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Evaluation of Pedestrian Hybrid Beacons on Arizona Highways

Arizona Department of Transportation Research Center

ADOT

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The pedestrian hybrid beacon (PHB) is a traffic control device used at pedestrian crossings. It was first included in the 2009 Manual on Uniform Traffic Control Devices. The focus of this Arizona Department of Transportation (ADOT) research was to: investigate the safety and operational impacts of the PHB installations that have occurred on Arizona's state highways (higher-speed roads) to understand their impacts on vehicles and pedestrians; investigate the relationship between crashes at PHB locations and the spacing from nearby signalized intersections; investigate the relationship between crashes at PHB locations and other roadway characteristics; and determine whether modifications to ADOT guidance are needed to advise ADOT on site selection and use of PHBs.

While the PHB has shown considerable potential in improving pedestrian safety and driver yielding, questions arose about whether the device performs at a similar level on higher-speed roads. This study selected 10 Arizona locations representing higher-operating-speed conditions (85th-percentile speed ranging between 44 and 54 mph). The final dataset reflected about 40 hours of video data and included 1,214 pedestrians or bicyclists crossing at PHBs. Overall, driver yielding for the 10 sites averaged 97 percent. This study's safety evaluation covered 343 sites— 186 PHBs along with 56 signalized intersections and 101 unsignalized intersections used for comparison purposes. Previous studies found a safety benefit with the installation of PHBs, and this study supports that finding. Crash reductions were found for severe crashes (25 percent), pedestrian crashes (46 percent), severe rear-end crashes (29 percent), and various other crash types. The study developed recommendations for ADOT's guidance in locating, designing, and operating PHBs on Arizona roadways.</td></tr>
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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AADT	Annual average daily traffic
ADOT	Arizona Department of Transportation
ADT	Average daily traffic
APS	Accessible pedestrian signal
CMF	Crash modification factor
DDOT	District Department of Transportation (District of Columbia)
EB	Empirical Bayes
FDW	Flashing DON'T WALK
FHWA	Federal Highway Administration
FI	Fatal and injury
HAWK	**H**igh-intensity **A**ctivated cross**W**al**k**
ITE	Institute of Transportation Engineers
LED	Light-emitting diode
MAG	Maricopa Association of Governments
MOAS	*Manual of Approved Signs*
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
PAG	Pima Association of Governments
PDO	Property damage only
PHB	Pedestrian hybrid beacon
pph	Pedestrian crossings per hour
RRFB	Rectangular rapid flashing beacons
RTM	Regression to the mean
SPF	Safety performance function

STEP	Safe Transportation for Every Pedestrian
TCS	Traffic control signal
TGP	*Traffic Engineering Guidelines and Processes*
TWLTL	Two-way left-turn lane

EXECUTIVE SUMMARY

BACKGROUND

The pedestrian hybrid beacon (PHB) is a traffic control device used at pedestrian crossings. It was first included in the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) and was based on the HAWK (**H**igh-intensity **A**ctivated cross**W**al**k)** beacon developed in Tucson, Arizona. The focus of this Arizona Department of Transportation (ADOT) research effort was to:

- Investigate the safety and operational impacts of the PHB installations that have occurred on Arizona's state highways (including higher-speed roads) to understand their impacts on vehicles and pedestrians.
- Investigate the relationship between crashes at PHB locations and the spacing from nearby signalized intersections.
- Investigate the relationship between crashes at PHB locations and other roadway characteristics.
- Determine, based on the findings, whether modifications are needed to Section 640 of ADOT's *Traffic Engineering Guidelines and Processes* (TGP 640).

The PHB has shown considerable potential for improving pedestrian safety and driver yielding. While previous studies have proven the effectiveness of PHBs, questions on the effect of PHBs on higher-speed roads and on rear-end crashes or severe crashes for all road types had not been fully addressed because of limited sample size.

OPERATIONS

Ten locations in Arizona representing higher-operating-speed conditions (85th-percentile speed ranging between 44 and 54 mph) were selected for inclusion in this study. The final dataset reflected about 40 hours of video data and included 1,214 pedestrians or bicyclists crossing at PHBs.

Overall, driver yielding for these 10 sites averaged 97 percent (see Table 1). In a 2016 Federal Highway Administration (FHWA) study, data were collected at 20 sites where the posted speed limit ranged between 30 and 45 mph. That study found an overall yield rate of 96 percent with per-site yield rates ranging between 87 percent and 100 percent. The FHWA study included 12 sites in Tucson, Arizona, and eight sites in Austin, Texas. The average driver-yielding rate for the 12 Arizona sites was 97 percent. The current ADOT study that focused on higher-speed roads (posted 45 to 50 mph) found a similar driver-yielding rate (97 percent) as observed on lower-speed roads. This finding shows that the PHB also operates well on higher-speed roads posted up to 50 mph.

While drivers are yielding to pedestrians in most cases, they are not as compliant with the traffic control device. Only 90 percent of the drivers stopped and stayed stopped until the end of the steady red indication. During the flashing red indication, about 59 percent of the drivers rolled through the intersection without stopping initially. Most of those rolling stops occurred during the queue discharge after the pedestrian had completed the crossing maneuver.

Actual (non-staged) pedestrians and bicyclists were preferred in the data collection efforts, but at sites where pedestrian volumes were low, members of the research team conducted staged crossings to obtain a larger sample of motorist behavior data. A large proportion of the non-staged pedestrians and bicyclists observed activated the PHB or crossed when the device was operational. At a few sites, many pedestrians and bicyclists crossed without activating the PHB. These sites had large gaps where the pedestrian or bicyclist was able to cross without affecting the major-road traffic. The percent of the pedestrians and bicyclists observed using the pedestrian pushbutton was only 66 percent, which reflects the large number of pedestrians and bicyclists using the large vehicle gaps for their crossings. The 2016 FHWA study found that a greater number of pedestrians activated the device when on 45-mph posted speed limit roads than on 40-mph or less roads. The study also found that when the hourly volume for both approaches was 1,500 vehicles per hour or more, the percent of pedestrians activating the PHB was always 90 percent or more.

Table 1. Driver Yielding Rates by Site.

Site	City	Posted Speed Limit (mph)	85th Percentile Speed (mph)	Number of Vehicles [a]	Driver Yield Rate [b]
BH-01	Bullhead City (ADOT)	45	47	274	96%
GI-03	Gilbert	45	44	290	93%
PH-33	Phoenix	45	53	265	100%
SD-02	Scottsdale	50	53	133	95%
SD-03	Scottsdale	50	54	208	93%
SV-01	Sierra Vista (ADOT)	45	48	199	99%
TP-01	Tempe	45	Not available	294	99%
TU-089	Pima County	40	50	295	100%
TU-124	Tucson	45	48	275	99%
TU-129	Tucson	50	54	93	100%
All sites				2,326	97%

[a] Number of Vehicles = total number of vehicles that approached the crossing pedestrians and bicyclists.
[b] Driver yield rate = percent of approaching drivers who should have yielded and did so.

SAFETY

The safety analysis from this study included 343 sites, which consisted of 186 PHBs, 56 signalized intersections, and 101 unsignalized intersections. Installation dates were obtained for the PHBs from the various government agencies, and 52 PHBs that were installed between 2011 and 2015 were identified for use in the before-after empirical Bayes (EB) analysis. Reference groups consisting of signalized and unsignalized intersections were chosen from intersections in close proximity to the 52 before-after PHB sites and were used in the EB before-after analysis.

The safety performance of PHBs could be compared only to unsignalized intersections or to both unsignalized and signalized intersections. In most cases, a PHB is installed at an intersection that previously was unsignalized; however, in some cases, the PHB replaces a traffic control signal (TCS). The level of pedestrian activity at a PHB intersection is more similar to signalized than unsignalized intersections; therefore, comparing PHBs to signalized intersections may be more valid.

Each reference group has potential limitations; therefore, the research team considered three different reference groups: unsignalized intersections, signalized intersections, and both unsignalized and signalized intersections combined.

For the signalized and combined unsignalized and signalized intersection groups, all crash types considered showed statistically significant reductions in crash frequency (e.g., total crashes, fatal and injury crashes, rear-end crashes, fatal and injury rear-end crashes, angle crashes, fatal and injury angle crashes, pedestrian-related crashes, and fatal and injury pedestrian-related crashes). Previous studies found a safety benefit with the installation of a PHB, and this study supports that finding (see Table 2).

Table 2. Results of EB Before-After Safety Evaluations Based on 52 PHB Sites Using Unsignalized Intersections and Signalized Intersections as a Reference Group.

Crash Type	Percent Crash Reduction at PHBs
Total	18.2**
Fatal and injury	25.2**
Pedestrian related	45.7**
Fatal and injury pedestrian related	45.0**
Rear end	20.5**
Fatal and injury rear end	28.6**
Angle	22.6**
Fatal and injury angle	24.5*

Statistical level indications:
* Statistically significant results with 90 percent confidence level
** Statistically significant results with 95 percent confidence level

A cross-sectional study was conducted with a larger number of PHBs to identify relationships between roadway characteristics and crashes at PHB sites, especially with respect to the distance between a TCS and a PHB. The cross-sectional study could include more PHB sites because crash data before the installation of the PHB were not needed; therefore, more of the older installations (prior to 2011) could be considered.

For total crashes, the roadway geometry variables that have a relationship to crash frequency at PHBs include the number of lanes on the major roadway, median treatment, bike lane presence, and number of lanes on the cross street. These relationships are as expected, with more lanes on either the major or cross street being associated with more crashes, and with the presence of a raised median or pedestrian refuge island being associated with fewer crashes. The presence of a bike lane at the PHB being associated with fewer total crashes is a desirable finding. Several studies have documented the benefit of a raised median/refuge island for pedestrians, and this ADOT study supports that finding. The distance to an adjacent traffic signal variable only remained in the total rear-end and fatal and injury rear-end crash type models where it was significant at the 0.1 level (rather than the 0.05 level). When reviewing the magnitude of the effect on rear-end crashes, the distance between TCS and PHB is less influential than median presence or speed limit groups (35 mph or less versus 40 mph or more).

This ADOT study included a larger number of sites and a larger number of months of before and after data than other recent studies, which aided in the ability to provide statistically significant results. Crash reductions were found to be significant at the 0.05 significance level for total crashes, fatal and injury crashes, fatal and injury rear-end crashes, and pedestrian-related crashes regardless of the reference group considered. Other crash types were also associated with significant reductions depending on the reference group being used and statistical significance level being accepted.

RECOMMENDATIONS

As discussed in the final chapter of this report, the research team used this study's findings to develop detailed recommendations regarding the design and operation of PHBs on Arizona roadways. Further discussion is available in the study's technical memorandum on recommendations.

- Section 640 of the ADOT *Traffic Engineering Guidelines and Processes* (TGP 640) provides guidance on the evaluation of candidate locations for installing PHBs. The following are recommended changes to the TGP 640:
    - Add direction to first consult with the FHWA Safe Transportation for Every Pedestrian (STEP) Guide or the Arizona-specific STEP guide when determining if a location is suitable for a PHB or for an alternate crossing treatment.
    - Revise the PHB application consideration based on the posted speed limit by raising the accepted speed limit to 50 mph.
    - Expand the evaluation criteria in Exhibit 640-A for PHB locations.
    - Add information for potential consideration of latent crossing demand as criteria for a PHB.
- To encourage consistency in PHB design, the research team recommended developing a PHB standard drawing and outlined specifics to address.
- Consider two-stage PHB crossings when wide raised medians, sufficient to accommodate expected number of pedestrians, either exist or can be installed. Note accordingly to the standard drawing once it is developed.
- Consider developing separate design and guidelines to implement the concept of side-by-side pedestrian/bicyclist crossings at busy multi-use trails crossing state highways.
- To complement the primary standards, guidance, and options for the operation of PHBs contained in the MUTCD and the Arizona Supplement within Sections 4F.02 and 4F.03, the research team suggested adding extensive operational guidance to the TGP 640, making it more useful as a full set of guidelines.
- Additional research may determine under what circumstances it is desirable to synchronize PHBs with the adjacent traffic signals to avoid unnecessarily stopping motorists at the signal or the PHB crossing; unnecessary stops might cause more red-light violations or rear-end crashes at either the signal or the PHB.
- Research is also suggested for determining how to best educate drivers, pedestrians, and bicyclists on the appropriate use of and response to PHBs.

CHAPTER 1: INTRODUCTION

BACKGROUND

Pedestrian hybrid beacons (PHBs) were developed in Tucson, Arizona, by Dr. Richard Nassi starting in 2000. Through research and safety evaluation, this traffic control device was approved for optional use in the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) in Chapter 4F (Federal Highway Administration [FHWA] 2009). Arizona adopted the 2009 MUTCD with an Arizona Supplement via Department Directive 12-01 on January 13, 2012. The Arizona Supplement (Arizona Department of Transportation [ADOT] 2012) included a number of changes to Chapter 4F from the federal manual. One such change is the Option statement in Section 4F.01 of the Arizona Supplement, paragraph 02, which states: "Agencies may develop warrants or guidelines for the installation of Pedestrian Hybrid Beacons on roadways under their jurisdiction."

Section 640 of ADOT's *Traffic Engineering Guidelines and Processes,* referred to as TGP 640*,* (ADOT 2015) provides guidance on the evaluation of candidate locations for the use of PHBs, with the most recent update in June 2015. TGP 640 includes general guidance about the design and operation of PHBs in the following two statements:

> If used, PHBs shall be used in conjunction with signs and pavement markings to warn and control traffic at locations where pedestrians enter or cross a street or highway. A PHB shall only be installed at a marked crosswalk.
>
> The design and operation of pedestrian hybrid beacons should follow the guidelines set forth in the MUTCD.

There are no known standard details for the design of PHBs or operational guidance known to exist within ADOT outside of TGP 640 and the Arizona Supplement to the MUTCD. The only known ADOT standard drawing relating to PHBs is T.S. 8-5, Flashing Beacon Signal Face Assembly (last updated in January 2012), which includes a standard drawing for PHB faces. This standard drawing provides for square backplates and requires the use of a 2-inch fluorescent yellow prismatic ASTM D4956 Type VIII retroreflective border around the entire perimeter of the backplate. The Arizona *Manual of Approved Signs* (MOAS) also includes an Arizona-modified R10-23AZ sign that is currently required to be used with all PHBs (note that the sign code is the designation from the MUTCD Arizona Supplement). The Arizona modification to the CROSSWALK STOP ON RED sign eliminates the symbolic circular red ball from the sign. The National Committee on Uniform Traffic Control Devices on January 10, 2019, recommended to FHWA that the R10-23 sign be optional in the next edition of the MUTCD (NCUTCD 2019).

OBJECTIVES OF STUDY

The goal of this project was to evaluate the effects PHBs have on safety and operations. Specifically, the objectives were to:

- Investigate the safety and operational impacts of the PHB installations that have occurred on Arizona's state highways (including higher-speed roads) to understand their impacts on vehicles and pedestrians.
- Investigate the relationship between crashes at PHB locations and the spacing from nearby signalized intersections.
- Investigate the relationship between crashes at PHB locations and other roadway characteristics.
- Determine whether modifications to ADOT TGP 640 are needed based upon findings from the previous objectives.

STUDY APPROACH

To accomplish the goals and objectives of this study, the research team conducted the following efforts:

- Reviewed previous research studies
- Gathered design, PHB application/location criteria, and operational guidelines from other agencies that have implemented multiple PHBs
- Identified and selected study sites, identified relevant measures of operational effectiveness, and collected and analyzed the field data needed to quantify these measures
- Conducted a safety analysis that investigated changes in crash frequency, severity, and crash types (e.g., rear-end crashes) due to PHB presence, as well as in crashes involving pedestrians and bicyclists
- Made recommendations on revisions to the selection, design, and/or operation of PHBs and refinements to Arizona guidelines for evaluating, installing, and operating PHBs on state highways including suggestions on modifications to existing state documents (TGP 640, standard details, etc.) using the research findings from previous tasks
- Developed an implementation plan for ADOT to update its reference documents and implement the findings from this research

CHAPTER 2: EXISTING PRACTICES

LITERATURE REVIEW

Driver Yielding

A recent FHWA study (Fitzpatrick et al. 2016) explored questions about driver and pedestrian behavior at existing PHBs. A developed dataset, reflecting over 78 hours of video data recorded at 20 locations in Austin, Texas, and Tucson, Arizona, included 1,979 pedestrians crossing during 1,149 PHB actuations. Driver yielding to pedestrians averaged 96 percent, indicating that in almost all crossings, drivers are appropriately yielding to the crossing pedestrians.

