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Factors influencing road user behaviors and motivations around pedestrian hybrid beacons and rectangular rapid flashing beacons in North Carolina

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ABSTRACT

The safety and operational effectiveness of pedestrian hybrid beacons (PHBs) and rectangular rapid flashing beacons (RRFBs) are well established. However, such performance depends upon pedestrians crossing at the designated locations and actuating these traffic control devices prior to crossing. This research investigated factors linked to those pedestrian behaviors in pedestrian crossings through an observational study of actuation and yield rates based on field video footage and a survey of pedestrian attitudes and motivations at urban locations in North Carolina. Among other findings, the observational study found evidence of a link between pedestrian refuges and increased actuation and yield rates, whereas those two metrics were found to worsen at crossings where a sidewalk is absent on one side. We found higher odds of yielding for PHBs, while we found pedestrians less likely to actuate those devices compared with RRFBs. In general, factors such as increased traffic and longer crossing distances were associated with higher ARs. Accordingly, survey responses indicated that conditions and roadway elements that increase friction or safety risk during the crossing (heavy traffic, fast cars, and longer crossing distances) motivate pedestrians to actuate the devices more frequently. A comparison of pedestrian waiting times showed that pedestrians experienced 52.0% shorter wait times at actuated RRFBs compared with actuated PHBs, a finding that might help explain the higher rates of actuation at RRFB sites.

Keywords: crosswalks, pedestrian crossings, RRFB, rectangular rapid flashing beacons, pedestrian hybrid beacons, PHB, pedestrians, driver yielding, actuation rates, geometric design, pedestrian behavior.

INTRODUCTION

The effectiveness of pedestrian hybrid beacons (PHBs) and rectangular rapid flashing beacons (RRFBs) has been established in the past two decades by multiple works of research (*1-5*). The expected improved safety performance from these traffic control devices (TCDs), however, depends upon a pedestrians' decision to (1) cross at locations treated with these countermeasures and (2) actuate (i.e., intentionally activate) the devices prior to crossing.

LITERATURE REVIEW

The effectiveness of RRFBs and PHBs has been widely studied using two main criteria, namely, their effects on (1) crashes, particularly those involving pedestrians, and (2) driver yielding to pedestrians. The latter has been studied either using staged pedestrians or naturalistic observations of pedestrians. The following four subsections summarize and highlight some of the most influential works evaluating the effectiveness of these devices.

Safety Effectiveness Based on Pedestrian Crashes

Many research works have established the safety effectiveness of RRFBs and PHBs directly through estimating linked crash reductions. Fitzpatrick and Park conducted one of the earliest studies using this approach (*6*). They contrasted historical crashes between 21 sites with PHBs and 102 unsignalized intersections. This research produced a crash modification factor (CMF) for pedestrian crashes of 0.31, meaning that the device is associated with a 69% crash reduction.

In 2017, Zeeger et al. estimated multiple CMFs for both devices of interest as well as for pedestrian refuge islands (*4*). Researchers report various CMFs, including a statistically significant CMF of 0.244 for PHBs plus advanced pavement markings and a CMF of 0.671 for refuge islands that was not statistically significant. The CMF estimates from a cross-sectional analysis of a larger dataset were 0.526 for RRFBs and 0.675 for PHBs, both of which were not statistically significant; and 0.699 for refuge islands, which was statistically significant.

More recently, Fitzpatrick et al. studied 186 locations in Arizona with PHBs for a before–after crash evaluation and found a 45% reduction in fatal and injury pedestrian-related crashes associated with PHB installations (*7*).

Safety Effectiveness Based on Driver Yielding for Staged Crossings

The effectiveness of these devices has also been widely established in terms of driver yielding, defined as the ratio of the number of drivers yielding to pedestrians to the total number of drivers who had sufficient time and space (i.e., stopping sight distance) to yield at a given crossing. Most past studies have followed a staged-crossing protocol (i.e., when a researcher poses as a pedestrian to prompt motor vehicles to yield the right of way). Generally, these studies tend to indicate good yielding behavior around both device types (*8*). For example, Ross et al. used staged crossings and found that the yield rate tripled to 79% after installing RRFBs compared with before installing RRFBs at two locations in Bend, OR (*9*).

Fitzpatrick et al. evaluated different flashing patterns at RRFBs at eight locations in two cities in Texas. Using a staged-crossing protocol, they found no differences between flashing patterns, with yielding rates averaging 88% (*10*). Using a similar approach, Fitzpatrick et al. reported high yielding rates for both PHBs (89%) and RRFBs (86%) in Texas (*11*).

Naturalistic Observational Studies

Brewer and Fitzpatrick used a mix of staged and naturalistic observations to compare yielding rates before and after an RRFB installation at a crosswalk in Garland, TX. They found that the RRFB tended to increase driver yielding when present and active for the staged proportion of the data, while no significant changes were observed for the naturalistic part of the study (*12*).

Based on video footage, researchers studied driver yielding at uncontrolled midblock RRFB crosswalks at two Montana locations. The study found that active RRFBs were associated with increased yielding as well as other factors such as proximity of pedestrians to the crosswalk, size of the group crossing, and peak periods. Researchers emphasized the visibility of crosswalk users as a very important determinant of driver yielding (*13*).

A recent study in Vermont evaluated driver yielding at six locations representing rural and suburban transition zones. Using a paired before-after-with-comparison group design, researchers found statistical evidence of RRFB effectiveness: increased odds of driver yielding but increased odds of pedestrians crossing out of the crosswalk (*14*).

An observational study of 600 pedestrians at six locations in Seattle, WA, found increased odds of pedestrians waiting for the signal to cross when they actuated RRFBs in the absence of rain, at corners, and with longer cycle lengths (*15*).

Studies on TCD Actuation Rates

Less work has been done on the factors associated with the actuation of RRFBs and PHBs. A recent evaluation studied 112 PHB locations in Tucson, AZ, examining both pedestrian actuation and pedestrian and bicycle crash proclivity (*16*). For the analysis, the researchers used pedestrian and bicycle crash records from 2018 to 2021 and classified their sample by crash history and the availability of actuation data. This study found that young male pedestrians were less likely to actuate PHBs. Results also indicated that locations with higher operational speeds tended to be associated with fewer crashes. Findings also suggested a link between increased crashes and nighttime crossings, regardless of actuation status.

A study based on 20 locations in Las Vegas, NV, by Kutela and Teng found that the odds of pedestrian actuation increased for RRFBs (odds ratio [OR] = 3.61) and for circular flashing beacons (OR = 4.54) compared with PHBs and traffic control signals. Actuation odds similarly increased with larger vehicle platoons and with increasing speed limits. No significant differences were observed among the number of lanes present except for 8–10 lanes, which had higher actuation odds than 5 lanes (*17*).

Study Motivation and Objective

This research aims to document the factors influencing the decisions of pedestrians to actuate RRFBs and PHBs and to improve current understanding of their performance by studying actuation and driver-yielding behavior. We aim to articulate the relationship between pedestrians' proclivity to actuate and of drivers' decisions to yield. Although various efforts to study those aspects have been documented, there is a need to better understand how these metrics relate to each other. The safety benefits of these depend upon periods of proper operation of these devices and road users behaving as expected under those conditions. Identifying and understanding factors that make users more or less likely to engage in those behaviors should be helpful to agencies in deciding whether and where to deploy these devices in the future and how to modify current installations for improved performance. The current effort comprised two complementary parts: (1) an observational study based on field video footage to record and document pedestrian behavior immediately preceding the crossing, and (2) a survey of pedestrian attitudes and motivations at a subset of the study locations.

OBSERVATIONAL STUDY

In coordination with the North Carolina Department of Transportation (NCDOT), we evaluated the characteristics of multiple pedestrian crossings derived from video footage. NCDOT provided a file with their 2022 statewide inventory of RRFB and PHB devices, totaling 234 locations.

The study design matrix was constructed to minimize confounding between any potential PHB and RRFB effects. Regarding a contrast between RRFB and PHB sites, we noted clear imbalances in the distributions of key variables such as speed limit, annual average daily traffic (AADT), number of lanes, and surface width. RRFBs tend to be primarily at locations with a posted 35-mph speed limit and with fewer lanes, narrower crossings, and lighter traffic. Even with a large sample, interpreting a comparison between devices might be confounding with these key variables.

Site Selection

We used unequal probabilities to obtain a probability sample of 15 locations from NCDOT's state inventory to improve the quality of comparisons between PHBs and RRFBs for this study. We selected the sample from balancing the variables that could potentially influence both yielding and actuation that were available at the sample design phase: AADT, speed limit, number of lanes, and surface width.

We assigned probabilities of site selection based on the propensity scores obtained from logistic regression. We limited the study to the vicinity of Charlotte and Raleigh, where there were 66 PHBs and 80 RRFBs, or 62% of the statewide inventory. The random sample was selected based on the concept of "overlap population," (*18*) meaning that the sample consists of locations that are equally likely to have either RRFBs or PHBs. Figure 1 shows the distributions of the key covariates; statewide in the first row, and for the final sample of 15 locations in the second row where it is apparent that the imbalances in key covariates are softened compared with the statewide distributions.

