the short pedestrian were 0.65 times the odds for the tall pedestrian.** • **Day: Detection accuracy was higher when the pedestrian was tall compared to short. Odds of accurate detection for the short pedestrian were 0.64 times the odds for the tall pedestrian.**	• **Night: Center had more accurate responses compared to either side. Higher accuracy at center compared to either side.** • Day: Same trend as night, but evidence is only suggestive.	• **Night: Odds of accurate detections for oldest participants (85 years old) about 0.16 times the odds for the youngest (21 years old).** • **Day: Odds of accurate detections for oldest participants (83 years old) are about 0.04 times the odds for the youngest (19 years old).** However, this difference is not practically significant, since both accuracy rates for these participants are above 95%.
Discomfort	• **Night: Odds of higher discomfort for the short pedestrian were 0.86 times the odds for the tall pedestrian.** • Day: Not statistically significant.	• **Night: Odds of higher discomfort nearly doubled (i.e., multiplicative factor of 1.84) when placing pedestrian at either side, compared to center of the crosswalk.** No difference in discomfort level between pedestrian and no-pedestrian conditions. • Day: Not statistically significant.	• **Night: Odds of higher discomfort changed by a multiplicative factor of 0.98 with each additional year of age.** • Day: Not statistically significant.

Note: Bold text indicates the results were statistically significant.

Average nighttime detection time for the participants to search and determine which direction a cutout pedestrian was walking was 1.473 and 1.292 s for older and younger participants, respectively. Average daytime detection time for the participants was, as expected, faster (1.281 and 0.971 s for older and younger participants, respectively, during the day).

LED intensity had a measurable adverse impact on detection time at night but not during the day. Under nighttime conditions, detection time increased 8.5 percent for 2,000 candelas compared to 0 candelas (no LEDs). Similar to detection time, LED intensity adversely affected accuracy at night but not during the day. Regarding discomfort glare, LED intensity had an adverse impact under both daytime and nighttime conditions.

LED location affected nighttime detection times but had no detectable daytime effect. At night, detection time was 6 percent longer for LEDs below compared to LEDs within (or 12 percent longer for LEDs below compared to LEDs above). Likewise, detection times with LEDs within were 6 percent longer than for LEDs above. Discomfort glare was different by LED position at night with higher discomfort level with LEDs below compared to LEDs above.

Flash pattern affected detection times during both nighttime and daytime conditions. During the day, only the 2-5 flash pattern had a significantly larger detection time (5.2 percent longer) than no flash pattern. At night, both the 2-5 and wig-wag flash patterns were found to delay detection compared to no pattern (increases of 6.0 and 13.7 percent, respectively). For accuracy and discomfort glare, no significant differences among flash patterns were found under both daytime and nighttime conditions.

Pedestrian height impacted detection time both day and night. During the day, detection time for the short pedestrian increased by 3.9 percent during the day and by 3.6 percent at night compared to detection time for the tall pedestrian. Similarly, accuracy was higher when the experiment involved the tall pedestrian instead of the short pedestrian.

Pedestrian position had an impact on detection time, both during the day and at night. Under both conditions, detection was faster when the pedestrian was located at the center of the crosswalk. Also, for both light conditions, detection times for pedestrian at left or at right were not statistically different from each other. Accuracy trends by pedestrian position were similar to detection time trends, though only at night were these trends statistically significant. Pedestrian position was found to influence discomfort glare at night with higher discomfort when searching for the pedestrian at either side of the crosswalk as compared to when the pedestrian was at the center.

Age of participants drew a clear gradient of increasing detection times, both during the daytime and nighttime. Accuracy of detection decreased by age, both during the day and at night.

The survey found that multiple flashes within a short time period were better at communicating the need to stop for a pedestrian at a crosswalk as compared to few or no flashes such as the wig-wag or no LED illuminated conditions.

The survey also found that when observing close-up views of a sign assembly consisting of a pedestrian crossing sign and LEDs either embedded or below the sign, the patterns that used multiple pulses communicated greater urgency in needing to yield to a pedestrian. The participants indicated that LEDs below communicated more urgency than the LEDs within.