In a 2006 study, drivers yielding at five PHBs (known as the high-intensity activated crosswalk beacon [HAWK] at the time of the study) had an average driver yielding rate of 97 percent (Fitzpatrick et al. 2006). For the sites included in the study, the number of lanes (two, four, or six lanes) did not affect driver performance. The driver yielding was very high compared to the other pedestrian devices included for the speed limits (either 35 or 40 mph) and intersection configurations (four-leg, T, offset T, or midblock crossings) represented in the dataset.

A Texas Department of Transportation study (Fitzpatrick et al. 2013) explored the factors associated with driver yielding at pedestrian crossings with TCSs, PHBs, and rectangular rapid flashing beacons (RRFBs) in Texas. Members of the research team conducted staged crossings to obtain a consistent sample of motorist behavior data. The percentages of drivers yielding to a staged pedestrian were collected at 7 TCS sites, 22 RRFB sites, and 32 PHB sites. Overall, TCSs in Texas have the highest driver yielding rates with an average of 98 percent. The average driver yielding for RRFBs in Texas was 86 percent, while the average for PHBs was 89 percent. 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 for the PHB and Garland for the RRFB) had higher driver yielding rates than cities where the device was only used at a few crossings. Comparing the number of days since installation revealed statistically significantly higher driver yielding rates for those PHBs that had been installed longer. The authors concluded, based on the statistical evaluation of the 32 PHB sites, that the results support the use of the PHB on roadways with multiple lanes or a wide crossing. For RRFBs, lower compliance was observed for the longer crossing distances, which indicates a crossing distance where a device other than the RRFB may be considered.

A study of three PHB installations in Charlotte, North Carolina, (Pulugurtha and Self 2015) found an increase in the number of motorists yielding to pedestrians. Because the authors collected data for several periods after installation, they were able to conclude that improvements seem to be relatively more consistent three months after the installation of the PHB; in other words, it may take three months for pedestrians and motorists to adapt to the new device.

A 2018 paper reported on a Georgia study (Bolen et al. 2018) where driver yielding at four PHB sites was measured. The posted speed limit was 35 mph for one of the sites and 30 mph for the other three sites. Data were collected during morning peak, evening peak, and weekend high-volume periods using video.

The authors found between 75 and 84 percent of the drivers stopped and yielded to crossing pedestrians. The authors note that these results were lower than expected and lower than past studies. They theorized that part of the reason could be that a high number of vehicles that initially stopped for pedestrians but then proceeded into the crosswalk too early were counted as non-stopping vehicles.

An installation in San Antonio (Brewer et al. 2015) resulted in yielding going from 0 (no drivers yielding to staged pedestrians in 39 crossing attempts) to 95 percent for 60 staged pedestrian crossings. An increase in the number of non-staged pedestrian crossings was observed after the PHB was installed.

Pedestrians Activating the PHB

The 2016 FHWA study (Fitzpatrick et al. 2016) identified the percentage of pedestrians who activated the PHB upon arriving at the crossing when the PHB was not already active. A high number of pedestrians (93 percent) activated the device on the 45-mph posted speed limit road. For the 40-mph or less roads, a large range of actuation was observed—between 75 and 100 percent. The percent pushing the button was always greater than 83 percent for the longer crossing distances (greater than 110 ft). The 1-min vehicle 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 count was adjusted to an hourly equivalent value by multiplying by 60. When the equivalent hourly volume is 1500 veh/hr or more, the percent of pedestrians activating the PHB is always 92 percent or more.

Vehicle Delay and PHB

One of the benefits of the PHB to vehicle operations is the ability for drivers to proceed during the flashing red portion of the cycle if the crosswalk is clear. A study by Godavarthy and Russell (2016) determined whether the motorist delay was decreased at a PHB by comparing the operations at two PHB midblock locations to that at a signalized midblock site in Lawrence, Kansas. More than 90 percent reduction in delay was observed for drivers at the PHB at midblock crossings compared to the signalized crossing.

SAFETY FINDINGS

In a 2010 FHWA study (Fitzpatrick and Park 2010), researchers conducted a before-and-after evaluation of the safety performance of the HAWK, now known as the PHB. Using an empirical Bayes (EB) method, their evaluations compared the observed crash frequency after installation of the treatment (PHB) to the EB estimate of the expected crash frequency for the same after period without the treatment (the counterfactual crash frequency obtained as a combination of the observed crash frequency for the before period, prediction from the safety performance function [SPF], and an adjustment factor that accounts for time trends and traffic volume changes between before and after periods). To develop the datasets used in the evaluation, researchers counted the crashes occurring three years before and up to three years after the installation of the PHB. The crash categories examined in the study included total, severe injury, 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)

A 2017 National Cooperative Highway Research Program (NCHRP) report (Zegeer et al. 2017a) and paper (Zegeer et al. 2017 b) investigated the safety effectiveness of the PHB and developed crash modification factors (CMFs) as shown in Table 3.

Table 3. Recommended CMFs from NCHRP Study (Zegeer et al. 2017b).

Treatment	Crash Type	Estimate	Standard Error	Study Basis
PHB	Pedestrian	0.453	0.167	Median from two studies
PHB and advance yield or stop pavement markings and signs	Pedestrian	0.432	0.134	Median from two studies
	Total	0.820	0.078	Before-after
	Rear-end sideswipe total	0.876	0.111	Before-after

Source: Portions of Table 2 in "Development of Crash Modification Factors for Uncontrolled Pedestrian Crossing Treatments" (Zegeer et al. 2017b).

STATE AGENCY GUIDELINES

Agencies in Arizona and several other states were contacted to provide standards, guidelines, and current practices on aspects of PHBs. The research team received 37 survey responses, representing 34 agencies. The highest number of responses were from state departments of transportation with 17 responses. Thirteen city/town agencies and four county agencies responded to the survey as did one consultant who worked for various governmental agencies. Seven agencies reported installing between 10 and 34 (or more) PHBs. An effort was made to contact the seven agencies to obtain additional information on their current practices.

The survey asked if there were certain conditions where a PHB would **not** be used. Of the agency respondents who reported that they currently operate at least one PHB, the following responses were provided (multiple responses were allowed) where a PHB will **not** be used by their agency:

- At an intersection (9 responses)
- Within 500 ft of an existing traffic signal (9 responses)
- High-speed roads (8 responses)
- Rural roads (4 responses)
- Within 300 ft of an existing traffic signal (3 responses)
- Within 100 ft of a railroad grade crossing (1 response)
- On crossings of two-lane roads (2 responses)

Three respondents reported not having any restrictions on the use of PHBs based on the choices listed on the survey form.

The District Department of Transportation (DDOT) in Washington, D.C., reported that it synchronizes all PHBs with adjacent traffic signals along the corridor because that was a requirement for use. Furthermore, DDOT reported that a PHB in Washington, D.C., uses the same standards as a signal in terms of ramp design, signal pole location and style, and crosswalk markings (DDOT typically marks both crosswalks at an intersection, although some T intersections only have one crosswalk marked). On the other hand, the advance stop line is placed 20 ft in advance of the PHB indications, which are all side mounts in Washington, D.C. DDOT further does not use a minimum green time between subsequent PHB activations.

Some of the responding agency representatives reported they are currently working on developing guidelines for PHB application and design and were seeking guidance from other sources. Only one agency reported information about streetlights and stated, "Streetlights must be included at the crossing if not already in the immediate area." This is not to indicate that streetlights are not used for PHBs in other agencies, but no other respondent specifically mentioned the use of streetlights.

LOCAL AGENCIES' GUIDELINES AND PRACTICES

The PHB was based on the HAWK device that was developed and field-tested in Tucson, Arizona, under the provisions for experimentation contained in the MUTCD, which resulted in its adoption in the 2009 MUTCD. The City of Tucson likely has installed more PHBs than any other agency and has developed both two-stage PHB applications and those that accommodate bicycle crossings such as along bicycle boulevards, which are aptly named BikeHAWKs. The City of Tucson and Pima County (Arizona) Department of Transportation jointly developed a HAWK Striping and Signing Detail for PHBs that was adopted in August 2008. A representative from Pima County stated that the county is working on updating the signing and striping standard drawing.

Information was primarily obtained from Pima County and from the cities of Tucson, Phoenix, Scottsdale, and Mesa, Arizona. A review of agency websites was conducted, and some agencies known to use PHBs were contacted for additional information. The following guidance was identified:

- **Prioritization of PHB installations**—The cities of Tucson, Phoenix, and Mesa have developed guidance on the prioritization of locations for installation of PHBs using a point system based on criteria such as average daily traffic (ADT), pedestrian crossing volume, distance to the nearest controlled crossing, and prior pedestrian crashes, among others. In addition to the aforementioned items, the City of Mesa also considers power availability, environmental and cultural issues, and the availability of right of way in the decision to install PHBs. Scottsdale has not developed prioritization criteria for PHBs.
- **Striping practices**—Phoenix, Tucson, and Pima County use ladder crosswalks at PHBs. For school crossings in Tucson and Pima County, the crosswalks will be ladder-style yellow markings used with school portable in-street signs and a 15-mph speed limit during school crossing times. Phoenix and most other cities in the Phoenix metropolitan area do not use yellow crosswalks, 15-mph speed zones, and portable signs at school crosswalks where PHBs are installed. The Mesa standard drawing shows two parallel crosswalk lines (15 ft apart), which is consistent with

its two PHB installations. The City of Scottsdale has not developed any standard signing or striping standard details or guidelines for PHBs.

- **Operation**—Information provided by the City of Tucson traffic engineer reported that Tucson HAWKs are typically hot-button, and some locations have a guaranteed dark time of 30 sec programmed between successive activations. Phoenix has most of its PHBs operating in hot-button operation; however, new PHBs installed on arterial streets can operate in sync with adjacent traffic signals during morning and afternoon peak traffic hours (Monday through Friday) and allow hot-button operation during off-peak hours including weekends. The City of Scottsdale PHBs have hot-button operation except for a two-stage PHB, which it attempts to synchronize with the two adjacent traffic signals. Scottsdale does not have a standard dark (vehicle go) time after a PHB actuation but has used 15 sec between subsequent PHB actuations.
- **Pedestrian crossing, change, and clearance intervals**—Phoenix, Tucson, and Scottsdale use a short clearance interval after the start of red display and before the onset of the WALK interval. Phoenix uses a 2-sec all-red interval, while Tucson uses 1 sec. Tucson also flashes the red beacons for 4 sec after the flashing DON'T WALK counts down to zero as an additional pedestrian clearance prior to the start of cross-street traffic. Scottsdale also uses a short all-red interval prior to the start of the WALK interval but did not specify the duration. Phoenix uses a minimum of 7 sec of WALK time, but for school crossings the WALK time is increased to 11 sec (during school arrival and dismissal). The pedestrian change interval (flashing DON'T WALK) is based on a walking speed of 3.5 ft/sec. Tucson typically uses 7 sec of WALK time at PHB crossings.
- **Flashing and solid yellow intervals**—Tucson flashes yellow indications for 3 sec before providing a solid yellow vehicle change interval. The duration of the solid yellow interval in Tucson is calculated in accordance with ADOT Traffic Engineering Policies, Guidelines, and Procedures, Section 621.1, March 2001, that is, 1+(1.47V/2a + 64.4g). Phoenix flashes the yellow interval for 5 sec, followed by a solid yellow vehicle change interval that is calculated based on a duration that would be used for a traffic signal.
- **High-speed roadways**—The City of Mesa Warrant Policy states, "PHBs should not be used on roadways with speed limits greater than 45 mph." No such guidance was found from the City of Tucson, Pima County, or City of Phoenix; however, speed limits within urban or suburban areas are not frequently above 45 mph. The Tucson and Pima striping-and-signing detail states, "For posted speeds of 45 mph or greater, stop bars may be 24 inches" in width.
- **Other**—The City of Tucson typically provides a W11-2 advance pedestrian crossing sign on each approach to its HAWK/PHB crossings. Both the City of Phoenix and Tucson/Pima County convert the lane lines on the approach to the PHB crossings to a solid lane line. The Tucson/Pima County standard drawing indicates the length of the solid lane line to be 200 ft for speeds less than or equal to 35 mph, and 280 ft for speeds that are greater than or equal to 40 mph. This practice is constant with Phoenix for multilane approaches to uncontrolled crosswalks. The Tucson/Pima County guidelines provide for the optional use of a symbolic No Pedestrian Crossing (R9-3) signs for the unmarked crossing on the opposite side of the intersection (the sign code is the designation from the MUTCD). The City of Phoenix guidelines recommend placing the stop line

at least 60 ft in advance of the mast arm to allow for driver visibility of the PHB signal heads. In Phoenix, a STOP HERE ON RED (R10-6) sign will accompany the stop line. Tucson typically places the advance stop line 40 ft in advance of the PHB mast arm indications.

CHAPTER 3: OPERATIONAL DATA ANALYSIS

INTRODUCTION

The objective of the data analysis was to describe the operational performance of PHBs on higher-speed roadways in Arizona. The research team identified and selected 10 study sites, identified relevant measures of effectiveness, and collected and analyzed the field data needed to quantify these measures.

STUDY APPROACH

Measures of Effectiveness

The goal of the field study was to examine driver and pedestrian/bicyclist behaviors at PHBs on higher-speed streets. The specific measures of effectiveness used for this evaluation include the following:

- Major-road driver behavior
  - The percentage of drivers yielding to pedestrians during steady red and flashing red indications
  - The number of drivers not stopping or not staying stopped during the steady red indication
  - The number of drivers not stopping during the flashing red indication
- Pedestrian/bicyclist behavior
  - The percentage of pedestrians using the pushbutton when necessary
  - The percentage departing from the curb by PHB indication (dark, flashing yellow, steady yellow, steady red, and alternating flashing red)
- Conflicts (erratic maneuvers) observed during interactions between pedestrians, bicyclists, and vehicles

Overview of Field Study

The preferred data collection and reduction approach used on-site and recorded video observations to document the various pedestrian and driver behaviors and vehicle operational characteristics. The protocol was developed and refined based on experiences from the Transit Cooperative Research Program/NCHRP project Pedestrian Treatments at Unsignalized Intersections (Fitzpatrick et al. 2006), a Texas Department of Transportation study on pedestrian treatments (Fitzpatrick et al. 2013), and the recent FHWA PHB study (Fitzpatrick et al. 2016).

In general, the following protocol was used in the observation studies:

- Daylight times were selected when sufficient vehicle volume was anticipated to ensure that many of the crossings would have drivers that need to decide whether to yield or not yield.
- A minimum of 100 pedestrian crossing events or four hours of data (the smaller of the two) was recorded at each location.
- The research team favored the observation of actual pedestrians but also conducted staged crossings as necessary to obtain a sufficient sample of driver behavior observations. Fitzpatrick

et al. (2013) documented the details of the staged pedestrian protocol. In general, the staged pedestrian is a member of the research team and wears a gray t-shirt or sweat shirt, blue jeans, and predominantly dark shoes while completing the street crossings. A baseball cap and sunglasses are permitted. The staged pedestrian is trained to approach the crossing in a similar manner for each location to minimize the effects of pedestrian behavior on drivers.

- Members of the research team were positioned at inconspicuous locations near the pedestrian crossing to make anecdotal notes of the crossing events. These anecdotal notes did not include quantitative data on the measures of effectiveness listed previously but instead focused on qualitative observations about vehicle and driver behavior.
- The research team attempted to make the observers and video recording devices inconspicuous from the pedestrians, bicyclists, and drivers.
- The research team asked the road owner if it had an existing speed study that it would be willing to share, or if it would be willing to conduct a speed study and contribute the data to this research study.