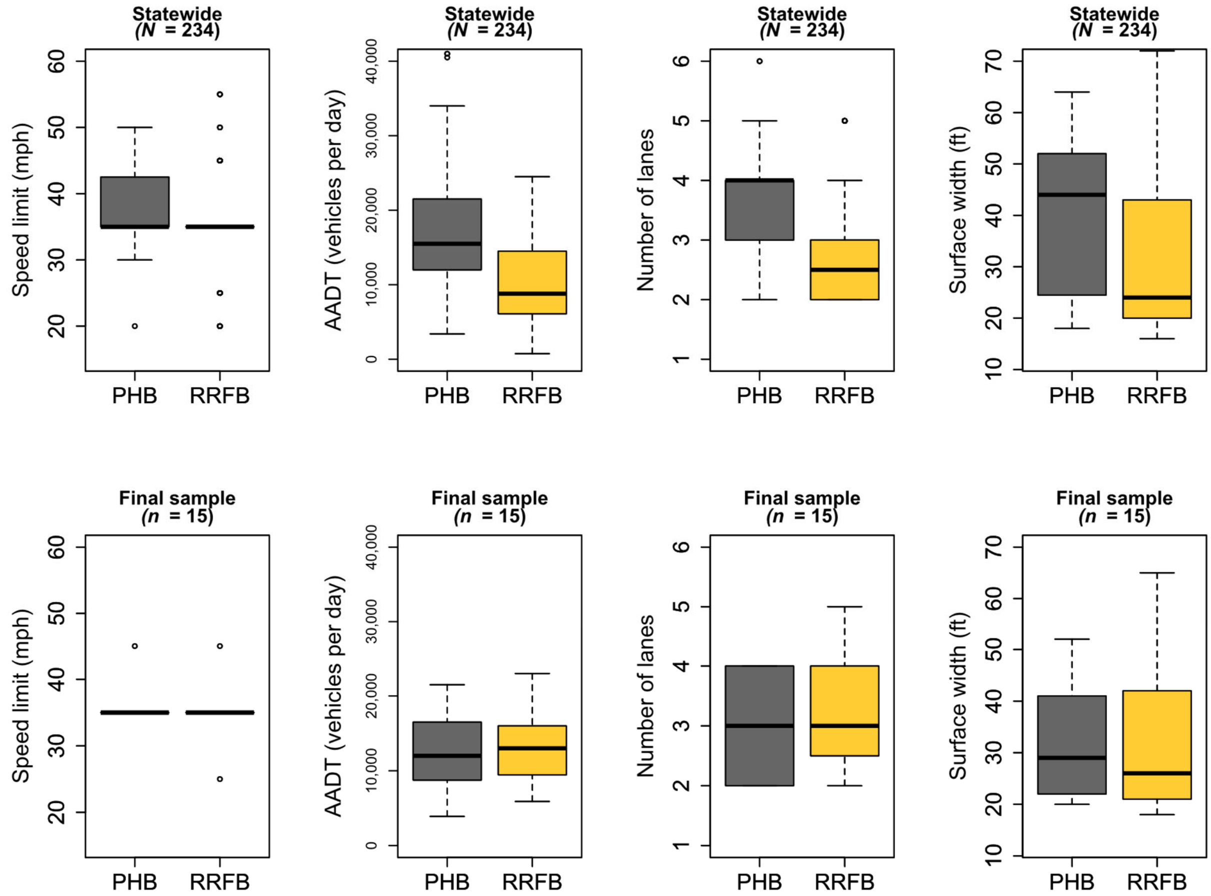

Figure 1. Marginal distributions of covariates by device type

Although the balance in the final sample is better and, therefore, it allows for clearer comparisons between device types, this comes at the cost that such comparisons are valid for a reduced range of covariate values as the Figure 1 also shows. For instance, because the statewide availability of RRFBs is heavily concentrated in locations with 35-mph speed limits, the final sample tends to include PHBs at roads with a similar range of speed limits. Consequently, the final sample includes two locations with 25-mph speed limits (1 RRFB and 1 PHB), 10 locations with 35-mph limits (6 RRFBs and 4 PHBs), and three locations with 45-mph limits (1 RRFB and 2 PHBs). Note that PHBs tend to be installed under a wider range of conditions statewide in North Carolina than represented in this study. We do not recommend interpreting this study's results outside the range of covariates in our final sample.

Data Collection and Reduction

The setup for a typical study location is shown in Figure 2. Two cameras were installed to document the behavior of arrivals from both sides. The placement was optimized to observe the actuation button of the TCD, the PHB lenses, or the RRFB LEDs to determine if the device was actuated before an observed crossing.

A regional traffic-engineering company was hired to collect a complete week of footage (7 days, 24 hours a day) during the fall of 2023 (October–November) and manually extract the characteristics of each crossing using a template provided for that purpose. We performed quality control over the collected data and communicated with the contractor during the 2 months following the initial data collection. After cleaning incomplete data, a total of 3,624 valid crossings were coded for analysis. Table 1 shows descriptive statistics for the key variables collected or calculated as described.

A few notes are needed to help define some variables in this table. Regarding the indicator variable "Intersection proximity," we coded the situations where the midblock crossings were in close proximity to an intersection (100 ft or less) so that vehicles negotiating the intersection might affect the operations at the crossing. The variable "Trail or shared path" represents locations where either a trail or a shared path crossed a road, and the crossing had one of the two devices under study in this research.

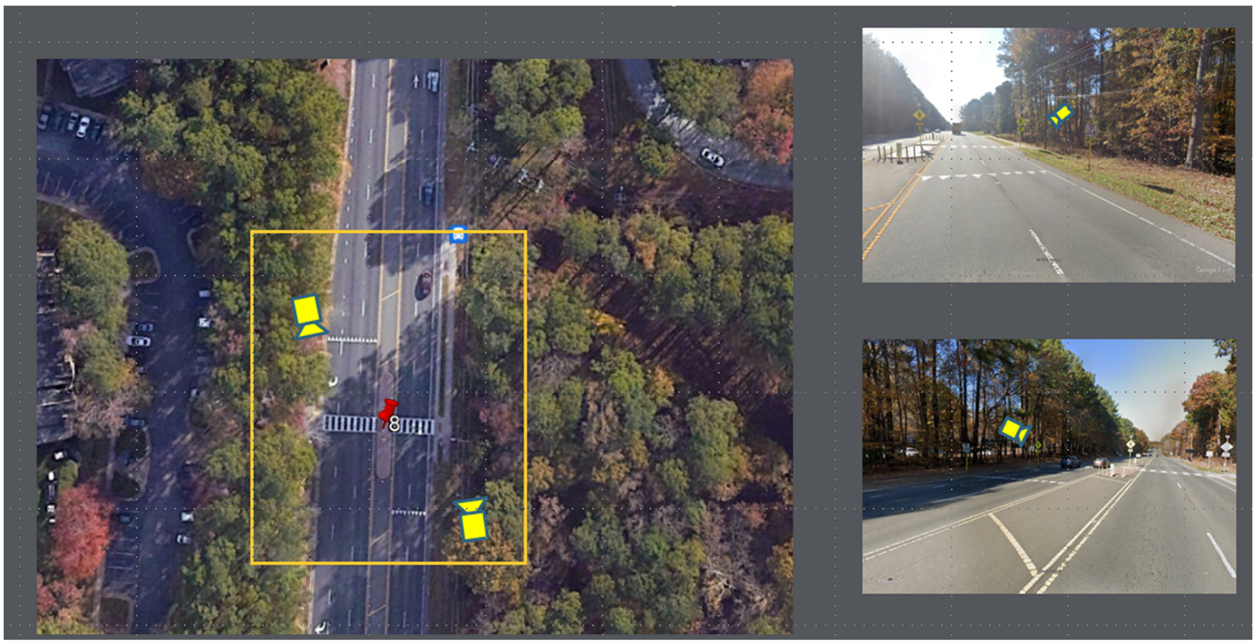

Figure 2. Video collection setup for a typical location

The variable "Pedestrian refuge island in median" represents a condition that also requires a median to be present; pedestrian refuge islands are always present at raised medians. In this dataset, only three out of 15 locations had medians (other than raised) but no pedestrian refuges. Regarding the "Crossing out of the crosswalk" variable, the longest recorded distance between the crosswalk and a crossing pedestrian was 200 ft, so the dataset does not capture crossings with a greater distance outside of the crosswalks. The definition of "Actuation" includes only pedestrians who pressed the button (actuated). Pedestrians who did not actuate but crossed when the device was actively controlling traffic were considered to have not actuated.