When asked to count the number of pulses in a light bar with the 2-5 flash pattern, the majority of the participants (77 percent) correctly counted two pulses; however, almost none of the participants correctly counted the five faster pulses. Only four participants provided the correct answer. The majority of the participants (55 percent) saw three pulses when five pulses were presented.

Discussion

The flash pattern along with the brightness of LEDs, whether used within beacons or embedded in a sign, can help draw drivers' attention to a device and the area around the device. However, characteristics of the LEDs, such as brightness or flash pattern, can also make it more difficult for drivers to see objects around a device (disability glare) or result in drivers looking away from a device (discomfort glare). This study used several measures to gain an understanding of how brightness and flash pattern affect driver's ability to detect a pedestrian within a crosswalk. These measures included time to correctly identify pedestrian walking direction and participant's rating of discomfort glare.

The brightness intensity of the LEDs used in this study ranged from 0 candelas (i.e., the LEDs were not on) to 2,200 candelas. In another FHWA study, devices installed in the field were measured with higher brightness intensity; the range used in this closed-course study did not reflect the wider range currently being used in on-road installations.(5) The brightness of LEDs in the field appears to be highly variable. Part of the reason could be that current requirements only specify a minimum intensity. The minimum intensity is defined within SAE Standard J595; the minimum measured at a horizontal angle of 0 degrees and vertical angle of 0 degrees for class I yellow peak luminous intensity is 600 candelas.(15)

For this study, brightness intensity did not have a significant impact on detection time for daytime conditions while being significant for nighttime conditions. Nighttime detection time increased by 8.5 percent at 2,200 candelas (the maximum used in the study) as compared to when the LEDs were off. The brighter the LEDs, the longer it took for the participants to determine which direction the pedestrian was facing. In other words, lower brightness was associated with reduced disability glare.

Some of the flash patterns used with the devices were associated with longer detection times. Of the six flash patterns tested, only two flash patterns—the 2-5 and the wig-wag flash patterns—were associated with statistically significant longer detection times as compared to the no flash pattern condition. Both of these patterns had longer on times (the 2-5 flash patter was on 69 percent of the cycle, and the wig-wag pattern was on 100 percent of the cycle) as compared to the other patterns (range of 10 to 38 percent on time). The LEDs being constantly on may have caused the participants to look away from the LEDs. In addition, the lack of sufficient dark period(s) between the flashes may have limited the participants' ability to adequately search for the pedestrian. A better flash pattern than the current 2-5 flash pattern should retain multiple pulses (since the survey results found that participants felt patterns with multiple pulses were associated with greater urgency), more dark periods (since the study found longer detection time for patterns with less dark periods), and a maximum intensity that limits discomfort when attempting to detect objects while still commanding driver attention (i.e., resulting in high driver yielding).

The findings for pedestrian position and LED location indicate that the distance between the pedestrian and the light source affected the ability to quickly detect the pedestrian. When the pedestrians were located at the edge of the crosswalk (i.e., next to the assembly) and when the LEDs were located below the sign (i.e., closer to the pedestrian), detection time was longer and detection accuracy was lower. These findings support the idea of placing the LEDs above rather than below the sign and investigating the benefits of locating the LEDs over the roadway rather than on the roadside.

The shorter height pedestrian required more time to detect and had lower detection accuracy, which were expected findings. The smaller target provided by a child-sized pedestrian was a known concern for pedestrian crosswalks.

This study found strong evidence that there was potential value in mounting the LEDs above the sign instead of below. Nighttime detection time was fastest when LEDs were above the signs, with a 6 percent increase when LEDs were within the sign and a 12 percent increase when LEDs were below the sign. Both of these findings were statistically significant. This finding supports the idea that separating the pedestrian from the light source may benefit the driver's ability to search and identify the location of the pedestrian.