Site Selection

The intent of the operational analysis was to review the effectiveness of PHBs on higher-speed streets in Arizona and to observe driver and pedestrian/bicyclist behavior as well as their interactions at these locations. The goal for site selection was to select sites using the following criteria:

- PHB crossings of streets with higher posted speed limits (45 mph or 50 mph)
- PHB crossings on ADOT highways
- Non-school crossings (no yellow school crosswalks or 15-mph portable signs at the crossings)
- Statewide data collection to the extent practical
- PHBs at a mix of midblock crossings or intersections/driveways with side-street traffic

The preliminary list of candidate locations provided to the panel included 10 recommended study sites and three alternate sites. All candidate sites were identified as having posted speed limits of 45 or 50 mph, and two were located on state highways. Information provided to the panel for each site included the location (global positioning system coordinates, street name, and city), Google aerial and street view photos, the number of through and turning lanes, crossing distances, area type, ADT, and posted speed limit. Based on feedback from the panel, 10 sites were selected for the operational study.

The geographic distribution of the sites includes one site in northwest Arizona (Bullhead City), five in central Arizona municipalities (two in Scottsdale and one each in Phoenix, Tempe, and Gilbert), three in the Tucson region (one site under Pima County jurisdiction and two in Tucson), and one in southeast Arizona (Sierra Vista). Table 4 and Table 5 list key site characteristics, which include the posted speed limit, roadway geometry, traffic volumes, pedestrian crossing distance, and driveway density. Table 6 summarizes the distribution of these sites by lane count, posted speed limit, and roadway jurisdiction.

Table 4. Study Site Speed Limit and Geometry.

Site ID	City	Posted Speed Limit (mph)	Number of Legs	Number Through Lanes (Major)[a]
BH-01	Bullhead City (ADOT)	45	4	4
GI-03	Gilbert	45	3	4
PH-33	Phoenix	45	3	5
SD-02	Scottsdale	50	3	2
SD-03	Scottsdale	50	4	4
SV-01	Sierra Vista (ADOT)	45	4	4
TP-01	Tempe	45	3	4
TU-089	Pima County	40	2	4
TU-124	Tucson	45	4	4
TU-129	Tucson	50	4	2

[a] All sites had a two-way left-turn lane (TWLTL) or left-turn lane present. A median pedestrian refuge island was not present at any of the sites.

Table 5. Study Site Characteristics.

Site ID	PHB Install Year	Crossing Distance (ft)[a]	ADT	ADT Source[b]	Sidewalk Presence (Major)[c]	Distance to Nearest Signal (ft)	Driveway Density (Driveways per Mile)[d]
BH-01	2013	70/75	27,668	ADOT, 2016	2	1,263	60
GI-03	2017	90/100	25,200	MAG, 2015	1	641	22
PH-33	2017	73/68	20,400	Phoenix, 2016	2	652	16
SD-02	2010	70/63	15,250	Scottsdale, 2014	0	5,254	2
SD-03	2009	86/90	19,100	Scottsdale, 2014	0	4,892	5
SV-01	2015	78	15,675	ADOT, 2016	1	1,099	22
TP-01	2010	82/90	25,000	MAG, 2015	2	1,068	25
TU-089	2002	78	24,028	PAG, 2012	0	1,779	28
TU-124	2016	74/72	18,366	PAG, 2012	2	2,559	36
TU-129	2015	79/65	10,300	PAG, 2012	0	2,335	6

[a] The crossing distance is the approximate distance from the pedestrian pushbutton to the far side edge line or edge of pavement. If the distance varies by direction, the crossing distances are provided as westbound/eastbound or northbound/southbound.
[b] ADOT = Arizona Department of Transportation, MAG = Maricopa Association of Governments, PAG = Pima Association of Governments.
[c] Sidewalk presence: 0 = no sidewalks, 1 = sidewalk on one side, 2 = sidewalk on both sides.
[d] The driveway density was calculated by determining the number of driveways on both sides of the major street for a 1-mile segment (0.5 miles on either side of the PHB).

Table 6. Number of Sites by Key Criteria.

Posted Speed Limit (mph)	Number of Through Lanes	Roadway Jurisdiction	Number of Sites
45 mph	4 or more	State highway	2
45 mph[a]	4 or more	City or county road	5
50 mph	2	City or county road	2
50 mph	4 or more	City or county road	1

[a] One of the 45-mph sites was later determined to have a 40-mph speed limit.

PHB Displays

For each study site, the PHB interval displays are summarized by the motorist display (Table 7) and by the pedestrian display (Table 8). From the driver's view, the PHB indications sequence through dark, flashing yellow, steady yellow, steady red, flashing red, and then once again dark. The pedestrian signal rests in steady DON'T WALK. The pedestrian timing intervals are shown for the red clearance (steady DON'T WALK), pedestrian WALK, pedestrian flashing DON'T WALK (FDW) with countdown display, and an additional clearance interval (steady DON'T WALK).

Table 7. PHB Motorist Display Operation.

Site ID	Interval I	Interval II	Interval III	Interval IV
	Flashing Yellow upon Activation (s)[a]	Steady Yellow (s)	Steady Red during Pedestrian WALK (s)	Alternating Flashing Red during Pedestrian Clearance (s)
BH-01	4	4	10	19
GI-03	10	4	11	30
PH-33	5	4	10	15
SD-02[b]	9	4	17	20
SD-03	9	4	9	19
SV-01	4	4	10	23
TP-01	4	4	9	21
TU-89	7	4	11	22
TU-124	3	4	8	20
TU-129	3	3	8	20

[a] All study PHBs were designed with hot-button (immediate) activation operation.
[b] The SD-02 site had an additional interval of 4 sec of steady red followed by 2 sec of alternating flashing red after the standard sequence.

Site Survey

The sites were initially examined using aerial and street-level photography that is available online. Characteristics that could not be measured using online photography sources were measured in the field, such as the distance from the pushbutton to the far-side edge line or edge of pavement. Other measurements, such as crosswalk width and placement of advance stop lines or warning signs, were confirmed at the sites. Additionally, street-level photographs were taken during the site survey. These photographs showed all site approaches from the perspectives of drivers and pedestrians, the configuration of the PHB hardware, placement of advance and crosswalk signing, and any other site features of interest.

Table 8. PHB Pedestrian Display Operation.

Site ID	Vehicle Interval II: Steady Red		Vehicle Interval IV: Flashing Red	
	Red Clearance (s)	Pedestrian WALK (s)	Pedestrian Flashing DON'T WALK (s)	Additional Clearance after FDW
BH-01	3	7	16	3
GI-03	1	10	30	0
PH-33	2	8	15	0
SD-02[a]	2	15	20	6
SD-03	2	7	19	0
SV-01	3	7	20	3
TP-01	2	7	21	0
TU-89	1	10	22	0
TU-124	1	7	16	4
TU-129	1	7	13	7

[a] The SD-02 site had an additional interval of 4 sec of steady red followed by 2 sec of alternating flashing red after the standard sequence.

Video Footage Collection

Data were collected in spring 2018 before the heat of summer, which would allow for more observations of natural (non-staged) crossings. Actual data collection in the field started April 25 and was completed by May 8, 2018. The video recording of the crossing was accomplished with video camcorders and pole-mounting hardware, or from inside parked vehicles if poles were not available for camera mounting. The cameras were arranged to capture the following site elements:

- PHB indications (which are identical in the two major-street travel directions and can be used to determine the pedestrian signal head indications)
- Both crosswalk approaches, including the pushbuttons and pedestrian queue storage area
- Both major-street approaches, including the stop line
- All minor approaches (streets or driveways) where applicable, including a view of the brake lights of departing vehicles

Figure 1 shows an example of the camera positioning for a study site. The main camera is positioned on the major street to capture the PHB, the crosswalk approaches, and the major-street approaches. Secondary cameras are used to capture the minor-street approaches and are positioned to capture the view of the departing vehicles.

Actual, or non-staged, pedestrians or bicyclists were preferred in the data collection efforts, but at sites where pedestrian volumes were low, members of the research team conducted staged crossings to obtain a larger sample of motorist behavior data. Staged pedestrians wore outfits consisting of a gray t-shirt, jeans, and sneakers that were not solid white in color. The consistent outfit was used to ensure that the staged pedestrians appeared to be members of the general public and appeared to be similar on different days and at different sites. The staged pedestrians activated the PHB while vehicular traffic was approaching and waited until all queued vehicles cleared before beginning another staged crossing so no drivers observed two consecutive PHB actuations.

Source of base map: Google Earth

Figure 1. Example of Camera Positioning from Study Site BH-01.

For all observations, pedestrians were included in the study if they crossed within the crosswalk area, which was defined as the marked crosswalk plus an additional 10 ft of pavement on either side of the crosswalk.

Operating Speed

The research team requested operating speed data from the roadway owners of the PHB study sites. Speed data were provided for nine of the 10 sites. Some roadway owners provided past historical speed data, and others collected new data for the purpose of this study. The collected data are a combination of short-term, manual spot-speed data and longer-term (24- to 48-hour) pneumatic tube counts. Table 9 provides the operational speed data. Only one site has an 85th-percentile speed that is less than the posted speed limit (GI-03 where the 85th-percentile speed is 44 mph compared to the 45-mph posted speed limit). For all other sites, the posted speed limit is between 2 and 10 mph lower than the 85th-percentile speed.

Video Data Reduction

The video footage was post-processed manually to document behaviors of interest. These behaviors included driver stop compliance, driver yielding behavior, pedestrian behavior (pushbutton usage and departures), and pedestrian-vehicle conflicts. Stop compliance is relevant during the entire duration of the steady or flashing red indications, regardless of whether pedestrians are present, but yielding behavior can only be observed while pedestrians are present.

Table 9. Operational Speed Data near PHB Sites.

Site	Site Name	Posted Speed Limit (mph)	Operational Speed Data Collection			
			Date	Duration	85th-Percentile Speed (mph)	Difference (mph)
BH-01	Highway 95 at 5th St.	45	9/2017	1 hr	47	+2
GI-03	Baseline Rd. at Eastern Canal Trl.	45	5/2018	24 hr	44	−1
PH-33	19th Ave. at Sun Circle Trl.	45	4/2018	48 hr	53	+8
SD-02	Pima Rd. at Dixileta Dr.[a]	50	2005	24 hr	53	+3
SD-03	Pima Rd. at Jomax Rd.[a]	50	2005	24 hr	54	+4
SV-01	State Route 90 at Toscanini Ave.	45	4/2018	1 hr	48	+3
TP-01	McClintock Dr. at Western Canal	45	No speed data available			
TU-89	Palo Verde near Columbia St.	40	5/2018	24 hr	50	+10
TU-124	Nogales Highway at Olive St.	45	5/2018	1 hr	48	+3
TU-129	Valencia Rd. at Frost Dr.	50	5/2018	1 hr	54	+4

[a] Use caution when interpreting data. The speed data for the Scottsdale sites were collected in 2005, and the data were collected during a high-profile speed enforcement campaign. It is likely that the free-flow speeds are greater than what is shown in the table. Also, the PHBs at SD-02 and SD-03 did not exist at the time the speed data were collected in 2005.

RESULTS

Sample Size

A total of 822 PHB actuations and 1,214 pedestrians/bicyclists were observed across the 10 study sites. Table 10 lists the distribution of pedestrians/bicyclists and actuations by site. At all but two sites, staged pedestrians accounted for more than half of the observed PHB actuations. The two exceptions were sites TP-01 and TU-129, which were both located at trail facilities that saw large numbers of pedestrians, including recreational trail users like joggers or runners, and bicyclists.

Driver Yielding Behavior

Driver yielding is a safety surrogate measure that demonstrates the behavior of drivers in response to a traffic control device and to the presence of pedestrians/bicyclists. Drivers were included in this analysis when the driver arrived at the PHB-controlled crosswalk during the steady or flashing red indications of a PHB actuation sequence and a pedestrian or bicyclist was present. The analysis considered the driver's behavior when the pedestrian (or bicyclist) was on the roadside facing the roadway in a position consistent with intent to cross, was in the crosswalk, or had just completed the crossing.

Table 10. PHB Actuation Count by Site.

Site	Pedestrian/Bicyclists Count			Actuation Count by Pedestrian/Bicyclist Type		
	Staged	Non-staged	All	Staged	Non-staged	All
BH-01	52	41	93	52	31	83
GI-03	65	35	100	65	14	79
PH-33	79	6	85	79	2	81
SD-02	72	3	75	72	1	73
SD-03	58	10	68	58	6	64
SV-01	60	21	81	60	10	70
TP-01	11	301	312	11	94	105
TU-089	90	2	92	90	2	92
TU-124	65	54	119	65	32	97
TU-129	3	186	189	3	75	78
All Sites	**555**	**659**	**1,214**	**555**	**267**	**822**

Drivers who did not yield to pedestrians/bicyclists were counted as non-yielders. Figure 2 provides illustrations of the non-yielding events. The pedestrian could have been on the sidewalk clearly communicating the intent to cross or on the pavement. Some may argue that a driver passing the pedestrian who is on the sidewalk, even though clearly communicating intent to cross, should not be considered a non-yielding vehicle. Arizona Law in section 28-793, paragraph A, states:

> …if traffic control signals are not in place or are not in operation, the driver of a vehicle shall yield the right-of-way, slowing down or stopping if need be in order to yield, to a pedestrian crossing the roadway within a crosswalk when the pedestrian is on the half of the roadway on which the vehicle is traveling or when the pedestrian is approaching so closely from the opposite half of the roadway as to be in danger. A pedestrian shall not suddenly leave any curb or other place of safety and walk or run into the path of a vehicle that is so close that it is impossible for the driver to yield.

Within the law is the phrase "within the crosswalk," implying that the pedestrian needs to be off the curb and on the street pavement. Because pedestrians may not feel comfortable waiting on the pavement until they can verify that the driver will come to a complete stop, the research team included those situations when the driver did not yield to a pedestrian on the sidewalk who was clearly communicating the intent to cross. Table 11 shows the distribution of the non-yielding vehicles by pedestrian position and vehicle position. Most of the non-yielding vehicles were vehicles that passed a pedestrian waiting on the sidewalk when the PHB was showing a steady red. While there could be debate about whether that vehicle be considered a non-yielding vehicle, there is no debate that the vehicle is in violation of the steady red indication.

For each PHB actuation sequence, the maximum number of yielders is one per lane during the steady red indication, while the maximum number of non-yielders is limited only by the time duration of the steady and flashing red indications.

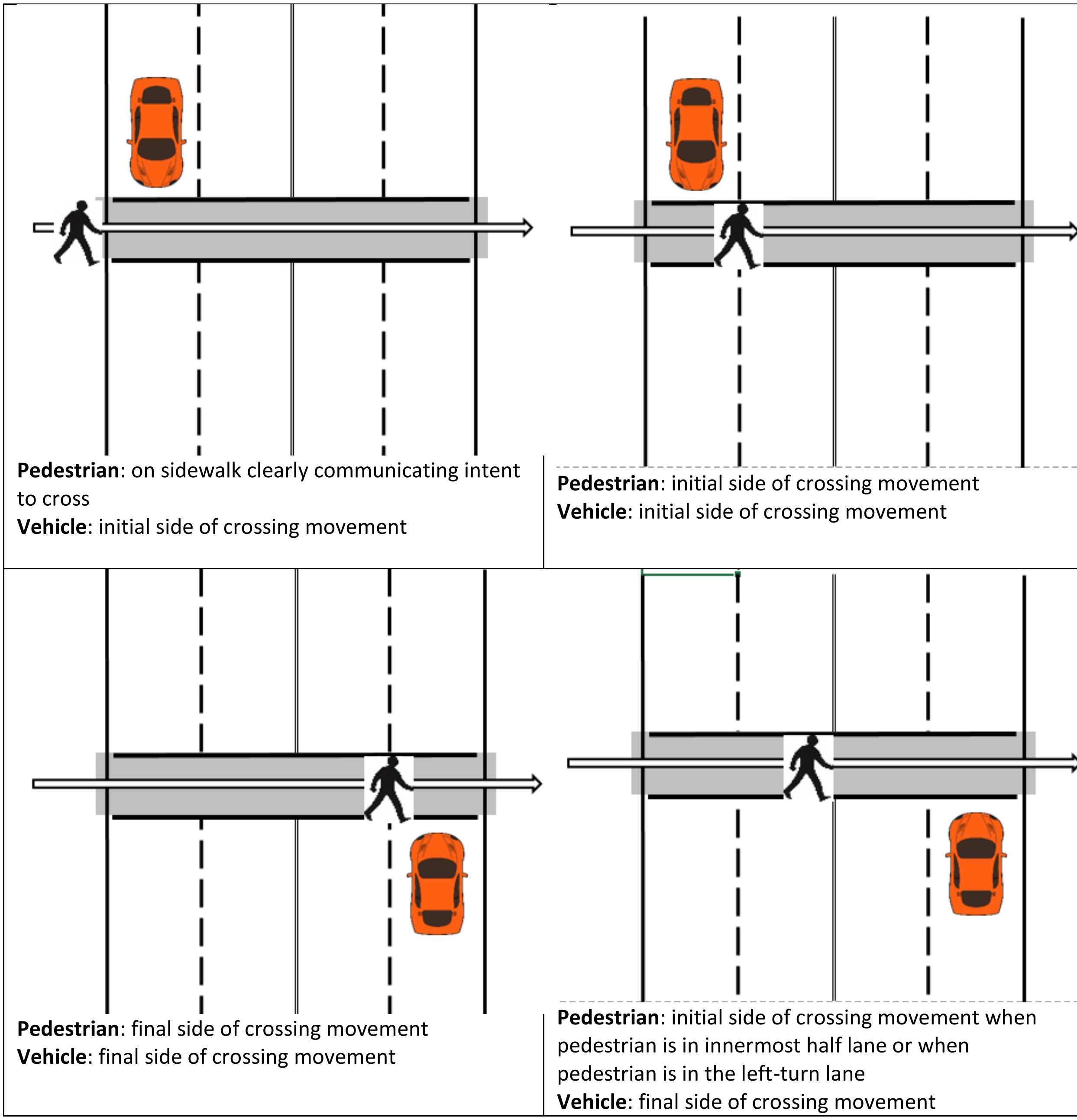

Figure 2. Example Diagrams of Pedestrian and Vehicle Positions during Non-yielding Events When the Pedestrian Starts the Crossing on the Left Side of the Diagram.