Table 1 Descriptive Statistics per Crossing (*n* = 3,624)

Variable	Mean	*SD*	Median	Min	Max
Nearside vehicles during crossing	2.88	4.11	1	0	28
Far side vehicles during crossing	3.19	4.71	1	0	35
All yielding vehicles	1.02	1.24	0	0	4
All non-yielding vehicles	2.07	4.53	0	0	45
AADT (vehicles per day [vpd])	13,436	55,922	12,000	33,900	23,000
Daytime crossing (yes or no)	0.91	0.28	1	0	1
Speed limit (mph)	35.77	3.21	35	25	45
Trail or shared path (yes or no)	0.18	0.38	0	0	1
Intersection proximity (yes or no)	0.76	0.43	0.83	0	1
Number of travel lanes	2.6	0.97	2	1	5
Number of bicycle lanes	0.22	0.63	0	0	2
Median present (yes or no)	0.5	0.5	0	0	1
Pedestrian refuge island in median (yes or no)	0.28	0.45	0	0	1
Crossing distance (ft)	47.82	16.57	48	24	74
Sidewalk at origin of crossing (yes or no)	0.88	0.32	1	0	1
Sidewalk at destination of crossing (yes or no)	0.94	0.24	1	0	1
Distance to bus stop (ft)	298	439	84	5	1,100
Number of pedestrians in group	1.68	1.82	1	1	34
Number of pedestrians in queue at arrival	3.97	8.85	0	0	71
Crossing out-of-crosswalk (yes or no) [coded CoX]	0.07	0.26	0	0	1
Vague behavior (yes or no) [coded VgB]	0.11	0.32	0	0	1
Actuation (yes or no) [coded Act]	0.66	0.47	1	0	1
Waiting time (s)	8.09	11.67	4	0	266

Note:
AADT = annual average daily traffic

While most variables were observed and recorded directly, some relevant variables (e.g., time between arrivals, number of pedestrians in queue) were computed using other available variables. For example, we defined an indicator variable for vague behavior (from the drivers' standpoint) because we observed arrivals when pedestrians waited a long time without conveying through body language their intent to cross to the drivers present. After considering a few alternative ways to flag these cases systematically in the data stream, we adopted the following definition: a crossing with at least six observed vehicles where 60% of the drivers had an insufficient stopping sight distance. We spot-checked that most events we flagged as vague behavior would be captured by this rule. However, we also noticed that this definition might have captured events other than waits where pedestrians did not clearly signal to the drivers their intention to cross.

Table 1 shows that on average, nearly one vehicle yielded and two did not yield at each crossing. This table also shows statistics for vehicles that were classified as yielding and as non-yielding. We classified vehicles as non-yielding if they either (a) crossed the stop bar when the PHB was in the solid red phase, or (b) arrived at the stop bar more than 4 s after the RRFB activation—i.e., a vehicle travelling at 35 mph should take 4.9 s to cover the corresponding stopping sight distance of 250 ft, given standard assumptions from the American Association of State Highway and Transportation Officials' calculation (*19*).

It is also notable from the binary variables in Table 1 that most crossings occurred during daytime (91%), and 50% were at locations with medians while 28% were at locations with pedestrian refuges present. Most crossings had a sidewalk at the origin point (88%) or the destination point (94%). Most crossings were recorded within the crosswalk, as indicated by the variable Crossing out of the crosswalk (7%), and 66% of the pedestrians actuated the TCD prior to crossing. Only 11% of the involved pedestrians were classified as behaving vaguely.

Next, Table 2 shows actuation and yielding rates aggregated by device and actuation status. These calculations excluded the 262 crossings that were out of the crosswalk. Yielding rates in this table are the average of yielding rates at the crossing level. These rates were computed on a smaller subsample of crossings (reported in parentheses) because it is only possible to calculate a yielding rate when there is at least one vehicle with a sufficient stopping sight distance to the crosswalk.

Table 2 Actuation and Yielding Rates by Device and Actuation Status

Device	Actuation rate	Yield rate (actuated)	Yield rate (not actuated)	Yield rate percent change with actuation
RRFB	0.803 (*n* = 1,832)	0.598 (*n* = 1,167)	0.328 (*n* = 65)	+82.3%
PHB	0.561 (*n* = 1,530)	0.443 (*n* = 769)	0.183 (*n* = 224)	+142.1%

Table 2 shows a disparity in actuation and yielding rates. On average, RRFBs were actuated more often and drivers yielded more often at those sites, compared with locations with PHBs. Additionally, this table shows higher yielding rates for both devices when actuated compared with when not actuated. The last column shows the percentage increase in yielding rates for crossings with actuation compared with no actuation. This column suggests that actuation at PHBs might have a larger positive effect in terms of yielding than actuation at RRFBs.

Modeling Pedestrian and Motor Vehicle Observed Behaviors

We performed statistical analyses on the probability of three key variables: (1) crossing out of the crosswalk, (2) actuation, and (3) yielding. The three response variables are related to each other and can be understood as links in a chain of events: a pedestrian decides to cross within the crosswalk (they might behave erratically or not), and they might actuate the TCD or not. The last link in that chain is the decision by drivers whether to yield if they have a sufficient stopping sight distance.

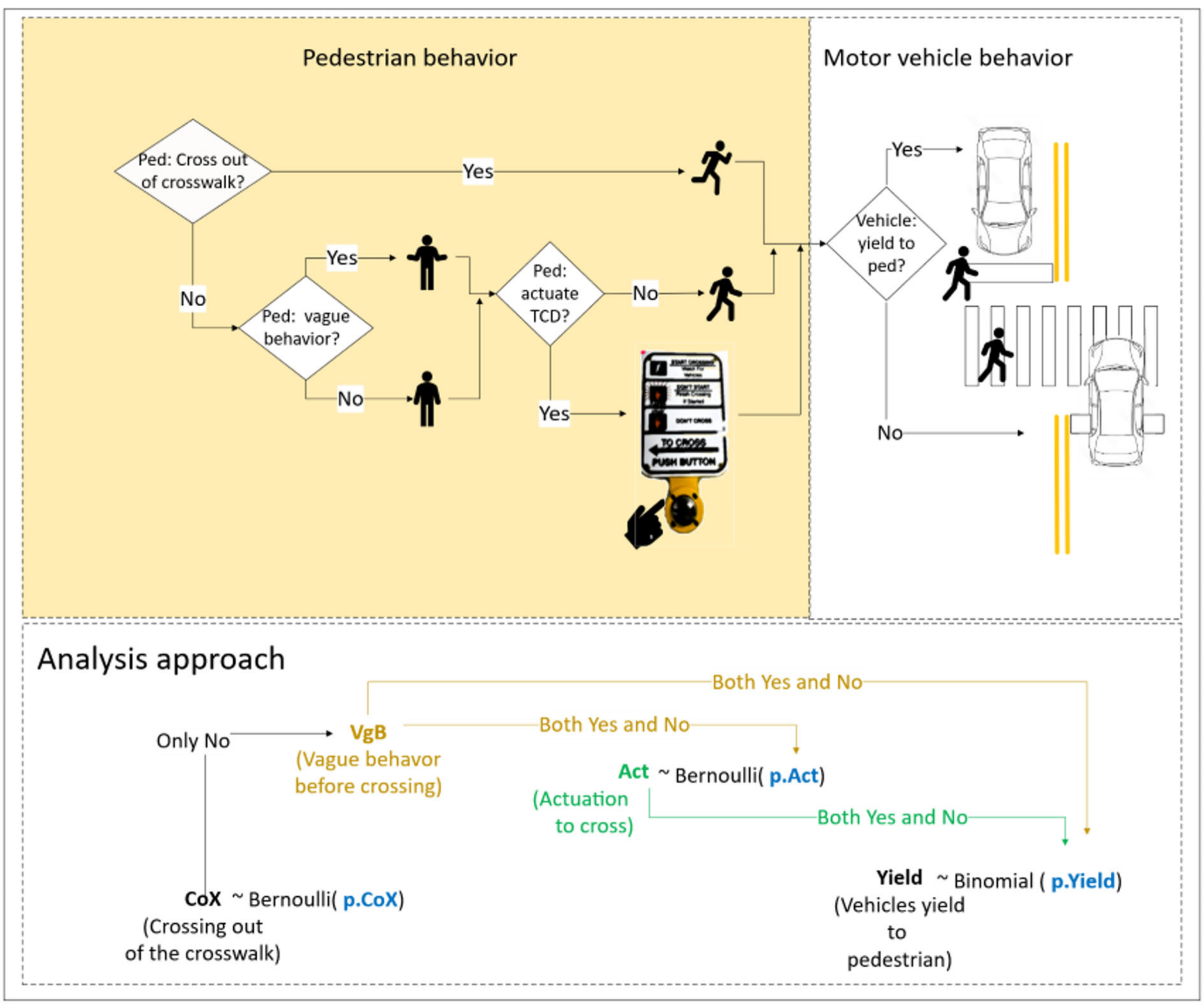

Figure 3 Relationship between response variables, coding, and modeling approach

We considered the state of past decisions as explanatory factors (i.e., vague behavior as explanatory in actuation, and both of these affect driver yielding). Note that the analyses considered the actual state of past decisions (either yes or no) rather than their predicted probabilities as is the case in path analysis. Figure 3 illustrates the conceptual chain of events and analysis approach as explained.