ABOVE-BELOW (OPEN-ROAD) STUDY

Summary/Conclusion

Based on the findings from the closed-course study, the following combination was examined in open-road settings: beacons located above the sign as compared to when the beacons were located below the sign.

The RRFB in positions above and below the pedestrian crossing sign were installed at 13 sites located in 4 States (Aurora, IL; Douglas County, CO; Marshall, TX; and Phoenix, AZ). At all 13 sites, after collecting data for the initial beacon position, the beacons were moved to the opposite position. The same flash pattern was used regardless of beacon position. The research team used a staged pedestrian protocol to collect driver yielding data to ensure that oncoming drivers received a consistent presentation of approaching pedestrians.

Because a previous study that included RRFBs found that posted speed limit, crossing distance, and city influenced driver yielding, the initial analyses were conducted with those variables along with the beacon shape variable.[35] An indicator variable for nighttime conditions was included in the final model to determine if the nighttime results were significantly different from daytime results. From the preliminary review of the findings (average daytime yielding was 64 percent when the beacons were above the sign and 60 percent when the beacons were below the sign), it appears that there were only minor, if any, differences between the above and below positions. The results from the GLMM indicate that there were no significant differences between the two positions (p-value = 0.1611).

In conclusion, the position of the yellow RRFB did not have an impact on whether a driver decided to yield to the waiting pedestrians. Variables that did have an impact on driver yielding include posted speed limit, intersection configuration, and city (yielding was lower in Illinois compared to the other States included in study).

Discussion

With respect to the location of the LEDs, the findings from the closed-course study for pedestrian position and LED location indicate that the distance between the pedestrian and the light source affected the ability to quickly detect the pedestrian. When the pedestrians were located at the edge of the crosswalk (i.e., next to the assembly) and when the LEDs were located below the sign (i.e., closer to the pedestrian), detection time was longer. These findings support the idea of placing the LEDs above rather than below the sign.

The open-road study found that the position of the RRFB (either above or below the sign) did not affect a driver's decision to yield. With the apparent benefits identified from the closed-course study (i.e., lower discomfort and improved ability to detect the pedestrian, as measured by identifying the direction the cutout pedestrian is traveling) and the finding that there was no difference in driver yielding due to position, locating the beacons above the sign could improve the overall effectiveness of this treatment. Based on these findings, FHWA is considering issuing an official interpretation to permit the placing of the beacons above the sign.

FLASH PATTERN (OPEN-ROAD) STUDY

Summary/Conclusions

When IA-11 was issued in July 2008 for the RRFB, the only flash pattern that had been tested was the 2-5 flash pattern in which the beacon pulses two times on one side followed by five faster pulses on the other side.[4] However, because the 2-5 flash pattern appears to the human eye to be a 2-3 flash pattern, IA-11 specified a 2-3 flash pattern and, up until official interpretation 4(09)-21 (I), many devices were installed with the 2-3 flash pattern rather than the 2-5 flash pattern.[9] The inability to accurately determine the number of pulses within a pattern was later confirmed in the closed-course study (see chapter 3). The same closed-course study found that certain flash patterns—those that could be characterized as having limited or no dark periods within the flash pattern—negatively influenced the amount of time participants needed to identify the direction a pedestrian is walking. Prior to developing the proposed provisions for incorporating a rapid-flashing beacon traffic control device into the MUTCD, it is important to determine which flash patterns are acceptable from the perspectives of effectiveness and simplicity.[1] There is a desire to know if a less complicated flash pattern or a flash pattern with different dark/light proportions would be equally or more effective than the 2-5 or 2-3 flash patterns.

An open-road study was conducted to examine different flash patterns with yellow RRFBs. The objective of the study was to determine if the use of simpler flash patterns used with RRFBs resulted in different driver yielding rates at uncontrolled crosswalks. The MOE was the number of drivers who did and did not yield for a staged pedestrian who activated the RRFBs and was attempting to cross the roadway. The study included eight sites located in either

College Station, TX, or Garland, TX. Most of the sites (seven out of eight) had four lanes with a 40- or 45-mi/h posted speed limit. The remaining site had two lanes and a 30-mi/h posted speed limit.