Table 12 presents the driver yielding rates observed at each site included in this study. For the 10 high-speed sites included in this study, the overall yield rate was 97 percent. In almost all of the crossings, drivers appropriately yielded to the crossing pedestrians (or bicyclists). An FHWA study included data collected at 20 sites, where the posted speed limit ranged between 30 and 45 mph (Fitzpatrick et al. 2016). That study found an overall yield rate of 96 percent with per-site yield rates ranging between 87 percent and 100 percent (see Table 13). The FHWA study included 12 sites in Tucson, Arizona, and 8 sites in Austin, Texas. The average driver-yielding rate for the Tucson, Arizona, sites was 97 percent with a range of 95 to 100 percent.

Table 11. Non-yielding Maneuver Characteristics (See Figure 2 for Example Illustrations of the Position for the Pedestrian and the Vehicle).

Pedestrian Position	Vehicle Position	PHB Indication	Maneuver Count	Percent of Total
Sidewalk	Initial side of crossing movement	Steady red	46	73%
		Flashing red	3	5%
Initial side of crossing movement	Initial side of crossing movement	Steady red	0	0%
		Flashing red	0	0%
Final side of crossing movement	Final side of crossing movement	Steady red	1	2%
		Flashing red	4	6%
Initial side of crossing movement	Final side of crossing movement	Steady red	5	8%
		Flashing red	4	6%
Total			63	100%

Table 12. Driver Yielding Rates by Site.

Site	Vehicle Counts			Yield Rate
	Yielders	Non-yielders	All Vehicles	
BH-01	262	12	274	96%
GI-03	269	21	290	93%
PH-33	265	0	265	100%
SD-02	127	6	133	95%
SD-03	193	15	208	93%
SV-01	197	2	199	99%
TP-01	291	3	294	99%
TU-089	294	1	295	100%
TU-124	272	3	275	99%
TU-129	93	0	93	100%
All sites	**2263**	**63**	**2326**	**97%**

Table 13. Average Driver Yield Rate for the Sites Included in FHWA Study (Fitzpatrick et al. 2016).

Posted Speed Limit (mph)	Number of Sites	Minimum Per-Site Yield Rate	Maximum Per-Site Yield Rate	Average Yield Rate
30	1	97%	97%	97%
35	9	91%	97%	95%
40	9	87%	100%	96%
45	1	98%	98%	98%
Total	**20**	**96%**	**96%**	**96%**

Only one of the study sites in the FHWA study had a posted speed limit of 45 mph, while the ADOT study had all but one site with a 45-mph or higher posted speed limit. In this ADOT study of high-speed sites (posted speed limits between 40 and 50 mph, and 85th-percentile speeds between 44 and 54 mph), finding a similar yield rate as the FHWA study of lower-speed roads (97 percent compared to 96 percent for sites in Tucson and Austin) indicates that the PHB also operates well on higher-speed roads.

Even though this ADOT study found an overall yield rate for the higher-speed sites similar to that for the lower-speed sites, the two sites with the lowest yielding rates were reviewed. Observations indicated that the two Scottsdale PHB sites were rarely actuated (since use was largely limited to infrequent trail rides), resulting in most drivers being accustomed to expecting the PHBs to be dark and not active. Furthermore, the two Scottsdale PHB locations are in rural, outlying areas that are 1 mile from the nearest traffic signal and where crossings are not frequently expected by drivers, which is especially true of the SD-02 PHB location.

The GI-03 PHB location had one of the lower driver yielding rates at 93 percent. This may possibly be due to the rise in the roadway at the canal crossing and the close proximity to the traffic signal located about 641 ft to the west, especially since it did not appear that there was any synchronization between the PHB and the adjacent traffic signal. However, PH-33 PHB was located almost the same distance from a traffic signal (651 ft to the north) but had 100 percent driver yielding compliance. The one difference was that the PH-33 site was level, while the GI-03 site had an elevation difference at the canal crossing, making it somewhat more challenging for approaching motorists to observe trail users, especially for eastbound motorists (the trail was located on the east side of the canal).

Stop Compliance

Table 14 provides the counts of vehicles arriving on steady or flashing red, categorized by their stopping behavior identified by the technicians reviewing the video. The research team noted if the vehicle came to a complete stop, stopped and went or stopped and waited until the end of the flashing red indication, did not stop, or did not stop and passed a stopped vehicle. For the steady red indication, drivers are defined as compliant if they arrive on steady red and stop and remain stopped until the start of flashing red. For each steady red indication, the number of compliant vehicles is limited to the number of lanes at the site, while the number of non-compliant vehicles is limited only by the time duration of the indication. These counts are independent of the presence of pedestrians. The data for the driver's decision when a pedestrian is present are provided in the "Driver Yielding Behavior" section.

Across all sites, 90 percent of drivers complied with the steady red indication. The lowest compliance rates were observed at sites SD-02 and SD-03 (82 percent and 74 percent, respectively). These sites were located within 2 miles of each other on the same road in an exurban area in Scottsdale and south of outlying Carefree. The road has a 50-mph posted speed limit, but actual traffic speeds appeared to be higher (see Table 9). Therefore, the low steady red compliance rates at these sites are likely a reflection of drivers' desire to traverse the sparsely populated area without stopping, as well as drivers' expectation to traverse the site without stopping because of the relative rarity of PHB actuations.

For the flashing red indication, drivers are defined as compliant if they arrive on flashing red and stop, whether they proceed after stopping or remain stopped until the end of the flashing red. A "stop and wait" movement can be considered a fail-safe movement because the driver complies with the stop requirement but then fails to take advantage of the opportunity to proceed (i.e., capacity is lost). Drivers arriving within the last seconds of flashing red during queue discharge that actually arrived at the PHB when the indication had just gone dark were categorized as "stop, then go" because their behavior was consistent with proceeding after coming to a complete stop. For each flashing red indication, the number of compliant vehicles is limited only by the time duration of the indication.

Table 14. Stop Vehicle Compliance Counts and Rates.

Site	SR[a] Stop	SR Stop Go or No Stop	SR No Stop Pass	SR Total	SR Veh ComR	FR Stop Go	FR Stop Wait	FR No Stop	FR Pass	FR Total	FR Veh ComR
BH-01	178	25	0	203	88%	125	30	243	9	407	38%
GI-03	175	28	0	203	86%	99	99	135	7	340	58%
PH-33	155	6	0	161	96%	66	45	172	7	290	38%
SD-02	116	25	0	141	82%	82	46	170	13	311	41%
SD-03	101	35	1	137	74%	21	89	33	3	146	75%
SV-01	129	7	0	136	95%	107	43	214	6	370	41%
TP-01	147	11	0	158	93%	206	26	356	9	597	39%
TU-089	194	4	0	198	98%	167	3	490	3	663	26%
TU-124	134	13	0	147	91%	137	16	294	3	450	34%
TU-129	44	5	0	49	90%	94	21	31	0	146	79%
All sites	**1,373**	**159**	**1**	**1,533**	**90%**	**1,104**	**418**	**2,138**	**60**	**3,720**	**41%**

[a] Column heading notes:
SR = steady red, FR = flashing red
SR Stop = vehicle stopped and stayed stopped during the steady red
SR Stop Go or No Stop = vehicle stopped and then drove through crosswalk or did not stop during the steady red
SR No Stop Pass = vehicle did not remain stopped during the steady red and passed a vehicle that did remain stopped during the steady red
SR Total = total number of vehicles observed during the steady red portion of the PHB cycle
SR Veh ComR = compliance rate for vehicles during the steady red
FR Stop Go = vehicle stopped and then proceeded through the intersection on the flashing red
FR Stop Wait = vehicle stopped and waiting until the end of the flashing red
FR No Stop = vehicle did not stop during the flashing red, typically rolling through the intersection
FR Pass = vehicle passed a vehicle that was stopped at the PHB
FR Total = total number of vehicles observed during the flashing red portion of the PHB cycle
FR Veh ComR = compliance rate for vehicles during the flashing red

The compliance rate for the flashing red indication (41 percent across all sites) was notably lower than the compliance rate for the steady red indication. However, many of the non-compliant maneuvers during the flashing red indication occurred when no pedestrians were present and can be described as either rolling incomplete stops or the slow discharge of a queue.

Because of the potential for creating the multiple threat condition for a pedestrian, drivers that passed a stopped vehicle were noted. As shown in the SR No Stop Pass and FR No Stop Pass columns in Table 14, 61 drivers passed a stopped vehicle. The vast majority of these maneuvers occurred at low speeds during queue discharge, when some drivers proceeded with creeping speeds instead of coming to a complete stop. A closer examination revealed that the three sites with the largest number of overtake maneuvers during flashing red were SD-02 (13 overtakes), BH-01 (9 overtakes), and TP-01 (9 overtakes). Twelve of the 13 overtakes at SD-02 occurred during three actuations that saw 5, 4, and 3 overtakes, respectively, during queue discharge while through vehicles passed by stopped left-turning vehicles in the adjacent left-turn lane. The vehicles stopped in the left-turn lane were waiting for a gap in the oncoming traffic before performing their left turn. The one driver who passed a stopped vehicle during the steady red indication did so early in the steady red indication, and the pedestrian was on the sidewalk.

Non-staged Pedestrian and Bicyclist Behavior

The non-staged pedestrians and bicyclists were observed to determine:

- How often they pushed the button before crossing
- The display on the PHB for drivers when the pedestrian (or bicyclist) departed the sidewalk and began the crossing movement.

These observations are only relevant for non-staged pedestrians because staged pedestrians always pushed the button and departed during the steady or flashing red indication.

Table 15 provides pedestrian button-pushing rates (in terms of the percentage of non-staged pedestrians or bicyclists) for the following scenarios:

1. When the pedestrian arrives at the site and neither pedestrian storage area is or recently was occupied by another pedestrian, and the PHB indication is dark
2. When the pedestrian arrives at the site and the pedestrian storage area is not, nor recently was, occupied by another pedestrian, but the opposing pedestrian storage area is or recently was occupied, and the PHB indication is dark
3. When the pedestrian arrives at the site and the pedestrian storage area is already occupied, and the PHB indication is dark
4. When the pedestrian arrives at the site, and the PHB sequence is active

In general, pedestrians were most likely to push the button in Scenario 1 (66 percent of pedestrians pushed the button in this scenario). When the pedestrian is the first to arrive at the site, it is logical to assume that another pedestrian has not already pushed the button. Conversely, in Scenarios 2 and 3, the pedestrian might assume that the previously arriving pedestrian has already pushed the button, and therefore will be less likely to push the button. In Scenario 4, the PHB sequence is already in progress, so there is no need to push the button, yet 7 percent of pedestrians still did, perhaps out of habit.

Table 16 provides counts of non-staged pedestrian (or bicyclist) departures by PHB indication. The dark indication includes any pedestrian or bicyclist who crossed at the site in the interval between two PHB activations, which could include periods of several minutes. The overall trend shows that 56 percent of pedestrians (or bicyclists) depart during the steady red indication. These pedestrians are defined as compliant because they are provided with their WALK indication while the vehicular beacon indications are showing steady red. The most common non-compliant behavior is departing during the dark indication (24 percent of pedestrians/bicyclists), followed by departing during the flashing red indication (15 percent of pedestrians). At the two sites with more than 100 non-staged pedestrians, compliance rates were in the 49 to 50 percent range. (These two sites had frequent large vehicle gaps.)

Table 15. Non-staged Pedestrian (or Bicyclist) Button-Pushing Rates.

Scenario	1 — No Other Pedestrian Present			2 — Opposing Storage Area Occupied			3 — Pedestrian's Storage Area Occupied			4 — PHB Active		
Site	**PB[a]**	**Total**	**Rate**	**PB**	**Total**	**Rate**	**PB**	**Total**	**Rate**	**PB**	**Total**	**Rate**
BH-01	29	30	97%	NS[b]	NS	NS	1	6	17%	1	5	20%
GI-03	14	20	70%	NS	NS	NS	NS	NS	NS	NS	NS	NS
PH-33	1	2	50%	NS	NS	NS	1	3	33%	NS	NS	NS
SD-02	1	2	50%	NS	NS	NS	NS	NS	NS	NS	NS	NS
SD-03	6	6	100%	NS	NS	NS	NS	NS	NS	NS	NS	NS
SV-01	9	9	100%	1	2	50%	NS	NS	NS	NS	NS	NS
TP-01	83	160	52%	2	16	13%	6	54	11%	3	71	4%
TU-089	2	2	100%	NS	NS	NS	NS	NS	NS	NS	NS	NS
TU-124	29	29	100%	NS	NS	NS	NS	NS	NS	3	10	30%
TU-129	66	103	64%	1	3	33%	7	37	19%	3	43	7%
All Sites	**240**	**363**	**66%**	**4**	**22**	**18%**	**15**	**129**	**12%**	**10**	**145**	**7%**

[a] PB = pedestrian or bicyclist pushed the button
[b] NS = scenario did not occur during data collection

Table 16. Non-staged Pedestrian (or Bicyclist) Departure Counts.

Site	Pedestrian Departure by PHB Indication						Pedestrian Compliance Rate
	Dark	**Flashing Yellow**	**Steady Yellow**	**Steady Red**	**Flashing Red**	**Total**	
BH-01	2	2	1	33	3	41	80%
GI-03	7	0	0	25	3	35	71%
PH-33	1	0	0	5	0	6	83%
SD-02	3	0	0	0	0	3	0%
SD-03	0	0	0	7	3	10	70%
SV-01	0	0	2	16	3	21	76%
TP-01	100	1	11	150	39	301	50%
TU-089	0	0	1	1	0	2	50%
TU-124	1	1	7	41	4	54	76%
TU-129	45	2	4	91	44	186	49%
All sites	**159**	**6**	**26**	**369**	**99**	**659**	**56%**
Percent of total	**24%**	**1%**	**4%**	**56%**	**15%**	**100%**	

The 2016 FHWA study (Fitzpatrick et al. 2016) was able to examine pedestrian button use by posted speed limit because that study had a wide range for that variable and by crossing distance and hourly volume. The FHWA study found that a greater number of pedestrians activated the device when crossing 45-mph posted speed limit roads than when crossing 40-mph 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/hr or more, the percent of pedestrians activating the PHB was always 90 percent or more.

Conflicts

The video footage was reviewed to obtain a count of pedestrian-vehicle conflicts. A conflict is defined as an event where the pedestrian (or bicyclist) and/or the vehicle abruptly changed direction and/or speed to avoid an imminent collision within the zone of the PHB-controlled crosswalk (defined as being 10 ft on either side of the markings). For example, a conflict could involve a pedestrian running, stopping, or sidestepping while a vehicle encroaches on the crosswalk.