All our analyses considered and accounted for variables at the individual crossing level. We found many of these variables (e.g., number of pedestrians in group, number of nearside or far side vehicles present at arrival) were important in explaining variation in the responses. However, when interpreting the results and further sensitivity analyses, we focused on the site-level variables we deemed actionable by transportation agencies, such as cross-section geometry and type of TCD at crossing. Variables for number of pedestrians in the group and pedestrians in queue to cross were treated separately in the pedestrian-behavior analyses but aggregated in the driver-yielding analysis because drivers should perceive them jointly. All analyses were performed using the statistical software R version 4.4.0 and its packages (*20*) and custom code to incorporate the described conceptual framework, develop counterfactual scenarios, and develop other calculations described later in this paper.

Table 3 shows the analysis results. The shading bands (white or gray) in this table show logical groups of explanatory variables. For example, Parameters 4 through 10 comprise the collection of ways the analyses accounted for motor-vehicle-exposure variables in the conceptual chain of events.

Table 3 Mixed Effects Logistic Model Estimates

Parameter	Explanatory variable	CoX[a]	Act[b]	Yield[c]
		Estimate (*SE*) [Signif.][h]	**Estimate (*SE*) [Signif.]**	**Estimate (*SE*) [Signif.]**
1	(Intercept)	4.0147 (2.1077) ~	−2.5015 (0.8313) **	0.6543 (1.0387) N.S.
2	VgB=1	N.A.[d]	−2.0104 (0.2238) ***	0.9818 (0.1083) ***
3	Act=1	N.A.	N.A.	0.3499 (0.9792) N.S.
4	Scaled AADT (increments of 1,000 vpd[e])	0.1576 (0.0727) *	N.A.	−0.1289 (0.0233) ***
5	All observed vehicles during crossing	−0.0706 (0.0197) ***	N.A.	N.A.
6	Nearside vehicles observed during crossing	N.A.	0.1692 (0.0196) ***	N.A.
7	Far side vehicles observed during crossing	N.A.	0.1211 (0.0186)	N.A.

Parameter	Explanatory variable	CoX[a]	Act[b]	Yield[c]
		Estimate (SE) [Signif.][h]	Estimate (SE) [Signif.]	Estimate (SE) [Signif.]
			***	
8	Vehicle flow rate in 15 min prior to crossing (vph[f])	−0.0024 (0.0009) **	N.A.	N.A.
9	Nearside vehicle flow rate in 15 min prior to crossing (vph)	N.A.	N.A.	−0.0001 (0.0003) N.S.
10	Far side vehicle flow rate in 15 min prior to crossing (vph)	N.A.	N.A.	−0.2475 (0.0611) ***
11	Posted speed limit	N.A.	N.A.	−0.1009 (0.0278) ***
12	**[Act=1]** × [Posted speed limit]	N.A.	N.A.	0.0456 (0.0285) N.S.
13	Posted speed limit = 45 mph	N.A.	−1.4766 (0.3764) ***	N.A.
14	Number of pedestrians in group (max: 6 or more)	−0.3834 (0.1072) ***	0.3402 (0.0531) ***	N.A.
15	Number of pedestrians in queue at arrival (max: 6 or more)	N.A.	0.1478 (0.0339) ***	N.A.
16	Pedestrians in queue and arriving in group (max: 8 or more)	N.A.	N.A.	0.0389 (0.0162) *
17	Inverse squared time since last arrival (s^ − 2)	1.0063 (0.1371) ***	−0.6795 (0.1249) ***	N.A.
18	Actuation occurred on last arrival within 30 s	N.A.	−0.5717 (0.2385) *	N.A.
19	Night or dusk	0.6005 (0.2905) *	0.4099 (0.2129) ~	N.A.
20	Trail or shared path	−1.3755 (0.5779) *	−1.2028 (0.2919) ***	N.A.
21	Intersection proximity	1.2397 (0.6188) *	−1.6684 (0.4145) ***	N.A.

Parameter	Explanatory variable	CoX[a]	Act[b]	Yield[c]
		Estimate (*SE*) [Signif.][h]	**Estimate (*SE*) [Signif.]**	**Estimate (*SE*) [Signif.]**
22	School zone	−2.8084 (0.662) ***	0.6183 (0.25) *	0.4989 (0.2383) *
23	Sidewalk absent at origin of crossing	1.4876 (0.9237) N.S.	N.A.	1.1317 (0.3536) **
24	Sidewalk absent at destination of crossing	3.8259 (0.8164) ***	−1.2944 (0.4544) **	N.A.
25	Scaled crossing distance (reference: 12 ft)	−0.4319 (0.2937) N.S.	0.600 (0.1146) ***	0.7763 (0.1206) ***
26	**[Act=1]** × [Scaled crossing distance]	N.A.	N.A.	−0.3434 (0.1028) ***
27	Median without pedestrian refuge island (flush or TWLTL[g] only)	N.A.	0.3128 (0.3253) N.S.	N.A.
28	Pedestrian refuge island	−1.2622 (0.5694) *	1.8863 (0.7644) *	−0.3336 (0.3689) N.S.
29	**[Act=1]** × Pedestrian refuge island]	N.A.	N.A.	1.5597 (0.3717) ***
30	[Scaled crossing distance] × [Pedestrian refuge island]	N.A.	−0.5054 (0.1781) **	N.A.
31	RRFB	−2.8088 (0.4563) ***	0.8790 (0.2521) ***	0.5840 (0.3204) ~
32	[RRFB] × [Trail or shared path]	2.7405 (1.0588) **	N.A.	N.A.
33	**[Act=1]** × [RRFB]	N.A.	N.A.	−0.7973 (0.3219) *

Notes:

[a] CoX = Pedestrian crossing out of the crosswalk; *n* = 3,490 observations

[b] Act = Pedestrian actuation; *n* = 3,190 observations

[c] Yield = Driver yielding; *n* = 3,162 observations

[d] N.A. = Not Applicable

[e] vpd = vehicles per day

[f] vph = vehicles per hour

[g] TWLTL = two-way left-turning lane

[h] Significance coded as follows:

Parameter	Explanatory variable	CoX[a]	Act[b]	Yield[c]
		Estimate (*SE*) [Signif.][h]	Estimate (*SE*) [Signif.]	Estimate (*SE*) [Signif.]

N.S. Not statistically significant;
~ $0.050 < p <= 0.100$;
* $0.010 < p <= 0.050$;
** $0.001 < p <= 0.010$; and
*** $p < 0.001$

Regarding Parameter 2 in the case of the actuation analysis (fourth column in Table 3), we found statistical evidence of a reduced actuation odds ratio (Act OR) when pedestrians behaved vaguely at the crosswalk (exp(−2.0104) = 0.134 Act OR) but increased yielding odds ratio (exp(0.9818) = 2.669 Yield OR).

Although Parameter 3 alone seems to indicate, not surprisingly, that the odds of drivers yielding increased when the devices were actuated, this parameter should not be interpreted alone, given that there are interactions between actuation and other variables in the yield model. We will discuss the implications of this variable and others interacting with it in more detail later in the paper.

Regarding Parameters 4 through 10, the statistical evidence in the third column of Table 3 indicates that pedestrians crossing out of the crosswalk (CoX) are more likely at locations with higher AADTs (Parameter 4) but during periods with fewer vehicles during the crossing (Parameter 5) and after 15-min periods with lower vehicle flow rates (Parameter 8). For Parameter 4, the fifth column indicates that yielding odds tended to decrease with increasing traffic as denoted by the AADT. As shown in the fourth column, the odds of actuation increased at crossings with more nearside and far side vehicles present (Parameters 6 and 7). In contrast, Parameter 10 indicates that drivers were less likely to yield to pedestrians in periods followed by higher vehicle flow rates on the far side of the crossing (i.e., this estimate is negative and statistically significant).

Regarding posted speed limits, Parameter 11 indicates that yielding odds tended to drop with increasing speed limits (a negative and statistically significant estimate), but that effect is mitigated at crossings involving actuation (Parameter 12 is positive but smaller in magnitude than Parameter 11). Parameter 13 indicates lower actuation odds at locations with a posted 45-mph speed limit compared with sites with either a posted 25- mph or 35-mph speed limit.

Although we can offer similar interpretations for Parameters 14 through 18, we will ascertain that pedestrian behavior and driver yielding varied with the number of pedestrians in the group, the number of pedestrians already in queue to cross, and the time since the last pedestrian arrival. Parameter 16 indicates that increasing yielding odds are associated with an increasing number of pedestrians, either arriving together or waiting in queue (a 4.0% increase per additional pedestrian, exp(0.0389) = 1.040 Yield OR); and Parameter 18 shows reduced odds of actuation if the prior pedestrian actuated within 30 s of the current pedestrian (0.565 Act OR).

Per Parameter 19, the odds of crossing out of the crosswalk and actuation increased at dusk and at night (1.823 CoX OR and 1.507 Act OR, respectively). This is an interesting mix of safer and riskier behaviors; the risky behavior seemingly shifts for some pedestrians from not actuating to actuating but for others, it shifts from crossing in the crosswalk to crossing outside the crosswalk.