A temporary light bar and controller were developed to permit the research team to have control over several of the beacons characteristics, such as flash pattern and brightness. The light bar was designed such that it was not obvious that the beacons being observed were any different from the permanent RRFB light bar they were mounted to. A remote control was used to activate the temporary light bar.

A flash pattern workshop along with meetings with FHWA resulted in the selection of the following patterns for testing:

- Pattern using a combination of long and short flashes (blocks).
- Pattern using a combination of WW+S flashes.
- The 2-5 flash pattern.

The research team used a staged pedestrian approach to evaluate driver yielding for the different patterns. Each staged pedestrian wore similar clothing (gray t-shirt, blue jeans, and gray tennis shoes) and followed specific instructions in crossing the roadway. A second researcher, who observed and recorded the yielding data on pre-printed datasheets, accompanied the staged pedestrian. Data were collected in February and March 2014.

The average driver yielding was 80 percent for the WW+S flash pattern, 80 percent for the blocks pattern, and 78 percent for the 2-5 flash pattern. While there was a small numeric difference of 2 percent, the statistical analysis found that this difference was not statistically significant. Logistic regression was used to model the yielding and not yielding relationships for the individual crossings. The results from the GLMM indicate that there were no significant differences between the tested flash patterns. The WW+S flash and block patterns developed as part of this research study were as effective as the 2-5 flash pattern.

Discussion

This study, combined with the closed-course study that found drivers were better at judging pedestrian direction when there were more dark periods (see chapter 3), suggest an advantage in using a flash pattern with a longer dark period during night time conditions and that this advantage was not offset by a reduction in driver yielding during the daytime conditions. This suggests the profession should consider using a flash pattern with increased dark periods when specifiying the pattern for RRFBs.

The findings from the research effort were presented to the NCUTCD STC during its June 2014 meeting. The STC recommended that the WW+S flash pattern should be used with future rapid-flashing pedestrian treatments. Based on the findings from this research, FHWA issued an official interpretation on July 25, 2014, to permit agencies to use either the previously approved 2-5 flash pattern or the optional WW+S flash pattern.[(2)] Although both flash patterns are available for use, the official interpretation mentions that FHWA favors the WW+S flash pattern because it has a greater percentage of dark time when both beacons of the RRFB are off and because the beacons are on for less total time. The greater percentage of dark time is important because this will make it easier for drivers to read the sign and to see the waiting pedestrian, especially under nighttime conditions. The less total on time will make the RRFB more energy efficient, which is important since they are usually powered by solar energy.

PHB STUDY

Summary/Conclusions

The PHB has shown great potential in improving safety and driver yielding; however, questions have been asked regarding actual driver and pedestrian behaviors. A total of 20 locations in Tucson, AZ, and Austin, TX, were selected for inclusion in this study representing a range of posted speed limit, median type, and number of major roadway lanes. Data were collected using a multiple video camera setup. The final dataset reflected over 78 h of video data and included 1,979 pedestrians.

The videos were reviewed to identify each occurrence when a vehicle stopped at the crossing when the PHB was displaying a dark indication. None of the drivers who stopped at the crossing when the PHB was dark appeared to be confused regarding the device. In the cases when a queue was present during the flashing red indication, about half of the crossings included at least one driver who did not completely stop prior to entering the crosswalk. Overall, driver yielding for these 20 sites averaged 96 percent. In almost all of the crossings, drivers appropriately yielded to the crossing pedestrians.

For the pedestrian crossings observed, only 124 of the 1,689 pedestrians (7 percent) departed during a dark indication. For the majority of these pedestrians, the roadway volume was such that the pedestrian was able to find sufficient gaps to cross. The 1-min/lane volume count was less than 4 vehicles/min for the majority of these crossings. An examination of departures on the dark indication revealed that pedestrians were more likely to depart on dark at coordinated sites compared to hot-button sites (13 versus 7 percent), but departures on dark were much less frequent at the coordinated site that had pushbuttons with red lights that illuminated when the button was pressed. The coordinated site with the red-lighted buttons had 10 percent of pedestrians departing on dark, while the coordinated site with the non-lighted buttons had 20 percent of pedestrians departing on dark.