Conflicts were found to be rare during the field studies, with three conflicts observed for the 1,214 pedestrians/bicyclists recorded at the 10 sites—one each at BH-01, SD-02, and TU-124. Minor-road drivers caused two of the conflicts. In one case, the minor-road driver was turning right into the pedestrian path, and in the other case the minor-road driver was turning left into the pedestrian path. The third conflict occurred when the PHB was not activated and was caused by a pedestrian who originated about 60 ft downstream of the PHB-controlled crosswalk, stepped into the street in front of through vehicles (causing two lanes of traffic to stop for him), and continued to walk on a diagonal path, finishing within the zone of the PHB-controlled crosswalk.

CHAPTER 4: SAFETY EVALUATIONS

INTRODUCTION

The focus of the safety analysis was on investigating changes in crash frequency, severity, and crash types (e.g., rear-end crashes) due to the PHB presence as well as in crashes involving pedestrians and bicycles. Previous studies have proven PHBs' effectiveness in reducing pedestrian crashes; however, questions on the effect of PHBs on rear-end crashes or severe crashes could not be fully addressed because of statistically insignificant results for those crash types. One of the main reasons for insignificant results was the limited data (i.e., the relatively small sample sizes for crash data associated with PHBs). In addition to the focus on severity and crash type was a request to investigate the relationship between crashes at PHB locations and the spacing to nearby signalized intersections.

METHODOLOGY

As part of the safety evaluations, researchers used two methods: an EB before-after study and a cross-sectional observational study.

The EB before-after evaluation method estimated the changes in crashes after installation of PHBs by comparing the observed crash frequency after installation of the PHB to the EB estimate of the expected crash frequency for the same after period without the PHB (the counterfactual crash frequency). The counterfactual crash frequency was obtained as a combination of the observed before period crash frequency, prediction from the SPF based on reference sites (similar in site characteristics but without a PHB), and an adjustment factor that accounts for time trends and traffic volume changes between before and after periods. In the cross-sectional observational study, the crashes for a group of PHB sites were examined to investigate the effects of other site characteristic variables on crashes at the PHB sites. The cross-sectional observational analysis included a larger number of PHB sites because it can include PHB sites for which before-period crash data were not available.

One potential bias that needs to be considered in a before-after safety evaluation is the fact that PHB sites may be overrepresented with pedestrian crashes in the before period. One major consideration in the PHB selection and ranking criteria used by ADOT, Phoenix, and Tucson is the presence of pedestrian crashes during the prior three to five years. For example:

- ADOT TGP 640 provides a point system for evaluating candidate locations and states that "a minimum score of 35 points merits Pedestrian Hybrid Beacon consideration." Each pedestrian crash in the prior five years is awarded five points in the ADOT criterion.
- The Phoenix PHB evaluation and ranking system requires a minimum of 30 points before a PHB may be considered for installation and awards points for pedestrian crashes that have occurred in the prior three years. Six points per pedestrian crash are awarded in the most recent 12-month evaluation period, four points for each pedestrian crash in the middle 12-month evaluation period, and two points for each pedestrian crash in the furthest 12 months.
- Tucson assigns points for pedestrian or bicycle crashes that occur in the prior four years of evaluation.

Therefore, there is a potential regression to the mean (RTM) bias at PHB locations for before-after evaluations based on the PHB selection criteria used by Arizona agencies. Because crashes during the before period are unnaturally high, crashes would tend to regress toward the true long-term averages during the after period, and as a result, those sites could experience a reduction in crashes even without PHBs. Not accounting for this bias will result in overestimation of the safety effectiveness of PHBs. The EB before-after evaluation method properly accounts for the RTM bias that may exist by combining information from two sources: the observed crash frequency in the before period at PHB locations and the predicted crash frequency (that is expected to be close to the true long-term mean crash frequency) based on reference sites with similar traffic and site characteristics as PHB locations.

The research team learned of another potential condition that can notably affect a before-after crash study. Tucson police stopped responding to property-damage-only (PDO) crashes in December 2010. Tucson motorists can still submit PDO reports, but a majority of motorists do not do so. Two approaches are available to help account for this change, and both were used in this study. The reference sites associated with Tucson PHBs were located in Tucson so that the change in reporting practices would affect both the treatment and reference sites. The other approach is to focus on the non-PDO crash (i.e., the fatal and injury crash) results over all crash results when sample size permits.

Site Identification and Geometric Data

The research team obtained the PHB locations and installation dates from the state and from several cities, and in early 2018 identified 209 known PHBs in Arizona. Roadway characteristic data were obtained using aerial photographs for each of these sites, and Google Street View was used to determine the posted speed limit at the crossing. Table 17 lists the roadway variables that were considered in the safety analysis. In some cases, a variable had to be regrouped during the analysis; for example, the posted speed limit along the major street (i.e., the street with the PHB) was regrouped into 35 mph and below, and 40 mph and above. In other cases, a variable was combined to decrease the total number of variables included in the model. For example, the presence of left-turn lanes was modified from being a per-approach variable (resulting in two variables per crossing) to a single variable that represented the entire crossing (M_LTL).

Sites Used in Analyses

PHBs installed within months of this research project (15 sites) were removed because crash data would not yet be available. Two PHBs were removed from consideration because the signal face assembly more closely resembled a traditional traffic signal design. That is, the signal face had three vertical indications rather than having the yellow indications centered below the two red indications (these were early prototype PHB designs that have not yet been updated to the MUTCD design). A few sites were removed because vehicle counts were not available.

Table 17. Roadway Variables Considered in Safety Analyses.

Variable	Description
C_Lanes	Cross: total number of lanes on the cross street
Legs	Number of legs at the intersection (2 = midblock, 3, or 4 legs)
M_Bike_01	Major: is a bike lane present? (1 = bike lane on one or both sides, 0 = none)
M_Lanes	Major: number of through lanes
M_LTL	Major: is a left-turn lane present on the major street (0 = neither approach has a left-turn lane, 1 = at least one of the approaches has a left-turn lane)
M_LTL_A	Major: number of approaches with an exclusive left-turn lane (0, 1, or 2)
M_MT	Major: median type (raised, TWLTL, none, or flush)
M_MT_R	Major: median type (raised = raised, all others such as flush, TWLTL; none = not raised)
M_PK_01	Major: is a parking lane present? (1 = parking lane on one or both sides, 0 = none)
Ped or PB_Vol_MC	Daily number of pedestrians at the intersection, sum of the pedestrian volume on the major and cross streets
PSL	Major: posted speed limit (mph)
PSL_group	Major: the posted speed limit for the main street grouped into either 35 mph and below, or 40 mph and above
Sig_Dist	Major: distance between the PHB and the nearest traffic signal in feet
Veh	Major: daily number of vehicles on the major street, also called ADT

PHBs installed in 2011 to 2015 were considered for the before-after study. Sites were removed from the before-after study if major roadway improvements occurred during that period. For example, one of the sites had been widened from two lanes to four lanes, or a driveway was added at the site. For the before-after study, 52 PHB sites were available. The cross-sectional study could include more PHB sites because crash data before the installation of the PHB were not needed; therefore, more of the older installations (prior to 2011) could be considered. The cross-sectional observational study included 186 PHB sites.

Reference Groups

Crash evaluations are beneficial when a reference group of similar sites without treatment is identified. Three potential reference groups were identified for the EB before-after evaluation:

- Reference group 1 included unsignalized intersections.
- Reference group 2 included signalized intersections.
- Reference group 3 included both unsignalized and signalized intersections.

The research team selected intersections near the PHB on the major roadway with the goal of finding intersections with a similar roadway cross section (e.g., number of lanes or median type), speed limit, and number of legs where pedestrians could be expected to be crossing the street. Number of legs could not be matched for those PHBs installed midblock. In general, one signalized and two unsignalized intersections were identified for use as comparisons for each PHB site included in the before-after evaluation.

Vehicle Counts

Several sources were used to obtain vehicle counts including traffic counts (or historical maps) available on the internet and historical counts from ADOT, the Pima Association of Governments, the Maricopa Association of Governments, and various cities. Vehicle counts from existing sources were identified for most of the major streets in the intersections. For most sites, traffic counts were available for about every third or fourth year. When a count was not available for a given year, the count was estimated as equal to the count from the last year with a known count, or the next year with a known count if the year in question occurred before the first available count. This method was used to estimate traffic volumes for the major streets at the study sites. In almost all cases, data were not available for the cross streets because the cross streets were largely low-volume residential streets.

Pedestrian Counts

The research team contacted the appropriate roadway owners for any available historical pedestrian count data. The following data were collected:

- **City of Phoenix PHB pushbutton actuation data**—For a particular PHB site, the number of pushbutton actuations are recorded over a period of time, typically several years. The data are provided in a total count, rather than hourly or daily counts. The daily counts were calculated based on the duration of the actuation data. Adjustment factors were used to relate the actuation counts to pedestrian counts. Phoenix data were obtained for approximately 25 study sites.
- **Pima Association of Governments (PAG) pedestrian and bicyclist data**—PAG collects data at approximately 80 to 100 consistent sites annually to track changes over time. The data are collected in periods of two to three hours. PAG data were obtained for approximately 15 study sites.
- **Historical count data from an FHWA study (Fitzpatrick and Park 2010)**—Pedestrian counts were collected during spring 2008 and spring 2009 in Tucson as part of an FHWA study. The FHWA data were used for approximately 25 study sites.
- **Miscellaneous pedestrian and bicyclist data**—These data include spot data collection efforts conducted as part of an engineering study or pedestrian crossing study. Data were obtained for five study sites from the City of Peoria, City of Glendale, and City of Tempe.

The majority of sites did not have pedestrian counts available. For sites that did not have any historical pedestrian or bicyclist data, the research team members provided their judgment on the general level of pedestrian activity at each site using their local knowledge and a review of the development near the site. The general level of pedestrian activity was then translated to pedestrian volume based on the traffic control present and whether it was the major road or the cross street using the values shown in Table 18**.** For example, if the general level of pedestrian activity at a PHB site was judged to be medium, then 170 pedestrians (daily) were assumed to be crossing the major street. While this approach has limitations, the resources available and the large number of sites required a different approach to collecting actual pedestrian volumes at the sites.

Historical pedestrian count data were used to establish typical pedestrian volumes by general level of pedestrian activity shown in Table 18. The pedestrian volume values are based on the data from the 2010 FHWA study (Fitzpatrick and Park 2010). The *Highway Safety Manual* (American Association of State Highway and Transportation Officials 2010) data are included in the table as a comparison.

Table 18. Assumed Pedestrian Volume by General Level of Pedestrian Activity.

General Level of Pedestrian Activity[a]	PHB[b] Ped. Maj. 24 hr	PHB Ped. Cross2 4 hr	PHB Ped. All 24 hr	Unsig.[c] Ped. Maj. 24 hr	Unsig. Ped. Cross 24 hr	Unsig. Ped. All 24 hr	Sig.[d] Ped. Maj. 24 hr	Sig. Ped. Cross 24 hr	Sig. Ped. All 24 hr	HSM[e] Sig. 3 Leg	HSM Sig. 4 Leg
High	950	1,180	2,130	320	290	610	820	700	1,520	1,700	3,200
Medium–high	490	480	970	190	180	370	410	530	940	750	1500
Medium	170	220	390	90	90	180	210	290	500	400	700
Medium–low	90	40	130	40	40	80	110	170	280	120	240
Low	40	20	60	10	20	30	60	60	120	20	50

[a] The team assumed the general level of high pedestrian activity to be the 90th-percentile value (rounded to the nearest 10) for the group of sites. The medium–high was the 75th percentile, the medium was the 50th percentile, the medium–low was the 25th percentile, and the low was the 10th-percentile value (rounded to the nearest 10). Other assumptions include that the PHB is controlling the vehicles on the major street and that the pedestrian count for "all" is the sum of the pedestrians crossing the major legs and the pedestrians crossing the cross street legs (if any).
[b] PHB values are based on 52 PHB (HAWK) intersections.
[c] Unsig. values are based on 33 signalized intersections.
[d] Sig. values are based on 98 unsignalized intersections.
[e] HSM values are from the HSM Table 12-15, pp. 12–37.

Crash Data

ADOT supplied crash data for the 10.75-year period of January 1, 2007, to September 30, 2017. The records included latitude and longitude coordinate variables for the crashes, which were used to identify crashes relevant to the study. The query initially included 1,238,183 crash records, but about 2.8 percent of these records had to be discarded because their coordinate variables were not populated.

A database was developed with the coordinates for every study site, and crashes were extracted from the statewide database if they occurred within 250 ft of the center of the intersection (or midblock crossing site) as determined by comparing the coordinates. A tolerance of 3 sec of latitude and longitude was used, which corresponds to a distance of about 250 ft in Arizona. A total of 17,400 crashes were identified at the study sites, 5,383 of which were at PHB sites (which includes both periods when the PHB was in operation or prior to installation).

The following crash types were evaluated in the safety analysis:

- Total crashes
- Fatal and injury (FI) crashes, which consist of the following severity levels: fatal, incapacitating injury, non-incapacitating injury, and possible injury
- Rear-end crashes
- Angle crashes
- Pedestrian-related crashes
- FI rear-end crashes

- FI angle crashes
- FI pedestrian-related crashes

The crash incident file from ADOT included a collision manner variable. This variable was used to identify rear-end crashes (coded as 4 for collision manner) and angle crashes (coded as 2 for collision manner, defined as front to side crashes, other than left turn). Pedestrian-related crashes were identified by merging the incident records with their corresponding unit records using the incident identification variable that was common to both files. The units were identified as vehicles, bicycles, or pedestrians. Any crash involving one or more pedestrian units was coded as a pedestrian-related crash. Also, the crash types identified in the preceding list are not mutually exclusive; for example, a rear-end crash involving two vehicles and one pedestrian would be classified as both a rear-end crash and a pedestrian-related crash.

BEFORE-AFTER EVALUATION

The before-after evaluation included 52 intersections as treatment sites for which the PHB were installed during the study period. Reference group 1 consists of 101 unsignalized intersections, reference group 2 consists of 56 signalized intersections, and reference group 3 consists of 157 unsignalized or signalized intersections. The reference groups represent sites similar to the treatment sites but without the PHB.

Study Periods

The before period at each site was defined as January 1, 2007, to two months prior to the installation date of the PHB. Crashes occurring in the two months prior to the installation date were removed because they were assumed to have occurred during construction. Crashes occurring in the two months following installation of the PHB were removed because they were assumed to occur during the acclimation period while drivers were becoming familiar with the treatment. The after period occurred two months following PHB installation until September 30, 2017.

The number of months in the after period for the 52 PHBs varied depending on when installation occurred. The average number of months in the before period was 79 with a range of 50 to 107 months. For the after period, the average number of months was 52 months with a range of 23 to 81 months. Reference group sites were assigned the same period in their before and after periods as their corresponding PHB site.

Before-After Crash Data

Table 19 contains the total number of crashes, Table 20 the annual crashes adjusted by period duration, and Table 21 the percentage for each type of crash by site type for the before and after study periods. As Table 20 shows, crashes adjusted for period duration decreased over the period (from before to after) for all crash types considered at treatment sites. Total crashes, angle crashes, and FI rear-end crashes increased at unsignalized intersections. FI crashes, pedestrian-related crashes, FI angle crashes, and FI pedestrian-related crashes increased at signalized intersections. In addition, Table 21 shows that the percentage of pedestrian-related crashes decreased notably (53 percent reduction) at the PHB sites. The reduction was smaller (39 percent reduction) at unsignalized intersections. The percentage of pedestrian-related crashes increased (by 36 percent) at signalized intersections.

Table 22 contains the summary of site characteristic variables for PHB sites, unsignalized intersections, and signalized intersections used in EB before-after evaluations.

Table 19. Total Number of Crashes during Each Period.

Site Type	**PHB**		**Unsignalized Intersection**		**Signalized Intersection**	
Crash Type	**Before**	**After**	**Before**	**After**	**Before**	**After**
Total crashes	1,064	600	1,446	940	5,594	3,627
FI crashes	408	230	529	337	2,063	1,421
Rear-end crashes	468	206	561	303	2,230	1,182
Angle crashes	199	112	285	184	1,114	718
Pedestrian-related crashes	70	19	48	19	114	101
FI rear-end crashes	175	78	179	118	701	408
FI angle crashes	66	42	111	66	464	314
FI pedestrian-related crashes	62	19	44	18	99	96
Number of sites	52	52	101	101	56	56
Number of days in each period (summed over sites)	123,677	80,423	239,543	152,957	131,210	88,590

Table 20. Annual Crashes Adjusted by Period Duration.