Findings from Parameter 20 indicate that, all else things being equal, the odds of crossing out of the crosswalk and actuation were lower at trails or shared paths. The two estimated effects of crossings near intersections indicated undesired behaviors: crossing out of the crosswalk was more likely at these locations (3.455 CoX OR), while actuation was less likely (0.189 Actuation OR), per Parameter 21. In contrast, all estimates for Parameter 22 (i.e., school zone) suggest desired behaviors by both user types: a very large and significant drop in the odds of crossing out of the crosswalk (0.060 CoX OR), a large and significant increase in actuation odds (1.856 Act OR), and a large and significant increase in driver-yielding odds (1.647 Yield OR).

Impacts of Actionable Variables

We paid special attention to the explanatory variables related to physical features of the sites and TCD types (Parameters 23 through 33) because they could suggest actionable strategies to improve pedestrian behavior and driver compliance in current and future locations.

Parameters 23 and 24 indicate one such factor: the absence of sidewalks on one side of the crossing— a condition present at 2 out of the 15 study locations. This condition was found statistically significantly related to worse pedestrian behavior, while driver yielding was found to compensate for that behavior. The odds of CoX and Yield both increased when a sidewalk was absent on one side of the crossing (4.426 CoX OR and 3.101 Yield OR when a sidewalk was absent on the nearside; 45.876 CoX OR when absent on the far side). Additionally, pedestrians were also less likely to actuate when the crossing lacked a sidewalk on the far side (0.274 Act OR).

Regarding the odds of crossing out of the crosswalk, Parameter 25 indicates decreased odds at wider crossings (0.649 CoX OR per each additional 12 ft of crossing), while Parameter 28 indicates that the presence of pedestrian refuge islands was associated with decreased odds of crossing out of the crosswalk (0.283 CoX OR).

Interestingly, CoX odds were found significantly higher at non-trail or shared path locations having a PHB compared with an RRFB (1/exp(-2.8088) = 16.590 CoX OR for PHB). No such differences by device type were observed at trail or share path locations (1/exp(-2.8088+2.7405) = 1.071 CoX OR for PHB).

We found the odds of actuation were higher at locations with RRFBs (2.409 Act OR, per Parameter 31) compared with PHBs. In contrast, our analysis found no statistically significant differences between devices regarding yielding odds when inactive, per Parameter 31 (1.793 Yield OR for inactive RRFB compared with PHB with a 0.068 p value).

Calculating and interpreting marginal effects from Parameter 25 through 30 estimates is not straightforward because effects are more intertwined (i.e., interacting variables). This set of parameters captures the impacts of the following variables: crossing distance, median type, presence of pedestrian refuge island at the median, and device type. We present the marginal effects derived from these parameters in the following subsections to ease the presentation, interpretation, and discussion of the results.

Actuation Odds by Cross Section

Figure 4 shows the joint effects on pedestrian actuation odds at some combinations of cross-sectional elements of interest. The reference scenario is a typical cross section of a 2-lane undivided road. For these scenarios, each lane or median is assumed to be 12 ft long. Although other researchers might chose different values in developing these scenarios, we argue that varying the chosen values should result in mild, likely inconsequential shifts of the estimates shown in Figure 4.

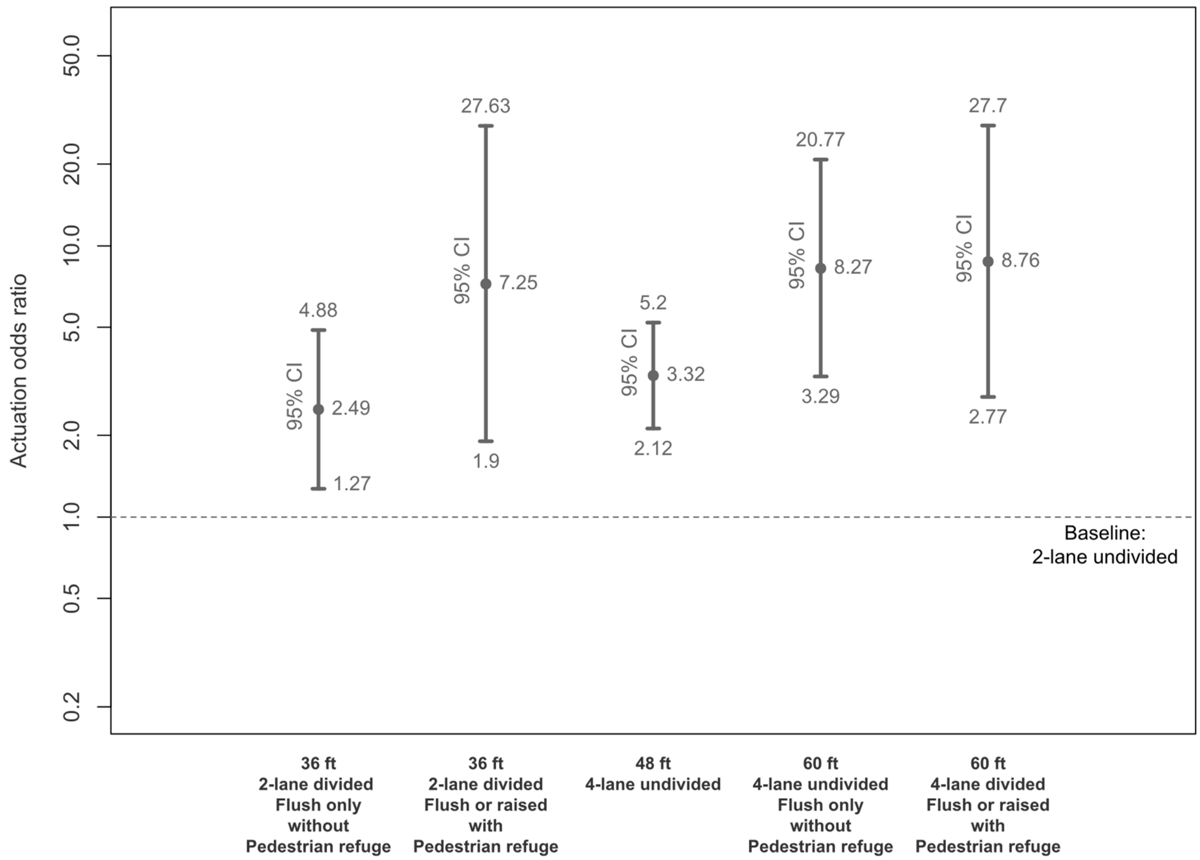

Figure 4. Actuation odds ratios for select cross-section scenarios

Results indicate statistically significant increased odds of actuation (at the 95% confidence level) for all scenarios (i.e., higher odds of actuation compared with 2-lane undivided roads). The trend of these effects suggests that in general, wider crossings are associated with increased odds of actuation, with a slight increase in actuation odds when a pedestrian refuge is present.

Driver Yielding by Device Type, Actuation, Cross Section, and Speed Limit

This section presents the marginal effects of incorporating multiple interactions for actuation status in the yield model. Figure 5 shows that there is a general trend of decreased yielding odds with increases to the posted speed limit, despite this marginal effect slightly improving with actuation.