Of the 1,979 arriving pedestrians, 290 were research team members who always activated the PHB. For the remaining 1,689 general public pedestrians, 157 did not push the button because the PHB was already active. For those who arrived when the PHB was not active, 91 percent pushed the button and activated the PHB. A review of the data by site characteristics shows trends for the highest values. A greater number of pedestrians activated the device when on 45-mi/h posted speed limit roads as compared to 40 mi/h or less roads. The percentage of pedestrians pushing the button was always greater than 80 percent for the longer crossing distances (longer than 110 ft). When the hourly volume for both approaches was 1,500 vehicles/h or more, the percent of pedestrians activating the PHB was always 90 percent or more.

All occurrences of pedestrian/vehicle conflicts and erratic maneuvers were noted when observed in the video footage. The conflict rate was found to be higher for non-compliant pedestrians than for compliant pedestrians. Slightly less than half of the observed conflicts occurred during the dark beacon indication and involved a through vehicle. These conflicts usually involved pedestrians who either crossed without pushing the button or pushed the button but did not wait for their walk indication and then paused in the raised-curb median while crossing.

Notable conflict rates for both compliant and non-compliant pedestrians were observed at several sites where the PHBs were located near supermarkets and multiple bus stops. At these sites, many bus riders would walk through the supermarket parking lots or run across the major street while transferring between bus lines. The presence of bus stops near access points with significant turning vehicle volumes tended to result in higher conflict rates.

Discussion

The PHB has shown great potential in improving safety. It is also associated with less delay for the major roadway as compared to a full TCS because of the PHB's flashing red indication that permits stop-and-go operations if the pedestrians have finished crossing their half of the roadway.

Experience of city traffic engineers has indicated that drivers did not understand that they can start the stop-and-go operations once the crosswalk is clear. In response to this need, a sign was created and has been installed in several cities. FHWA now recommends that a slightly different wording be used on such a sign (see figure 58 for an example).

The results from this research have shown, however, that drivers are not always stopping on the flashing red before proceeding through the cleared crossing. In about half of the actuations where a queue existed on the approach, at least one of the drivers in the queue did not come to a complete stop before driving through the crossing. A small number of drivers (about 5 percent) was observed staying stopped on the flashing red indication, sometimes when it would have been clear to proceed, but often because pedestrians were still crossing or conflicting minor movement vehicles were occupying the intersection.

Within the 78 h of video data reviewed, conflicts were observed with most of the conflicts associated with non-compliant pedestrians. Several conflicts were observed at a site with a nearby access point (e.g., driveway), which could indicate that access points should be limited within a certain distance to the PHB, especially if they serve major traffic generators. Additional research is needed to determine the distance(s) access points should be restricted. The research should also consider the type of access point or the anticipated volume from the access point as well as proximity to bus stops where pedestrians may be making transfers between bus lines.

Most of the PHB sites included in this study were at intersections or major driveways. Including midblock sites was a priority for the study, and four locations were identified. The midblock PHBs had driveways/intersections that were within 80 ft of the PHB. All of these sites were in Austin, TX. Conflicts were not counted at two of these sites because of minimal cross street volume or restricted movements (e.g., right in/right out turns only). For the other two sites, 1 had minimal conflicts, but the remaining site had 11 conflicts. Examination of the video footage revealed that the conflicts at this site occurred when left-turning drivers departed a major traffic generator and did not have adequate space on the major street to complete the turning maneuver before encountering the midblock crosswalk. This site did not have a median, so the back-left corner of the turning vehicles were still in the opposing through lanes when the vehicles were stopped in the diagonal position. The drivers wanted to move out of their awkward position (diagonal, partly encroaching on opposing through lanes) and sometimes encroached on pedestrians in the crosswalk while doing so. Hence, guidance for the placement of PHBs and/or access points near PHBs needed to account for turning vehicle paths.