Site Type	**PHB**		**Unsignalized Intersection**		**Signalized Intersection**	
Crash Type	**Before**	**After**	**Before**	**After**	**Before**	**After**
Total crashes	3.140	2.723	2.203	2.243	15.561	14.944
FI crashes	1.204	1.044	0.806	0.804	5.739	5.855
Rear-end crashes	1.381	0.935	0.855	0.723	6.203	4.870
Angle crashes	0.587	0.508	0.434	0.439	3.099	2.958
Pedestrian-related crashes	0.207	0.086	0.073	0.045	0.317	0.416
FI rear-end crashes	0.516	0.354	0.273	0.282	1.950	1.681
FI angle crashes	0.195	0.191	0.169	0.157	1.291	1.294
FI pedestrian-related crashes	0.183	0.086	0.067	0.043	0.275	0.396
Number of sites	52	52	101	101	56	56

Note: Crashes have been adjusted by period duration, that is, adjusted crash count = crash count/number of days in each period * 365, crashes/year.

Table 21. Percentage of Each Crash Type by Period and Site Type.

Site Type	PHB		Unsignalized Intersection		Signalized Intersection	
Crash Type	**Before**	**After**	**Before**	**After**	**Before**	**After**
FI crashes	38.4%[a]	38.3%	36.6%	35.9%	36.9%	39.2%
Rear-end crashes	44.0%	34.3%	38.8%	32.2%	39.9%	32.6%
Angle crashes	18.7%	18.7%	19.7%	19.6%	19.9%	19.8%
Pedestrian crashes	6.6%	3.2%	3.3%	2.0%	2.0%	2.8%
FI rear-end crashes	16.5%	13.0%	12.4%	12.6%	12.5%	11.3%
FI angle crashes	6.2%	7.0%	7.7%	7.0%	8.3%	8.7%
FI pedestrian crashes	5.8%	3.2%	3.0%	1.9%	1.8%	2.7%

[a] Percent crashes = number of crashes of each type/number of total crashes

Table 22. Descriptive Statistics for PHB Sites Used in Before-After Evaluations.

Variable[a]	PHB (52 Sites)			Unsignalized Intersections (101 Sites)			Signalized Intersections (56 Sites)		
	Min.	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**	**Min.**	**Max.**	**Avg.**
Legs	2	4	3.3	2	4	3.6	3	4	3.9
M_Lanes	2	9	5.0	2	9	5.3	2	10	5.5
M_LTL	0	2	0.9	0	2	1.5	0	2	1.9
M_PK_01	0	1	0.1	0	1	0.1	0	1	0.1
M_Bike_01	0	1	0.6	0	1	0.6	0	1	0.6
C_Lane	0	3	1.3	0	6	1.6	2	12	6.0
Veh (Period AADT[b])	5,400	47,627	23,959	4,937	47,627	24,377	5,400	48,512	24,421
PB_Vol_MC	10	1,670	297	10	480	99	30	1520	308
M_MT_R, Value (number of sites)	Not raised (33), raised (19)			Not raised (69), raised (32)			Not raised (35), raised (21)		

[a] See Table 17 for description of roadway variables.
[b] AADT = annual average daily traffic

Empirical Bayes Before-After Analysis

The EB method has been regarded as a statistically defensible method that can cope with several threats to the validity of observational before-after studies including RTM bias, changes in traffic volumes, and the effects of other unmeasured factors that might change from the before to the after period. Additional details on the method are contained in Hauer (1997) and Park et al. (2012). In the EB method, SPFs developed based on the data from the reference sites are used to estimate the expected crash frequencies at the treated sites had treatments not been applied. Negative binomial regression models are often used to derive the SPFs. Because the success of an EB evaluation largely depends on reliable estimation of SPFs, a reference group must be identified that is similar enough to the treatment group with respect to roadway characteristics, weather, and traffic volumes.

As mentioned previously, the following three reference groups were employed to assess the robustness of results and conclusions from the EB before-after analysis:

- Reference group 1: unsignalized Intersections
- Reference group 2: signalized Intersections
- Reference group 3: unsignalized Intersections and signalized Intersections

Details on the EB method are available elsewhere (e.g., Hauer 1997 and Fitzpatrick and Park 2010). The index of effectiveness is equivalent to the CMF.

Development of Safety Performance Functions

The first step in the before-after EB method was to develop and calibrate SPFs using data from a reference group. Development of the SPFs involved determining which predictor variables might be used in the model, how the variables might be grouped, and what model might be used. Negative binomial regression models are mostly used to derive the SPFs to accommodate over-dispersion in the crash data. The vehicle volume values (i.e., ADTs) are often the key variables in developing SPFs for intersections. In addition, pedestrian volumes are likely to play an important role. To account for the effects of vehicle volume and pedestrian volumes, researchers considered the period vehicle-volume values and the PB_Vol_MC volumes (see definition in Table 17). The period vehicle-volume values were obtained as the averages of vehicle-volume values for each before and after period using major-street vehicle volume values at each site in the reference group. The PB_Vol_MC volumes were obtained as the averages of the sum of major-street pedestrian-bike volumes and cross-street pedestrian-bike volumes for each period at each site in the reference group. To account for additional intersection-to-intersection variability (other than that caused by the differences in traffic volumes and pedestrian volumes), the following variables were also considered in the SPF predictions: number of legs (Legs), number of through lanes (M_Lanes), existence of raised median (M_MT_R), existence of left-turn lanes (M_LTL), existence of on-street parking (M_PK_01 with 0 = no on-street parking, 1 = on-street parking exists), existence of bike lane (M_Bike_01, with 0 = no bike lanes, 1 = bike lanes exist), and total number of entering lanes (C_lanes).

The negative binomial regression models with indicator variables for period to control for general trends from before to after periods, along with aforementioned variables as independent variables, were employed to develop SPFs based on the reference group. The predicted number of crashes at PHB sites (had PHBs not been installed) can then be obtained by the SPFs estimated by crashes at the reference group (in combination with the observed before period crash frequency and an adjustment factor that accounts for time trends and traffic volume changes between before and after periods). The estimated coefficients for SPFs for total, FI, rear-end, angle, pedestrian-related, FI rear-end, FI angle, and FI pedestrian-related crashes based on unsignalized intersections (reference group 1), signalized intersections (reference group 2), and unsignalized intersections and signalized intersections (reference group 3) are presented in Table 23, Table 24, Table 25, respectively.

Table 23. Estimates of Coefficients for Safety Performance Functions Developed Based on a Reference Group Consisting of Crashes at Unsignalized Intersections.

Coefficient[a]	Total	FI	Rear End	Angle	FI RearEnd	FI Angle	Ped_rel	FI Ped_rel
β_{0B}	−11.9403	−11.5226	−15.7498	−12.378	−15.7896	−12.1244	−15.4578	−15.9687
β_{0A}	−12.0754	−11.6312	−16.0486	−12.478	−15.8129	−12.2466	−16.0408	−16.5126
β_{Legs}	0.1009	0.0596	0[b]	0.2010	0	0.2454	0.1656	0.2603
β_{M_Lanes}	0.1478	0.1821	0.0561	0.2362	0.1299	0.2097	0.0988	0.0873
$\beta_{M\_MT\_R}$	0.3926	0.4216	0.3285	0.4808	0.3397	0.6767	0	0
β_{M_LTL}	−0.1509	−0.0977	−0.2209	−0.1071	−0.1902	−0.0817	0	0
$\beta_{M\_PK\_01}$	0.3809	0.2857	0.6189	0.3198	0.4417	0.2968	0	0
$\beta_{M\_Bike\_01}$	−0.7960	−0.5834	−0.8038	−0.7240	−0.6199	−0.6689	−1.2943	−1.3360
β_{C_Lanes}	0.2059	0.1528	0.2600	0.2874	0.1915	0.1656	0.0787	0.0877
β_{LnVeh}	0.5514	0.3470	0.9454	0.2988	0.7101	0.1673	0.3713	0.4483
β_{LnPed}	0.0324	0.1433	−0.0211	0.0778	0.1703	0.0960	0.5696	0.4292

[a] negative coefficient indicates that the number of crashes decreases with an increase in the value of the variable. A positive coefficient indicates that the number of crashes increases with an increase in the value of the variable. For example, the coefficient for number of legs is positive for total crashes (i.e., 0.1009), which indicates that more crashes are associated with four-leg than three-leg intersections.
[b] The coefficient 0 denotes that the corresponding variable was excluded from the model.

Table 24. Estimates of Coefficients for Safety Performance Functions Developed Based on a Reference Group Consisting of Crashes at Signalized Intersections.

Coefficient[a]	Total	FI	Rear End	Angle	FI RearEnd	FI Angle	Ped_rel	FI Ped_rel
β_{0B}	−11.421	−13.334	−13.225	−12.8435	−15.1351	−15.522	−21.434	−22.1790
β_{0A}	−11.658	−13.508	−13.578	−13.1207	−15.4234	−15.761	−21.509	−22.1791
β_{Legs}	0.9119	0.8809	0.8945	1.4091	0.6067	1.8794	1.9768	1.7445
β_{M_Lanes}	0.1157	0.1356	0.0534	0.1975	0.0295	0.1825	0.0926	0.0939
$\beta_{M\_MT\_R}$	0.4685	0.4399	0.3674	0.5880	0.4159	0.4601	0.3341	0.4363
β_{M_LTL}	−0.4095	−0.3507	−0.3751	−0.4328	−0.2963	−0.3904	0	0
$\beta_{M\_PK\_01}$	0.1590	0.0769	0.1518	0.1149	0.0955	0.0472	0	0
$\beta_{M\_Bike\_01}$	−0.2717	−0.1457	−0.2635	−0.1358	−0.1241	−0.1009	−0.3783	−0.3167
β_{C_Lanes}	0.1980	0.1618	0.2428	0.1145	0.2178	0.0629	0.1761	0.1693
β_{LnVeh}	0.2531	0.3307	0.3835	0[b]	0.5560	0.0334	0.2716	0.3955
β_{LnPed}	0.1480	0.1902	0.0862	0.2170	0.1271	0.2227	0.4077	0.4455

[a] negative coefficient indicates that the number of crashes decreases with an increase in the value of the variable. A positive coefficient indicates that the number of crashes increases with an increase in the value of the variable. For example, the coefficient for number of legs is positive for total crashes (i.e., 0.9119), which indicates that more crashes are associated with four-leg than three-leg intersections.
[b] The coefficient 0 denotes that the corresponding variable was excluded from the model.

Table 25. Estimates of Coefficients for Safety Performance Functions Developed Based on a Reference Group Consisting of Crashes at Unsignalized and Signalized Intersections.

Coefficient[a]	Total	FI	Rear End	Angle	FI RearEnd	FI Angle	Ped_rel	FI Ped_rel
β_{0B}	−12.208	−12.450	−14.6901	−13.091	−15.0960	−13.732	−15.558	−16.7892
β_{0A}	−12.357	−12.580	−14.9795	−13.232	−15.2513	−13.872	−15.861	−17.0110
β_{Legs}	0.2848	0.2699	0.1861	0.5763	0.1246	0.7313	0.3507	0.4063
β_{M_Lanes}	0.0823	0.1008	0.0078	0.1455	0.0240	0.0862	0.0658	0.0662
$\beta_{M\_MT\_R}$	0.4186	0.3653	0.3841	0.5271	0.3529	0.4530	0.1466	0.1841
β_{M_LTL}	−0.2440	−0.2138	−0.2805	−0.2236	−0.2574	−0.2163	0[b]	0
$\beta_{M\_PK\_01}$	0.3835	0.2202	0.5423	0.2731	0.3434	0.1351	0	0
$\beta_{M\_Bike\_01}$	−0.5514	−0.3950	−0.5235	−0.3937	−0.3570	−0.3425	−0.7398	−0.7446
β_{C_Lanes}	0.3435	0.3194	0.3776	0.2942	0.3379	0.2836	0.2145	0.2093
β_{LnVeh}	0.5035	0.3901	0.7516	0.2563	0.6646	0.1919	0.2897	0.3813
β_{LnPed}	0.1079	0.1826	0.0496	0.1739	0.1225	0.2165	0.5350	0.5280

[a] negative coefficient indicates that the number of crashes decreases with an increase in the value of the variable. A positive coefficient indicates that the number of crashes increases with an increase in the value of the variable. For example, the coefficient for number of legs is positive for total crashes (i.e., 0.2848), which indicates that more crashes are associated with four-leg than three-leg intersections.

[b] The coefficient 0 denotes that the corresponding variable was excluded from the model.

Table 26 shows the results of an EB before-after evaluation. For each crash type in this table, the SPFs estimated from the corresponding type of crashes at reference sites were used to predict the expected number of crashes at treatment sites had PHB not been installed. In general, the results support positive safety effects of PHBs for crash types considered regardless of reference groups. Based on reference group 1 (unsignalized intersections), the effects of PHBs are statistically significant for total, FI, rear end, and pedestrian-related crashes but not significant for angle, FI angle, and FI pedestrian-related crashes although the effects are still positive. Because the estimated SPF for FI pedestrian-related crashes is subject to larger uncertainty due to a small sample size, researchers also performed a sensitivity analysis by estimating the expected number of FI pedestrian-related crashes in step 2 of EB implementation using prediction from pedestrian-related crash SPF (developed based on a larger sample size and consequently subject to smaller uncertainty) after multiplying the ratio of FI pedestrian-related crashes and pedestrian-related crashes at unsignalized intersections. The estimated crash reduction for FI pedestrian-related crashes based on pedestrian-related crash SPF was statistically significant, which is deemed a consequence of more precise SPF estimation based on a larger sample size.

Based on reference group 2 and reference group 3, all crash types evaluated became statistically significant.

Table 26. Results of Empirical Bayes Before-After Safety Evaluations.

RG[a]	Crash Type	Observed	EB ($\hat{\pi}$)	$\hat{\theta}$ (SE)	95% CI for θ	90% CI for θ	%CR[b]
1	Total	600	679.1	0.883 (0.046)	(0.792, 0.973)	(0.807, 0.958)	11.7**
1	FI	230	283.8	0.808 (0.067)	(0.678, 0.939)	(0.699, 0.918)	19.2**
1	Angle	112	128.1	0.870 (0.103)	(0.668, 1.071)	(0.701, 1.039)	13.0
1	FI angle	42	41.9	0.991 (0.185)	(0.628, 1.353)	(0.687, 1.294)	0.9
1	Rear end	206	234.2	0.878 (0.074)	(0.733, 1.022)	(0.756, 0.999)	12.2*
1	FI rear end	78	121.5	0.639 (0.084)	(0.474, 0.805)	(0.501, 0.778)	36.1**
1	Pedestrian related	19	33.1	0.567 (0.143)	(0.288, 0.847)	(0.333, 0.801)	43.3**
1	FI pedestrian related	19	24.9	0.755 (0.191)	(0.381, 1.128)	(0.442, 1.067)	24.5
1	FI pedestrian related[c]	19	29.0	0.648 (0.164)	(0.326, 0.969)	(0.379, 0.916)	35.2**
2	Total	600	724.0	0.828 (0.043)	(0.743, 0.913)	(0.757, 0.899)	17.2**
2	FI	230	334.7	0.685 (0.056)	(0.575, 0.796)	(0.593, 0.777)	31.5**
2	Rear end	206	264.1	0.778 (0.065)	(0.651, 0.906)	(0.671, 0.885)	22.2**
2	Angle	112	157.8	0.706 (0.081)	(0.547, 0.866)	(0.573, 0.840)	29.4**
2	FI rear end	78	115.6	0.672 (0.087)	(0.501, 0.843)	(0.529, 0.815)	32.8**
2	FI angle	42	75.5	0.552 (0.099)	(0.359, 0.745)	(0.390, 0.713)	44.8**
2	Pedestrian related	19	29.9	0.630 (0.153)	(0.329, 0.930)	(0.378, 0.881)	37.0**
2	FI pedestrian related	19	31.8	0.591 (0.147)	(0.303, 0.879)	(0.350, 0.832)	40.9**
3	Total	600	732.2	0.818 (0.043)	(0.734, 0.903)	(0.748, 0.889)	18.2**
3	FI	230	306.6	0.748 (0.062)	(0.626, 0.870)	(0.646, 0.850)	25.2**
3	Rear end	206	258.5	0.795 (0.067)	(0.664, 0.927)	(0.685, 0.905)	20.5**
3	Angle	112	143.9	0.774 (0.092)	(0.595, 0.954)	(0.624, 0.925)	22.6**
3	FI rear end	78	108.7	0.714 (0.094)	(0.529, 0.899)	(0.559, 0.869)	28.6**
3	FI angle	42	55.0	0.755 (0.141)	(0.479, 1.031)	(0.524, 0.986)	24.5*
3	Pedestrian related	19	34.7	0.543 (0.133)	(0.282, 0.804)	(0.324, 0.761)	45.7**
3	FI pedestrian related	19	34.2	0.550 (0.137)	(0.281, 0.819)	(0.325, 0.775)	45.0**

[a] Abbreviations used in column headings:

- RG = reference groups, where 1 = unsignalized Intersections, 2 = signalized intersections, and 3 = both unsignalized and signalized Intersections
- Observed = observed crashes in the after period
- EB ($\hat{\pi}$) = EB estimate representing the predicted number of crashes in the after period had PHBs not been installed
- $\hat{\theta}$ = estimated index of effectiveness
- SE = standard error
- CI = confidence interval
- %CR = percent crash reduction = $100(1-\hat{\theta})$.