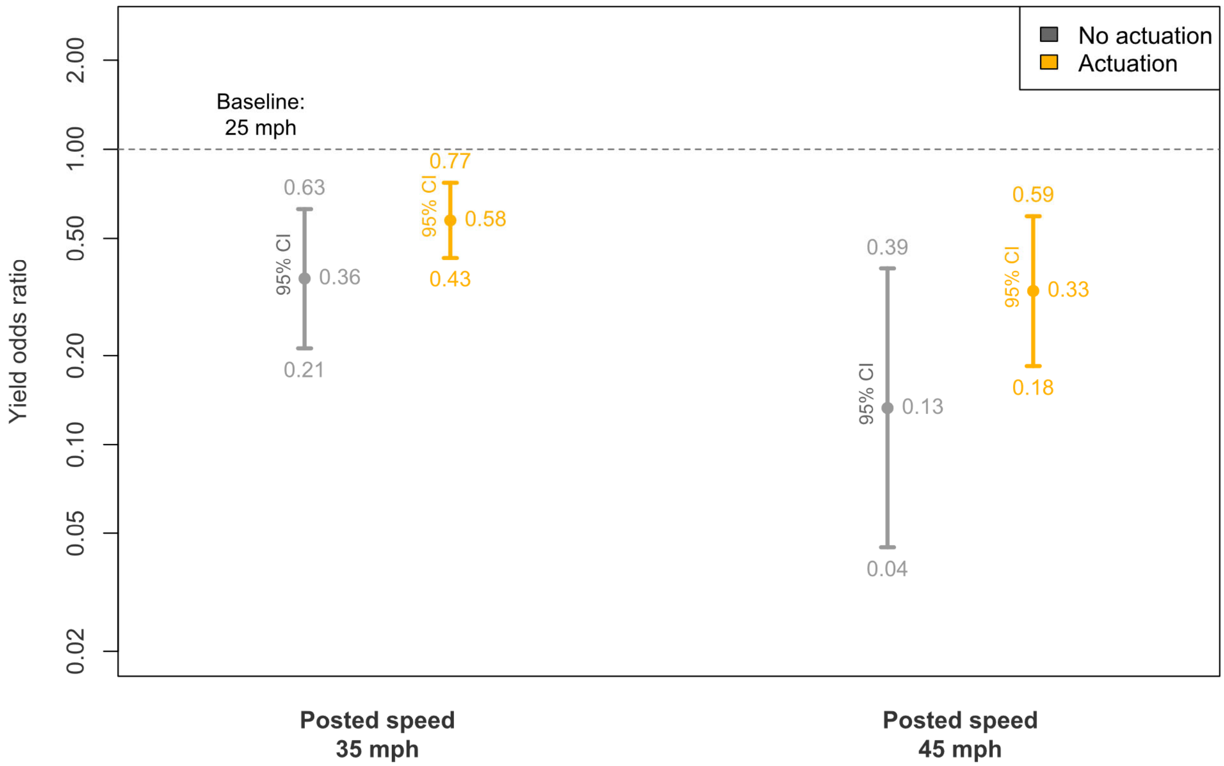

Figure 5. Marginal effects of the posted speed limit on driver yielding

Figure 6 shows the marginal effects of actuation with varying 2-lane cross sections, device type, and speed limits. Not surprisingly, we found that actuation was generally associated with positive and often statistically significant increases in driver-yielding odds. Two trends within the three groups in Figure 6 are: (1) PHB actuation seems generally more effective compared with RRFB actuation, and (2) Yield ORs tend to increase with actuation at increasing speed limits. The performances of 2-lane undivided and 2-lane divided roads are very comparable when there is no pedestrian refuge (i.e., flush or TWLTL medians only), but notably better when there is a pedestrian refuge in the median.

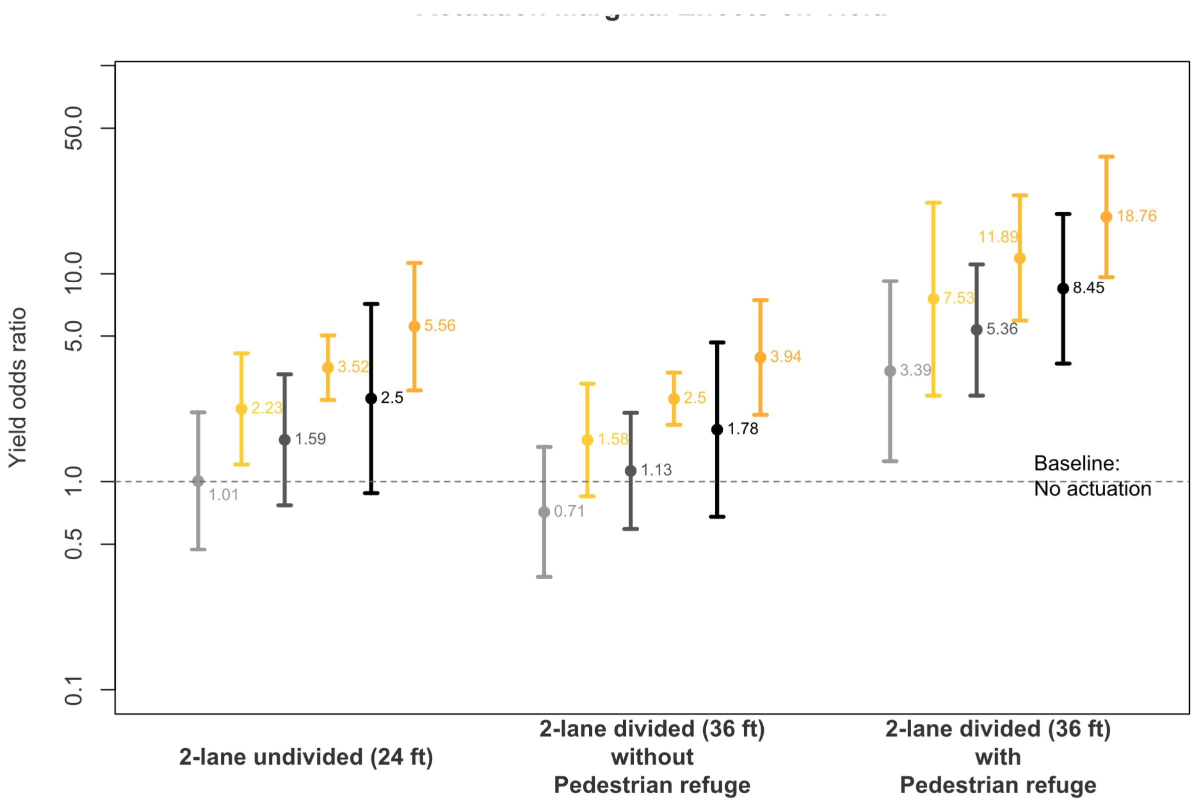

Figure 6. Marginal effects of actuation on driver yielding on 2-lane roads

Similar to Figure 6, Figure 7 shows the marginal effects of actuation at the corresponding 4-lane scenarios. Except for a general drop of all estimates compared with Figure 6, the trends remain unchanged (i.e., higher effectiveness of PHB and at higher speed limits). The estimates of RRFB actuation in this case tend to be statistically nonsignificant for the scenarios without a pedestrian refuge. For those scenarios, only 3 of the 6 estimates for PHB actuation indicate increased yielding odds.

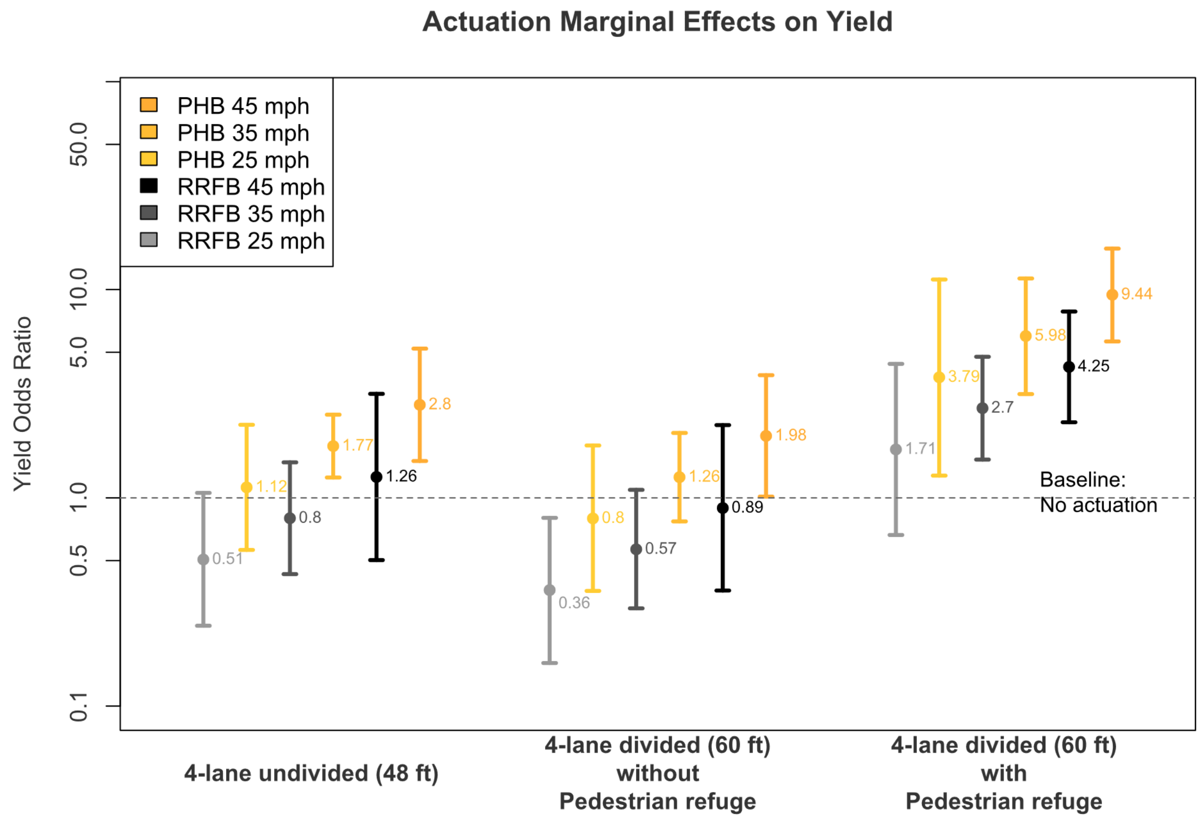

Figure 7. Marginal effects of actuation on driver yielding on 4-lane roads

However, stressing the importance of pedestrian refuges, all estimates indicate increased yielding odds when that feature is present. Except for RRFBs at 25 mph, all such estimates are statistically significant.

Counterfactual Scenarios of Select Potential Interventions

Although the marginal effects described in the prior section are useful, it is not straightforward to assess the overall impacts of these interventions (both on chances of pedestrian actuation and driver yielding), given the chain of decisions and events illustrated in Figure 3. For example, it was found that pedestrians tend to actuate RRFBs more often than PHBs, but drivers tend to yield more often at PHBs after controlling for other factors. To illustrate the overall impact of potential interventions that could have different impacts on actuation and yielding behaviors, we constructed counterfactual scenarios where the overall joint impacts are shown as shifts in the yielding and actuation rates at select locations.