While drivers stopping at a dark PHB were observed, it did not appear that the stopping was caused by a driver being confused with the dark device. Rather, drivers stopped because of congestion from a nearby driveway or intersection or because of crossing pedestrians or stopped buses.

This study identified high driver yielding (greater than 94 percent) for the site with the widest crossing and the site with the 45-mi/h posted speed limit. This finding, along with findings from previous studies and the overall high yielding for PHBs identified in this research (overall 96 percent), supports the use of this device at a variety of locations, including on high-speed and wide roads, at residential intersections, and elsewhere.[29,33]

FUTURE RESEARCH NEEDS

While several research studies have examined the effectiveness of the RRFB and the PHB, many research needs remain, as presented in this section. Several of these ideas were presented in a previous FHWA report but are included here for completeness.[5]

Based on the research conducted as part of this study, along with discussions held at professional society meetings and with other practitioners, additional research questions regarding RRFBs used at pedestrian crossings are as follows:

- **Appropriate brightness level of RRFBs**: The brightness of the RRFBs can help draw a driver's attention to a device and the area around the device. It can also result in drivers looking away from the device because the brightness is irritating or unbearable. When the discomfort glare is unbearable, drivers are more likely to divert their eyes away from the discomfort, which might result in drivers missing people or objects located near the glare source. Recommendations are needed for a maximum brightness for beacons used with pedestrian crossing signs and for other traffic control devices with embedded LEDs or supplemental beacons. The maximum brightness should vary between daytime and nighttime conditions.

- **When RRFBs should be dimmed and by how much**: Guidance is needed on whether to dim these devices during low light conditions and, if so, by how much. A study of disability glare and discomfort glare in both bright and dark conditions can be used to determine appropriate maximum nighttime and daytime brightness for RRFB. The investigation into brightness levels should consider an open-road portion to be able to associate different motorist yielding behavior with the different brightness levels.

- **Appropriate use of RRFB assemblies on only one side of the roadway approach**: The original IA for the RRFB requires the assembly to be located on the right-hand and left-hand sides of the roadway. There may be street widths where having two assemblies provides limited benefits. If so, the additional cost savings in purchasing and maintaining fewer devices at a site could provide additional resources to treat other locations.

- **Appropriate installation of RRFB assemblies overhead rather than on the roadside**: FHWA issued an interpretation in 2009 that indicated overhead mounting is appropriate and that if overhead mounting is used, a minimum of only one sign per approach is required, and it should be located over the approximate center of the lanes of the approach.(6) Presence of buses and street width are two examples of site conditions where RRFBs could be installed overhead rather than roadside, but there might be other criteria that should be considered when making this decision. In addition to identifying the applicable criteria, developing numeric guidance for these criteria is also needed (e.g., at what roadway width should overhead rather than roadside installation be considered). The guidance might also need to consider additional variables beyond primary characteristics such as roadway width. For example, if the sidewalks at the site are adjacent to the face of curb, then the roadside assembly might need to be located more than 5 ft from the curb, which would place the assembly beyond the driver's cone of vision. The research would need to consider if placing the beacons above the sign would satisfy some of the concerns expressed in this research idea discussion. This research effort may also need to consider if larger beacons are needed for overhead application along with some adjustments to direct them to the approaching driver since many LEDs are directional.

- **Identification of roadway and traffic variables that influence driver yielding**: This research would examine the relationship between driver yielding rate and geometric and/or traffic variables. Additional research is needed to identify what characteristics are influential so that the characteristics (e.g., better enforcement or overall street design) of those communities with higher driver yielding could be reproduced.