[b] Statistical level indications:

* Statistically significant results with 90 percent confidence level (also known as 10 percent significant level)

** Statistically significant results with 95 percent confidence level (also known as 5 percent significant level)

[c] Indicates the results from the sensitivity analysis using the prediction based on pedestrian-related crash SPF for prediction after being adjusted by the ratio of FI pedestrian-related crashes and pedestrian-related crashes at unsignalized intersections.

Cross-Sectional Observational Evaluation Based on After-Period PHB Sites

ADOT was also interested in assessing the effects of site characteristic variables on crashes at PHB sites, especially the distance between a TCS and a PHB. There are 186 PHB sites (with PHBs installed between 2000 and 2016) available for this analysis. Table 27 contains the summary of site characteristics variables for PHB sites used in this cross-sectional observational evaluation.

Table 27. Descriptive Statistics for PHB Sites Used in Cross-Sectional Observational Analysis.

Variable		**PHB (186 Sites)**		
		Minimum	**Maximum**	**Average**
Legs		2	4	3.4
M_Lanes		2	9	4.5
M_LTL		0	2	0.8
M_PK_01		0	1	0.1
M_Bike_01		0	1	0.6
C_Lane		0	6	1.4
Veh (AADT)		1,385	50,510	23,500
PB_Vol_MC		40	2,130	475
Sig_Dist (ft)		277	13,249[a]	1,548
M_MT_R	Value (number of sites)	Not raised (119), raised (67)		
PSL_group	Value (number of sites)	35 or less (97), 40 or more (89)		

[a] If Sig_Dist was greater than 1,500 ft, the value was set to 1,500 ft. At a certain distance, a TCS would probably not affect the operations or safety of a neighboring intersection. This distance was assumed to be 1,500 ft based on engineering judgment.

Crash prediction models based on crash data from PHB sites after installation of PHBs were developed using generalized linear models. The goal of this study was to identify relationships between roadway characteristics and crashes, by crash type. Variables were removed from the model if counter-intuitive results were found and the variable was not significant. In some cases, variables that were not statistically significant were retained in the models (as long as the signs of coefficients were not counter-intuitive) to examine trends. Table 28 contains the estimated regression coefficients for each crash type along with the p-value for the variable.

The negative binomial regression models with variables in Table 27 as independent variables were employed to develop prediction equations for crashes at PHB sites. The basic prediction equation being considered for the different crash type was:

$$\mu = exp\big(\beta_0 + \beta_{\text{Legs}} \times \text{Legs} + \beta_{\text{M\_Lanes}} \times \text{M\_Lanes} + \beta_{\text{M\_MT\_R}} \times \boldsymbol{I}[\text{M\_MT\_R} = NotRaised] + \beta_{\text{PSL\_group}} \times \boldsymbol{I}[\text{PSL\_group} = 35 \text{ or less}] + \beta_{\text{M\_LTL}} \times \text{M\_LTL} + \beta_{\text{M\_PK\_01}} \times \text{M\_PK\_01} + \beta_{\text{M\_Bike\_01}} \times \text{M\_Bike\_01} + \beta_{\text{C\_Lanes}} \times \text{C\_Lanes} + \beta_{\text{LnVeh}} \times Ln(\text{Veh}) + \beta_{\text{LnPed}} \times Ln(\text{Ped}) + \beta_{\text{Sig\_Dist}} \times \text{Sig\_Dist}\big)$$

Table 28. Estimated Regression Coefficients of SPFs Developed for Crashes at PHB Sites.

Coefficient	Total	FI	Rear End	FI Rear End	Angle	FI Angle	Ped_rel	FI Ped_rel
β_0	−13.5812 (<0.0001)	−15.948 (<0.0001)	−18.225 (<0.0001)	−23.4423 (<0.0001)	−12.940 (<0.0001)	−15.395 (<0.0001)	−21.029 (<0.0001)	−20.9389 (<0.0001)
β_{Legs}	0.0849 (0.4947)	0.0801 (0.4931)	0.1570 (0.1331)	0.0443 (0.6682)	0.2366 (0.1910)	0.1491 (0.4617)	0.2282 (0.3358)	0.3231 (0.2142)
β_{M_Lanes}	0.1234 (0.0557)	0.0496 (0.4600)	0.1365 (0.0657)	0	0.1541 (0.0904)	0	0.3856 (0.0073)	0.3787 (0.0159)
$\beta_{M\_MT\_R}$	0.2730 (0.0621)	0.2221 (0.1055)	0.3316 (0.0502)	0.3713 (0.0112)	0.2664 (0.2479)	0.1610 (0.4254)	0.9286 (0.0028)	0.8014 (0.0419)
β_{PSL_group}	−0.1407 (0.2427)	−0.1512 (0.2070)	−0.2826 (0.0328)	−0.2668 (0.0530)	0	0	0	0
β_{M_LTL}	−0.0376 (0.6418)	0	−0.1061 (0.2522)	0	−0.1076 (0.3659)	0	0	-0.1091 (0.5913)
$\beta_{M\_PK\_01}$	0	0	0.1246 (0.6083)	0.2633 (0.3430)	0.1065 (0.7460)	0	0	0
$\beta_{M\_Bike\_01}$	−0.2107 (0.0701)	−0.1073 (0.3747)	−0.1163 (0.3547)	−0.0764 (0.5782)	−0.3113 (0.0648)	−0.2440 (0.2165)	0.3677 (0.1642)	0.2737 (0.3140)
β_{C_Lanes}	0.1802 (0.0466)	0.2052 (0.0166)	0	0	0.3706 (0.0026)	0.4765 (0.0004)	0.1342 (0.4439)	0.0966 (0.6033)
β_{LnVeh}	0.6733 (<.0001)	0.8434 (<.0001)	1.0465 (<.0001)	1.5901 (<.0001)	0.3715 (0.0369)	0.5557 (0.0009)	0.5968 (0.0315)	0.5939 (0.0464)
β_{LnPed}	0.1131 (0.0642)	0.1140 (0.0750)	0.1799 (0.0074)	0.1172 (0.1121)	0.0714 (0.4152)	0.1678 (0.1146)	0.4706 (0.0008)	0.4478 (0.0020)
β_{Sig_Dist}	0	0	−0.0004 (0.0595)	−0.0004 (0.0608)	0	0	0	0

Notes:
1. The coefficient 0 denotes that the corresponding variable was excluded from the model.
2. P-values are provided in parentheses.
3. Cells are highlight in light gray when the p-value is between 0.05 and 0.1.
4. Cells are highlighted in dark gray with white text when the p-value is less than 0.05.

where:

- μ = predicted daily crashes
- **I =** indicator function taking a value 1 if the condition in [ ] is satisfied, and 0 otherwise
- 'Ln' represents a natural log
- C_Lanes = number of through lanes on the cross street
- Legs = number of legs at the intersection (2 = midblock)
- M_Bike_01 = 1 if a bicycle lane is present on either side of major street, and 0 otherwise
- M_Lanes = number of through lanes on the major street
- M_LTL = number of approaches on the major street with a left-turn lane
- M_MT_R = median type, raised or not raised
- M_PK_01 = 1 if a parking lane is present on either side of major street, and 0 otherwise
- Ped = major- and cross-street daily pedestrian volume
- PSL_group = posted speed limit group, 35 mph and less, or 40 mph and more
- Sig_Dist = the distance between the PHB and the nearest signal (ft), if Sig_Dist > 1,500 ft, then Sig_Dist = 1,500 ft
- Veh = major-road AADT

For total crashes, the roadway geometric variables that have significant effects on crashes for PHBs include the number of lanes on the major roadway, median treatment, bike lane presence, and number of lanes on the cross street. These relationships are as expected, with more lanes on either the major or cross street being associated with more crashes and the presence of a raised median or pedestrian refuge island being associated with fewer crashes. The presence of a bike lane at the PHB being associated with fewer total crashes is a positive finding.

Both pedestrian-related crashes and FI pedestrian-related crashes had stronger findings with respect to the number of lanes on the major street and the presence of a raised median. Both of these variables were significant at the 0.05 level for pedestrian-related crashes, compared to only being significant at the 0.1 level for total crashes. Several studies have documented the benefit of a raised median/refuge island for pedestrians (Zegeer et al. 2017a), and this ADOT study supports that finding.

The variable that was always significant for each crash type was vehicle volume, which was expected. Pedestrian volume was significant for most of the crash types. Angle crashes are the only crash type where having the pedestrian volume in the model was of questionable value. Posted speed limits were grouped into 35 mph and below, or 40 mph and above. The variable was only statistically significant for rear-end crashes. More rear-end crashes are predicted on roads 40 mph and above than on roads 35 mph and below. Speed limit grouping was not an important variable for pedestrian-related crashes, nor was it a significant variable for FI pedestrian-related crashes.

The distance to the traffic signal variable only remained in the rear-end and FI rear-end crash type models where it was significant at the 0.1 level. More crashes are associated with shorter distances between a TCS and a PHB; however, the effect of the distance to traffic signal variable on predicting rear end or fatal and injury rear end crashes is less influential than or similar to the effect of higher (compared to lower) speeds or the impact of not having a raised median (compared to having a raised median).

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

OPERATIONAL DATA ANALYSIS CONCLUSIONS

Ten locations in Arizona representing higher-operating-speed conditions (85th-percentile speed ranged between 44 and 54 mph) were selected for inclusion in this study. Data were collected using a multiple video camera setup. The final dataset reflected about 40 hours of video data and included 1,214 pedestrians or bicyclists crossing at PHBs.

Overall, driver yielding for these 10 sites averaged 97 percent. The study focused on higher-speed roads (45 to 50 mph) than did a 2016 FHWA study (Fitzpatrick et al. 2016) but found a similar driver-yielding rate as observed on lower-speed roads (97 percent).

While drivers are yielding to pedestrians in most cases, they are not as compliant with the traffic control device. Only 90 percent of the drivers stopped and stayed stopped until the end of the steady red indication. During the flashing red indication, about 59 percent of the drivers rolled through the intersection without stopping initially. Most of those rolling stops occurred during the queue discharge after the pedestrian had completed their crossing.

Actual, or non-staged, pedestrians or bicyclists were preferred in the data collection efforts, but at sites where pedestrian volumes were low, members of the research team conducted staged crossings to obtain a larger sample of motorist behavior data. A large proportion of the non-staged pedestrians and bicyclists observed activated the PHB or crossed when the device was operational. A few sites had many pedestrians/bicyclists crossing without activating the PHB. These sites had large gaps where the pedestrian or bicyclist was able to cross without affecting the major-road traffic. The percent of the pedestrians/bicyclists observed using the pedestrian pushbutton was only 66 percent, which reflects the large number of pedestrians/bicyclists using the large vehicle gaps for their crossings. The 2016 FHWA study (Fitzpatrick et al. 2016) found that a greater number of pedestrians activated the device when on 45-mph posted speed limit roads than on 40-mph or less roads. The study also found that when the hourly volume for both approaches was 1,500 vehicles/hr or more, the percentage of pedestrians activating the PHB was always 90 percent or more.

SAFETY EVALUATION CONCLUSIONS

The safety study included 343 sites. The sites consisted of 186 PHBs, 56 signalized intersections, and 101 unsignalized intersections. PHB installation dates were obtained from the various government agencies, and 52 PHBs installed between 2011 and 2015 were identified for use in the EB before-after analysis. Reference groups consisting of signalized and unsignalized intersections were chosen from intersections in close proximity to the 52 before-after PHB sites and were used in the EB before-after analysis.

Previous studies have found a safety benefit with the installation of a PHB, and this study supports that finding. When considering the reference group consisting of unsignalized intersections, crash reductions were found for the following crash types: total crashes, FI crashes, FI rear-end crashes, and pedestrian-related crashes. Crash reductions were also found for all other crash types studied when using the unsignalized intersection reference group; however, the reductions were not statistically significant.

The safety performance of PHBs could be compared to only unsignalized intersections or compared to both unsignalized and signalized intersections. In most cases, a PHB is installed at an intersection that previously was unsignalized; however, there are cases when the PHB replaces a TCS (or is installed in lieu of a traffic signal). The level of pedestrian activity for a PHB intersection is more similar to signalized than unsignalized intersections; therefore, comparing PHBs to signalized intersections may be more valid. Each reference group has potential limitations; therefore, the research team considered three different reference groups: unsignalized intersections, signalized intersections, and both unsignalized and signalized intersections combined. For the signalized and combined unsignalized/signalized intersection groups, all crash types evaluated showed statistically significant reductions in occurrence (e.g., total crashes, FI crashes, rear-end crashes, FI rear-end crashes, angle crashes, FI angle crashes, pedestrian-related crashes, and FI pedestrian-related crashes).

For the 52 PHB sites included in the EB before-after study, regardless of the reference group being considered, a reduction was observed in pedestrian-related crashes, as expected. Reductions were also observed for (total) FI crashes and for rear-end crashes, the two types where there was concern that installing the PHB might increase their occurrence.

A cross-sectional study was conducted with a larger number of PHB sites across Arizona to identify relationships between roadway characteristics and crashes at PHB sites, especially with respect to the distance between a TCS and a PHB. The cross-sectional study could include more PHB sites because crash data before the installation of the PHB were not needed; therefore, more of the older installations (prior to 2011) could be considered.

For total crashes, the roadway variables with relationship to crashes at PHBs include the number of lanes on the major roadway, median treatment, bike lane presence, and number of lanes on the cross street. These relationships are as expected with more lanes on either the major or cross street being associated with more crashes, and with the presence of a raised median or pedestrian refuge island being associated with fewer crashes. The presence of a bike lane at the PHB being associated with fewer total crashes is a positive finding. Several studies have documented the benefit of a raised median/refuge island for pedestrians, and this ADOT study supports that finding. The distance to the adjacent traffic signal variable only remained in the rear-end and FI rear-end crash type models, where it was significant at the 0.1 level. When reviewing the magnitude of the effect on rear-end crashes, the distance between TCS and PHB is less influential than median presence or speed limit groups (35 mph or less versus 40 mph or more).

This ADOT study permitted the inclusion of a larger number of sites and a larger number of months of before-and-after data than other recent studies, which enabled finding statistically significant results. Crash reductions were found to be significant at the 0.05 significance level for total crashes, FI crashes, FI rear-end crashes, and pedestrian-related crashes. Other crash types are also associated with significant reductions depending upon the reference group being used and statistical significance level being accepted.

DEVELOPING RECOMMENDATIONS FOR CHANGES TO ADOT DOCUMENTS

The methodology used to develop recommendations for the evaluation, design, and operation of PHBs is based on the following sources:

- Review of past literature on PHB evaluation, including guidance provided in the Institute of Transportation Engineers (ITE) *Traffic Control Devices Handbook* (ITE 2013)
- Review of the nationwide survey responses on the application, evaluation, design, and operation of PHBs that was conducted as part of this study and documented in Chapter 2 of this report
- Results of the research on driver and pedestrian behavior at PHB crossings on high-speed streets along with the research team's observations of PHB design and operation during that research (see Chapter 3 of this report)
- Results of the safety analysis of Arizona's PHB crossings (see Chapter 4 of this report)

For the operational analysis at 10 PHB locations on high-speed roadways, only two of those were on state highways. Furthermore, the majority of the PHBs evaluated across the state were PHBs installed by local jurisdictions. A variety of design and operational characteristics were employed in the PHBs implemented across the state although those used in the analysis appeared to be largely designed and operated in compliance with the MUTCD with the Arizona Supplement.