To construct counterfactuals, we coded the interventions of interest into the model design matrices and applied bootstrapping to capture the uncertainty of variation between sites and between individual crossings within sites. We also applied normal multivariate noise to the parameter estimates to each replication, given the parameter covariance matrices from the models, to capture parameter estimation uncertainty as well. Results for the two most promising scenarios are shown in Figure 8.

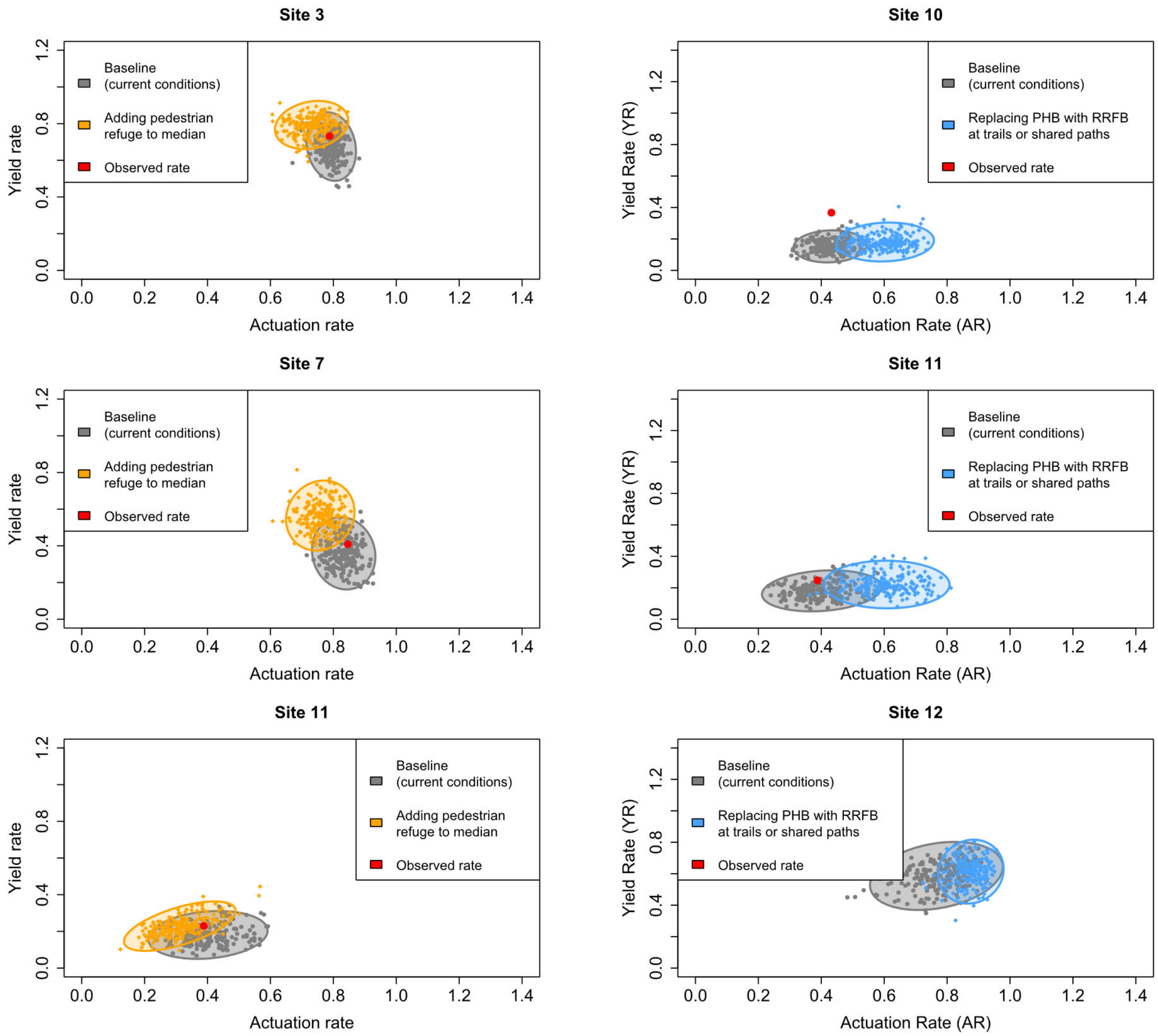

Figure 8. Yielding rate versus actuation rate for counterfactual scenarios at select locations

As can be seen in the left column of Figure 8, our research suggests a visible increase in yielding rates if pedestrian refuge islands were added at the three locations with flush medians but without pedestrian refuges. It is interesting that in those cases, a slight decrease in actuation rates is also anticipated. This is because of the small but statistically significant interaction between crossing distance and presence of a pedestrian refuge, per Parameter 30 in Table 3. Another scenario of promise is shown in the right column of Figure 8, where the counterfactual device performance at three locations having PHBs at trail or shared path crossings indicate increasing actuation rates, but with virtually no effect on yielding rates. According to our analysis, an increase in actuation should result in an increase in yielding, but because this is achieved by replacing the PHB for an RRFB the expected benefit is eroded given the reduced yielding expectations at RRFBs as shown in Figure 6 and Figure 7..

Next, we estimated the potential for improvement in yielding using a counterfactual scenario that assumes every crossing pedestrian actuates the corresponding device.

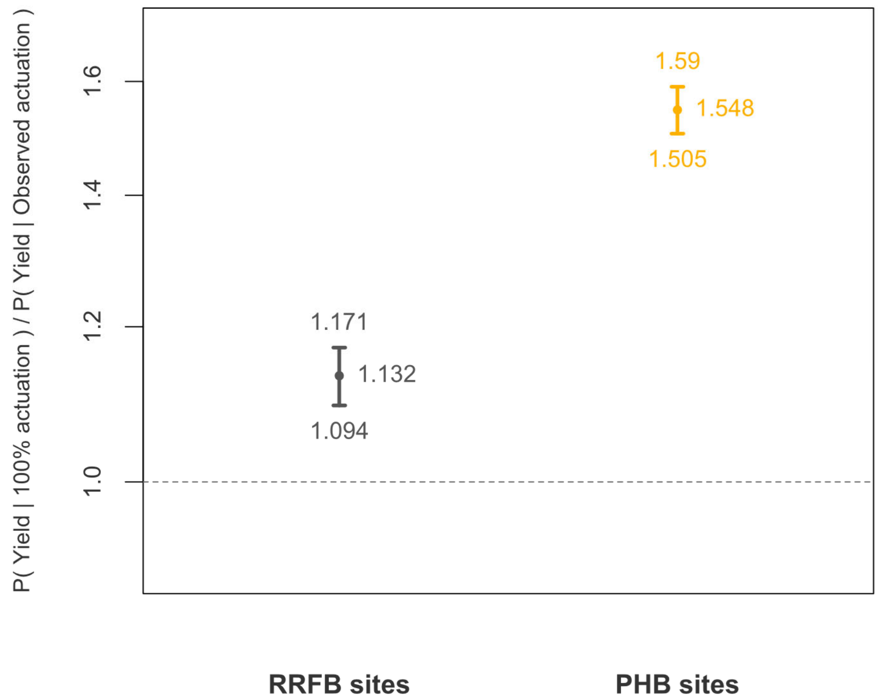

Figure 9. Potential for yield improvement in study sites by device type

As shown in Figure 9, we found a modest 13.2% average potential increase in yielding probability for the group of RRFB sites, compared with a notable 54.8% average potential increase in yielding probability for the group of PHB sites with all else being equal in the models.

SURVEY STUDY

We conducted a second study to survey pedestrians in the vicinity of a subset of study locations to supplement the observational study. Pedestrians were first observed using the crossing and then surveyed about their motivations given their observed behavior (i.e., decision to actuate the TCD or not). The survey also intended to document the public's understanding of how the TCDs work and what is expected from drivers and pedestrians around these devices.

The survey was conducted by a traffic-engineering company in North Carolina between May 28 and June 14, 2024, at five locations in the city of Raleigh, NC. We limited the survey to adult pedestrians ages 18 years or older. The Advarra Institutional Review Board deemed it exempt from review. Because participants were intercepted after they were observed crossing the road, we were able to record three distinct groups of pedestrians: (a) pedestrians who arrived at the crossing, actuated the TCD, and crossed while the TCD actively signaled to traffic; (b) pedestrians who did not actuate the TCD and crossed the road while the TCD was not active; and (c) pedestrians who did not actuate the TCD but crossed while the device was active.

Site Selection

Sites were selected based on the observed pedestrian volumes during the observational study to ensure a sufficient number of responses could be collected, keeping the covariate balance if possible. We avoided most crossings in school zones because of the age constraint for participants (i.e., adults only). The selected sites offered a good representation of device types (3 RRFBs), AADT range (3,900–23,000 vpd), crossing distances (24–73 ft), median presence (1 raised, 1 flush), presence of a pedestrian refuge (the same 2 sites with medians), closeness to intersections (3 sites), and trail or shared path crossings (2 sites). Unfortunately, the crossing distance ranged from 65–73 ft at RRFB sites, while the range was 24–35 ft at PHB sites. Because these two variables are, therefore, confounded (i.e., RRFBs paired with longer distances, PHBs paired with shorter distances), contrasts between device types and between crossing distances from the survey data are intertwined with each other and must be interpreted carefully.