- **Identification of optimal use of signing and pavement markings at pedestrian crossings**: This research would examine how signing can be used to improve a pedestrian crossing. Types of signs at some pedestrian crosswalks include warning signs used in advance of the crossing (sometimes with flashing beacon), signs at the yield or stop bar of the crossing to inform drivers of the appropriate place to stop, and signs at the crosswalk on the mast arm structure or roadside. Examples of signs being used at the crossing include regulatory signs such as the crosswalk stop on red [ball] and internally illuminated signs that say PEDESTRIAN CROSSING. Research questions could include (1) do the signs influence drivers' alertness at the crossing, (2) do the signs help to communicate the likelihood that a pedestrian will be at the crossing, or (3) how long are signs needed that provide information on stop-and-go behavior.

- **How driver yielding for LED-embedded pedestrian crossing signs compares to RRFBs**: Another flashing pedestrian treatment is signs with LEDs embedded into the sign face. The performance of this treatment as measured by driver yielding is needed.

Research needs associated with the PHB include the following:

- **Optimal location of the PHB.** At some sites, a logical place for a PHB is near a bus stop or other major traffic generator that may not be at a street intersection or a major driveway. At one of the sites in this research project, several conflicts were observed between vehicles and pedestrians with the vehicles turning in and out of a nearby driveway contributing to several of the conflicts. This research would examine tradeoffs for locating the PHB near a major access point. These tradeoffs may include changes in crosswalk utilization, pedestrian compliance, or conflict rate. A range of pedestrian volumes, access point volumes, and distances between crosswalk and access point should be considered along with identifying alternative treatments such as restricting some turning movements at the access point.

- **Pedestrian compliance at coordinated PHBs**: PHBs can be programmed to begin service to pedestrians instantly upon actuation (i.e., hot-button operation) or to begin service in coordination with adjacent traffic signals. Compared to instant service PHB operation, coordinated PHB operation reduces vehicular delay by preserving progression bandwidth and avoiding stopping the platoon of major street vehicles. However, a pedestrian actuating a coordinated PHB will often see delayed service and may conclude that the device is malfunctioning and then cross the street without the assistance and protection of the device. Research is needed to quantify pedestrian compliance trends as they are influenced by PHB operational mode (instant service versus coordinated), vehicular volumes, provision of visual or auditory feedback/guidance devices for waiting pedestrians (e.g., small indicator lights above the pushbutton that illuminate upon pressing), and other site characteristics. This insight would be used to formulate guidance on choosing between coordinated and instant service mode for a PHB.

- **PHBs within signal system**: Research is needed to determine the optimal background cycle length for a PHB (e.g., what should be the minimal major street green time between subsequent PHB activations?). The study could also investigate the minimum separation between a PHB and a signal that will allow a roadway to operate adequately. Investigate how that separation distance should change for various roadway features such as width of roadways.

- **BikeHAWK**: Research is needed to evaluate modifications to the PHB that can better accommodate bicyclist crossings along with pedestrians. Tucson, AZ, has developed a modified PHB called BikeHAWK, but there is a concern with the potential for late entry by bicyclists. Even though there is an R9-5 sign that instructs bicyclists to use the pedestrian signal, it is not known whether bicyclists know that there is a flashing red during the countdown. Even though the bicyclist can cross in the remaining time, a motor vehicle may be proceeding through the crossing. Other issues also exist in attempting to modify a PHB to better accommodate bicyclists along with pedestrians.

Other research needs for pedestrian treatments include the following:

- **Guidance on selection of appropriate pedestrian crossing treatment for a particular location**: In general, the PHB has higher yielding rates but costs more than RRFB assembly. The RRFB is more effective than many other pedestrian treatments; however, a Texas study found lower compliance for the RRFB for longer crossing distances.[35] This finding indicates that there is a crossing distance width for which a device other than the RRFB should be considered. The dataset included sites with total crossing distances that ranged between 38 and 120 ft. A research study with an objective of developing guidelines for selecting appropriate pedestrian crossing treatments would help to improve uniformity across the country. The study would also need to identify the site conditions that should be considered (e.g., roadway volume, pedestrian volume, crossing distance, posted speed limit, typical pedestrian walking speed at the site, etc.).