Using the findings from this research, the research team developed suggested changes to TGP 640. This chapter provides a synopsis of those suggestions. The technical details for the recommendations are contained in the technical memoranda of this study.

RECOMMENDATIONS FOR EVALUATION OF PEDESTRIAN HYBRID BEACON CROSSINGS

Existing Evaluation Criteria

The guidance for the evaluation of locations for PHBs by ADOT in TGP 640 was influenced by the evaluation criteria and ranking procedures developed by Tucson and Phoenix. The evaluation methods in Tucson and Phoenix are not only used to justify the application of a PHB at a location, but to prioritize and rank competing locations where budgets are limited to identify those locations most in need of pedestrian crossing assistance.

ADOT TGP 640 provides a point system for evaluating candidate locations. The existing evaluation guidelines recommend against installing PHBs on roadways with speed limits greater than 45 mph and encourage a comprehensive review of pedestrian crossing safety to identify the most effective treatment.

MUTCD Figures 4F-1 and 4F-2 use speeds, vehicles per hour, pedestrian crossings per hour (pph), and crosswalk length for evaluation purposes, noting that at least 20 pph applies as the lower threshold volume for pedestrian crossings to evaluate a location for application of a PHB. With respect to the speed variable, the MUTCD allows the consideration of posted or statutory speed limit or the 85th-percentile speed. The MUTCD does not provide guidance related to the maximum operating speed or speed limit where a PHB may be inappropriate. The revisions in the Arizona Supplement of the MUTCD remove the MUTCD guidance in Section 4F.02, paragraph 04, item A, regarding not installing a PHB within 100 ft of an intersection or a driveway controlled by a STOP or YIELD sign. The analysis in this study supports this revision because the cross-sectional analysis found no statistical difference in crashes between midblock locations and those PHBs at three- or four-leg intersections.

Recommended Changes in the PHB Evaluation Criteria

A 2017 FHWA publication, released as part of the Every Day Counts program, is referred to as the Safe Transportation for Every Pedestrian (STEP) Guide (Blackburn 2018). The STEP Guide was last updated in July 2018 to provide crossing treatments for practitioners to consider for different combinations of roadway configuration (number of lanes/raised median presence), posted speed limits, and vehicle ADTs. ADOT recently developed an internal Arizona-specific STEP guide for use by the state and local governments.

The following are suggested changes to TGP 640:

- **Reference the Arizona STEP** — Consult the FHWA STEP Guide or the Arizona-specific STEP guide as a first step in determining if a crossing location is a candidate for a PHB that would require further study per ADOT TGP 640 criteria, or if the location is a candidate for an alternate crossing treatment.
- **Revise location consideration based on posted speed limit**—The guidance statement in TGP 640 states that "PHBs should not be installed on roadways with speed limits greater than 45 mph". This guidance can be updated, based on the findings of this study, to revise the upper speed limit for PHB application. The results from the operational data analysis and safety analysis indicate that a PHB will operate at a good level of safety on a street with a posted speed of 50 mph. Furthermore, no other countermeasure is available for a higher-speed street other than a traffic signal. The ADOT research did not include any PHBs on streets of 55 mph or higher because no such installation is available to evaluate.
- **Update Exhibit 640-A for evaluating locations for a PHB**—The Arizona Supplement to the 2009 MUTCD allows for agencies within the state to develop and use their own methods and procedures to evaluate a crossing for PHB application. The tabular format in ADOT TGP 640 with a requirement of 35 points appears to be well thought out, straightforward, and easy to use. It does not require a burdensome amount of data collection. Researchers recommend retaining this exhibit but suggest some modifications to the exhibit. These include conducting pedestrian counts during peak crossing times rather than peak vehicular traffic; adding evaluation points for speeds of 50 mph; revising ADT levels to be consistent with the FHWA STEP guide; and guidance for using raised medians. More details of these and further suggestions are documented in a separate technical memorandum.
- **Add latent crossing demand information as criteria**— If needed, use an engineering study to provide guidance to allow for the evaluation of latent crossing demand that may exist at a

crossing. A latent crossing demand study (if conducted) would document the method used to estimate potential crossing numbers to determine if a controlled crossing (PHB) would be recommended on a state highway.

RECOMMENDATIONS FOR PEDESTRIAN HYBRID BEACON DESIGN

Existing Guidance on Design Features

TGP 640 provides little to no guidance for PHB design at a crossing, other than to reference the MUTCD. The only standard drawing that exists for PHBs involves the beacon face that is a part of Standard Drawing T.S. 8-5. Most PHBs are designed by consultants and are approved by the district traffic engineers, some of whom may not have previous experience with the design and operation of PHBs. To promote uniformity and to assist consultants and the district engineers in the design of PHBs, a standard drawing for a PHB crossing is recommended to include those features to be either considered or recommended for a PHB crossing.

Recommended Design Features for a PHB Crossing Standard Drawing

The research team suggests the following design features for a standard drawing of a PHB crossing:

- **Include an overview drawing**—An ADOT standard drawing for PHB crossings would include the recommended signs and pavement markings along with other features that are intended to optimize performance of the traffic control device. Other optional traffic signs and pavement markings that may be considered would be identified as “optional.”
- **Show crosswalk markings**—The MUTCD requires PHBs to have marked crosswalks. The standard drawing would show high-visibility crosswalk markings and provide an illustration for a 15-ft-wide crosswalk per the ADOT Standard Drawing M-2 (page 1 of 3) for a midblock crosswalk. A wider crosswalk may be considered for higher-speed streets or higher-volume crossings based on engineering judgment.
- **Provide a crossing on only one side of an intersection**—According to the Arizona Supplement of the MUTCD, PHBs may be installed at midblock locations or at intersections. When the PHB is installed at an intersection, it is beneficial to direct pedestrians crossing the main street to the crossing controlled by the PHB. The PHB is not intended to control the intersection or crosswalks on both sides of an intersection.
- **Prohibit crossing on the unmarked crosswalk at an intersection**—When used at an intersection, it is recommended to install DO NOT CROSS HERE/USE CROSSWALK (R9-3 series) signs (with an arrow pointing to the marked crosswalk) to eliminate the unmarked crosswalk on the other side of the intersection and to direct pedestrians to use the PHB.
- **Show an advance stop line**—Based on recent research (Zegeer et al. 2017a, 2017b), an advance stop line (along with a STOP HERE ON RED sign) placed 30 to 50 ft in advance of the marked crosswalk is expected to improve the safety performance of a PHB. To ensure a stopped motorist will be able to easily see the overhead beacon faces, the stop line would then also be located a recommended 40 to 60 ft in advance of the overhead signal mast arm (when one exists). A stop line that is 18 inches wide per ADOT Standard Drawing M-2 is recommended.

- **Show STOP HERE ON RED (R10-6) and STOP HERE FOR PEDESTRIANS (R1-5b or R1-5c) signs**—Arizona state law requires that motorists yield to pedestrians regardless of lack of signage or signal; in addition, the PHB requires motorists to stop for the red indication (similar to a traffic signal); therefore, the STOP HERE ON RED (R10-6 or R10-6a) sign is recommended for use at the advance stop line. The research team recommends that the standard drawing show a STOP HERE ON RED (R10-6 or R10-6a) sign placed at the advance stop line on each approach to the PHB crosswalk.
- **Include CROSSWALK STOP ON RED (R10-23AZ) sign**—The CROSSWALK STOP ON RED (R10-23) (with symbolic circular red ball) sign is mandatory per the MUTCD and is required to be placed adjacent to the PHB face. Arizona adopted a modified version of that sign for the MOAS without the symbolic circular red ball, which is recommended to be referenced on the standard drawing. While the National Committee on Uniform Traffic Control Devices has recommended FHWA make the R10-23 sign optional in the next edition of the MUTCD, for now the standard drawing may reference the CROSSWALK STOP ON RED (R10-23AZ) sign in the Arizona MOAS.
- **Show an optional sign that encourages motorists to proceed when appropriate**—A concern associated with PHBs is that drivers do not always realize that they may proceed once the pedestrian has crossed their half of the street. This is not a safety issue but relates to traffic efficiency, especially at PHBs that are not synchronized with adjacent traffic signals. The research team recommends that ADOT identify a regulatory sign that encourages motorists to proceed after stopping once the crossing is clear on their half of the street, add the sign to the Arizona MOAS, and show the sign as optional on the standard drawing.
- **Include guidance about pedestrian detection by pushbutton**—Pedestrian detection can be accomplished via several technologies, but the most common is through a pushbutton. In anticipation of the eventual approval of public right-of-way access guidelines, providing accessible pedestrian signal (APS) pushbuttons for all new PHB crossings is recommended, even when another form of automated pedestrian detection is provided. It is recommended that the APS pushbutton provide some form of feedback to the pedestrian indicating that the call has been placed into the signal controller (audible message and/or indicator light). The MUTCD (Figure 4E-3) recommends the pushbutton to be located between 1.5 and 6 ft from the back of the curb (when feasible). It is desirable to place the mast arm pole in the appropriate location (if there are no underground or overhead utility conflicts) to avoid the need to provide a second pushbutton pole on either side of the street.
- **Include guidance about nighttime lighting**—Nighttime lighting is recommended for PHB pedestrian crossings, especially when crossing activity is prevalent at night. For streets that have four or more lanes, providing lighting over both sides of the street is recommended. In instances where an overhead utility conflict exists over one side of the street, a longer mast arm with a light fixture at the end of the mast arm can be explored to provide double-sided lighting at wider street crossings. It is recommended to use Light-emitting diode (LED) light fixtures to minimize power costs, reduce maintenance needs, and provide a light source that allows drivers to better detect pedestrians at night.

- **Show the number and placement of PHB signal faces**—Provide at least two PHB signal faces that meet the minimum visibility requirements contained in Table 4D-2 from the MUTCD on each approach to a PHB. MUTCD Figure 4D-3 recommends that for a traffic signal, one signal face be installed over each through lane for approaches with posted, statutory, or 85th-percentile speed of 45 mph or higher. Since PHBs may be slightly less recognizable to motorists than a traffic signal, it is recommended that one PHB signal face be placed over each through lane for streets with an approach speed limit of 40 mph or higher. Supplemental right-side bracket mount and/or median-mount PHB faces may also be considered for higher-speed applications.
- **Show backplates for PHB faces**—The researchers recommend using a retroreflective border on the backplates for all new PHB applications and referencing ADOT Standard Drawing T.S 8-5 to include backplates with a reflective border.
- **Show advance pedestrian, bicycle, or school crossing warning signs (optional)**—Advance warning for a PHB crossing (if used) typically consists of an Advance Pedestrian Warning (W11-2) sign with a distance (specified in feet) or an AHEAD supplemental plaque. If the crossing is for a multi-use trail, the advance warning sign may be a Trail Crossing (W11-15) sign or Bicycle Crossing (W11-1) sign if placed in advance of a bikeway crossing. If the PHB is for a crossing used on a designated school route, the advance sign may be an advance S1-1 sign with the supplemental distance (specified in feet) or AHEAD plaque.
- **Pedestrian crossing warning sign assembly**—An evaluation on whether to place a Pedestrian Crossing (W11-2) sign with a supplemental W16-7P downward diagonal arrow plaque is to consider the geometrics and other signs placed at the PHB crossing to determine if it contributes to over-signing. The crosswalk assembly may be considered if there is a potential issue with limited visibility of the PHB crossing. Consideration may also be given to advance PED XING pavement stencils (instead using pedestrian crosswalk assembly signs) for limited-visibility conditions.
- **Comment on spacing of PHB crossings**—The researchers recommend requiring a PHB to be located at least 300 ft from another controlled crossing. If placed within 600 ft, consideration for synchronization of the PHB to the adjacent traffic signal is recommended.

Other Recommended Design Considerations for PHB Crossings

The research team suggests the following design considerations for PHB crossings:

- **Two-stage PHB crossings**— Researchers recommend noting on the standard drawing that a two-stage PHB may be considered if a raised median of sufficient width to accommodate pedestrians is present. Local agencies in the state have installed a few successful two-stage PHB crossings where a sufficiently large raised median is provided to accommodate pedestrians. One of the main advantages of a two-stage crossing is that the pedestrian clearance is much shorter. For crossing locations located near an adjacent traffic signal, the PHB can be synchronized with the adjacent signals in both directions and allow greater operational flexibility by making it easier to preserve bandwidth. In most instances, it is recommended to stagger the two-stage crosswalks, and corral pedestrians between the two crossings. For these applications, APS pushbuttons are to be provided in the median at both crossings, and the treatments used to corral the pedestrians in the median are to be forgiving to errant automobiles and meet applicable crash standards. For wider medians (20 ft or wider), there is typically not a need to stagger the crosswalks because pedestrians are less likely to look at the incorrect pedestrian signal face.

- **Accommodating bicycles and pedestrians at bike and trail crossings**—The Tucson BikeHAWK concept for side-by-side pedestrian and bicycle crossings with separate pushbuttons may be considered for potential use at busy at-grade trail crossings across state highways. It is recommended for ADOT to consider developing guidelines to implement this concept where appropriate.

RECOMMENDATIONS FOR PEDESTRIAN HYBRID BEACON OPERATION

The primary standards, guidance, and options for the operation of PHBs are contained in the MUTCD and its Arizona Supplement within Sections 4F.02 and 4F.03. The suggested operational guidance to be added to the TGP 640 was provided in a technical memorandum to ADOT and included discussion of the following:

- **Hot-button operation versus synchronization with adjacent traffic signals for most PHB applications.** Guidance as to when to not provide synchronization would allow flexibility in the operation and better pedestrian service, while also providing guidance when synchronization is beneficial for those locations close to an adjacent traffic signal.
- **The duration of the WALK interval, pedestrian clearance interval, and flashing and steady yellow intervals.** Guidance for most of these intervals are defined in the MUTCD and the Arizona Supplement, but it would be beneficial to include the information in the TGP 640 with some flexibility where desirable for determining intervals.
- **The all-red clearance interval prior to the start of the WALK interval.** Providing a short all red clearance interval between the onset of the red vehicle traffic signal and the start of the pedestrian WALK signal may be desirable. Guidance is provided on the duration of the clearance interval.
- **The buffer interval at the end of the pedestrian countdown sequence before the PHB becomes dark for motorists.** Because buffer intervals at some PHBs in the study were not consistent with the MUTCD Arizona Supplement guidance and a 2011 FHWA official interpretation (Kehrli 2011), inserting a recommendation in the TGP 640 for a consistent 4-second buffer would be desirable.
- **A minimum vehicle interval between subsequent PHB activations.** Because motor vehicle traffic needs to be served, language inserted in the TGP 640 would provide guidance for a minimum interval and a range of duration.
- **PHBs and school crossing locations.** ARS 28-797, in conjunction with ADOT Traffic Safety for School Area Guidelines, excludes locating a 15 mph school crossing at or within 600 ft of a traffic signal on state highways. The same provision could be made in the TGP 640 for PHBs.
- **The PHB display when an equipment malfunction occurs.** It could benefit pedestrians and motorists if the TGP 640 had guidance modeled after the ITE Traffic Control Devices Handbook (ITE 2013).

RECOMMENDATIONS FOR ADDITIONAL RESEARCH

Additional research might study ways to effectively educate motorists, pedestrians, and bicyclists on how to use and respond to PHBs.

While two of the sites in the study were PHBs modified by the City of Tucson as BikeHAWK beacons, more research is needed to better evaluate these novel traffic control devices. More information is needed on how to effectively communicate with bicyclists about using the pedestrian signal or establishing a separate signal for bicyclists.

For PHBs situated close to traffic signals, additional research is recommended to determine under what circumstances it is desirable to synchronize PHBs with the adjacent signals. By avoiding unnecessarily stopping motorists at the signal or the PHB crossing, there may be potential for fewer red-light violations or rear-end collisions at either the signal or the PHB.

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