- **Minimum number of pedestrians to justify a pedestrian treatment**: There is a growing use of the PHB and the RRFB for pedestrian crossings. Establishing guidance that can be consistently applied would help to facilitate use of these devices in appropriate settings. A particular question is whether there is a minimum number of pedestrians before a device should be considered. The MUTCD contains graphs that illustrate when to consider a PHB, and these graphs include a minimum of 20 pedestrians/h.[1] When deciding to recommend this minimum pedestrian number, the NCUTCD based its decision on a value developed through engineering judgment during an FHWA study on whether to mark crosswalks.[51] Research is needed to more fully consider what should be the minimum pedestrian value used for selecting various traffic control devices. For example, should this minimum number be a function of crossing distance or posted speed limit? In addition, should it consider the distance to the nearest crossing? A location that is only a few hundred feet from an established crossing should have a higher minimum number compared with a crossing that is more than one-fourth or one-half of a mile from a signal on a wide high-speed arterial.

- **Number of pedestrians induced as a result of installation of selected pedestrian treatments**: The primary objective of this study would be to determine reasonable values for estimates of latent pedestrian crossing demand (i.e., estimated number of pedestrians that would now use the site because of the installation of a specific pedestrian treatment). The results of the research could improve the process for selecting pedestrian treatments. The research should make appropriate suggestions for changes to key reference documents, such as design manuals or the MUTCD.[1] Improved guidance should help to improve conditions for pedestrians by identifying appropriate devices for crossings, which should improve pedestrian mobility and reduce the number of pedestrian crashes.

- **Drivers’ search patterns near flashing beacons**: There was evidence in this study that the closed-course drivers were more accurate in seeing objects beyond the signs with flashing beacons compared with seeing objects beyond the distractor signs. This could be an artifact of this study or it could be because the flashing beacons attracted the eye to the area. Additional research could focus on drivers’ search patterns when a flashing beacon is present to test the theory that the presence of the beacons or LEDs encourages drivers to search a particular area. By varying the brightness of the beacons along with the light source (e.g., beacons or LED-embedded signs), the study could also investigate whether drivers need additional time to search an area because of the brightness of the device.

- **Pedestrians' attitudes toward using treatments**: Observations of pedestrians in the open-road portion of this study (and in other studies) have documented crossing pedestrians that did not activate the beacon treatments when they were provided. Some of those pedestrians were not within the treated crosswalk to be able to use the beacon, while others crossed at the crosswalk but chose not to activate the beacon. This study would explore pedestrian decisionmaking and examine why pedestrians who have the opportunity to use a treatment (such as an RRFB) to support their crossing choose not to do so. For example, at crosswalks marked as school crossings, do adult pedestrians think that the treatment is for use only by schoolchildren? Results from this study could feed into the suggested educational campaign mentioned previously, and results could also be used to support guidance on where treatments should be installed and what information (e.g., instructional plaques next to the pushbutton) should be provided to crossing pedestrians.

- **Estimating pedestrian exposure**: With ADT being the key predictor of vehicle crashes, there is a desire to have similar types of data for pedestrians. With limited resources for collecting counts—vehicle, bicycles, or pedestrians—researchers could study what are the most effective means for obtaining pedestrian exposure.

- **Distance between crossings**: How far will a pedestrian be willing to walk to reach a crossing with a pedestrian treatment? How does that distance change based on the treatment type (e.g., PHB versus crosswalk markings only), on the presence of a median, on the posted speed limit of the major street, and other factors that influence pedestrians walking behavior? These are all questions that could be investigated with further studies.

- **National education campaign on the RRFBs and/or PHBs**: Research is needed to determine what education campaigns have been used by cities and jurisdictions that have implemented RRFBs and whether they were successful. For example, are there common themes that could be used on a national level? The campaigns could also include other considerations of pedestrian behaviors such as the need to activate the pushbutton as well as cautions against distracted walking and walking during nighttime conditions, blind spots around commercial vehicles, and others. Education campaigns could be directed toward drivers, pedestrians, or both. The portion of the campaign could be directed to police who have to enforce the device to provide them with information on what is and is not a violation within their State laws.

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