Questionnaire

The questionnaire consisted of six multiple-choice questions:

- Frequency of walking
- Purpose of current trip
- Length of current trip
- Factors influencing crossing behavior (traffic intensity, speed of cars, length of crossing, waiting time at device, specific phrasing varied by crossing group)
- Factors that would increase chances of actuation (similar factors to question on crossing behavior)
- Factors that would decrease chances of actuation (similar factors to question on crossing behavior)

In addition to the questions above, the interviewer coded four variables:

- Age (asked)
- Perceived gender (inferred)
- Crossing group (A, B, or C; observed)
- Crossing out of the crosswalk (observed)

Except for the question about frequency of walking, all questions offered the option "other" to capture reasons other than those provided in the questionnaire. Data were collected on tablets and mobile phones.

Demographics of Survey Responses

A total of 343 responses were obtained, as shown in Table 4, while 55 pedestrians declined to participate in the study. Table 4 shows the breakdown of recorded survey answers. Nearly two thirds (67%) of responses were from Group A, while responses from groups B and C amounted to approximately one sixth of the total each. This matches very well with the proportion of 69% actuations overall in the observational study. Similarly, the proportion of Group A responses at locations with RRFBs was 78% and 47% at locations with PHBs, roughly corresponding to the 80% RRFB and 56% PHB actuations in the observational study.

We performed homogeneity tests for the distributions of answers to each question comparing Group A—taken to be the reference distribution— and groups B and C. In no case was Group C found statistically significantly different from Group A (i.e., no evidence that the distributions were different), while we found two instances where Group B was statistically different from Group A.

Table 4 Survey Responses by Activation Group (*n* = 343)

Variable	Group A[a] (*n* = 228)	Group B[b] (*n* = 58)	Group C[c] (*n* = 57)	Total (*n*=343)
Age				
18–21	47 (21%)	9 (16%)	14 (25%)	70 (20%)
22–35	96 (42%)	25 (43%)	27 (47%)	148 (43%)
36–50	33 (14%)	6 (10%)	4 (7%)	43 (13%)
51–65	45 (20%)	15 (26%)	9 (16%)	69 (20%)
65+	6 (3%)	3 (5%)	2 (4%)	11 (3%)
Unknown	1 (0%)	0 (0%)	1 (2%)	2 (1%)
Perceived gender				
Male	94 (41%)	31 (53%)	16 (28%)	141 (41%)
Female	133 (58%)	27 (47%)	41 (72%)	201 (59%)
Uncertain	1 (<1%)	0 (0%)	0 (0%)	1 (<1%)
Walking frequency[d]				
Every day	**12 (5%)**	**0 (0%)**	1 (2%)	13 (4%)
Almost every day	**184 (81%)**	**36 (62%)**	47 (82%)	267 (78%)
At least once a week	**30 (13%)**	**21 (36%)**	9 (16%)	60 (17%)
At least once a month	**1 (<1%)**	**1 (2%)**	0 (0%)	2 (1%)
>1 time per month	**0 (0%)**	**0 (0%)**	0 (0%)	0 (0%)
Don't know	**1 (<1%)**	**0 (0%)**	0 (0%)	1 (0%)
Trip purpose[e]				
Work or school	**73 (32%)**	**8 (14%)**	17 (30%)	98 (29%)
Exercise	**102 (45%)**	**31 (53%)**	26 (46%)	159 (46%)
Personal chores	**51 (22%)**	**14 (24%)**	11 (19%)	76 (22%)
Other	**2 (1%)**	**5 (9%)**	3 (5%)	10 (3%)
Current trip length				
<10 min	114 (50%)	23 (40%)	36 (63%)	173 (50%)
10–30 min	99 (43%)	32 (55%)	17 (30%)	148 (43%)
>30 min	15 (7%)	3 (5%)	3 (5%)	21 (6%)
Unknown	0 (0%)	0 (0%)	1 (2%)	1 (<1%)

Notes:
[a] Group A = actuated, crossed with device signaling
[b] Group B = did not actuate, crossed when device not signaling
[c] Group C = did not actuate, crossed with device signaling
[d] statistically significant difference between Group A and Group B from homogeneity test ($X^2 = 22.13$, $p < 0.01$)
[e] statistically significant difference between Group A and Group B from homogeneity test ($X^2 = 17.4$, $p < 0.01$)
Categories not marked with [d] or [e] did not differ significantly from Group A ($p > 0.05$)

We found that trip purpose and walking frequency differed between groups A and B, with those who crossed with no activation (Group B) being less likely than activators (Group A) to walk as a means of transportation every or most days, in turn being more likely to walk at least once a week. Also, we found the proportion of non-actuators (Group B) who were traveling to work or school on this trip notably smaller than for actuators (Group A), and in turn having larger proportion of other stated trip purposes, in particular for "Other" and "Exercise." Age, perceived gender, and trip length did not differ significantly by group.

Stated Motivations for Behavior and Influential Factors to Future Crossings

When asked to note their top three reasons for their observed mode of crossing, we found that the most common reasons pedestrians who actuated (Group A) gave for pushing the device's button to flash its lights were heavy traffic (86%), fast cars (86%), long crossings (51%), and it's they felt is wasn't safer to cross with the device flashing (47%).

Group B pedestrians' most common answers to why they decided not to push the device's button to make it flash to traffic were light or no traffic (59%), they did not want to wait for the device (41%), and other (17%). In the other category, there were four answers (7% of group B) indicating negative attitudes toward the crossing: an unwillingness to walk to the crosswalk, feeling it's a waste of time, complaints that cars do not stop anyway, and they did not feel like it. The two most common reasons given by Group C for crossing while the device was flashing were because somebody else had pressed the button (98%) and they felt it was safer to cross with the device flashing (14%). Out of the 58 Group B respondents, we received no answers for the two options that would suggest a need for educating pedestrians about the devices (i.e., the options "Didn't know I should" and "Don't know how it works").

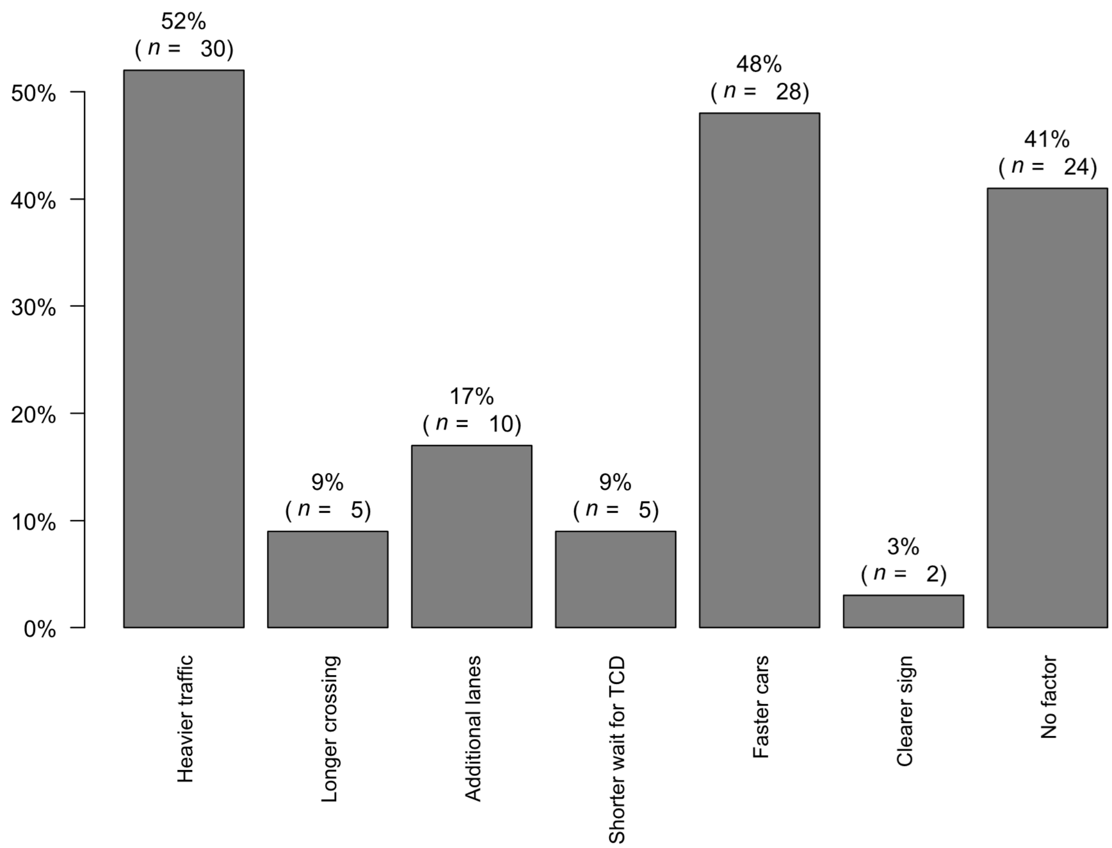

Figure 10. Stated factors that would increase chances of actuation in Group B (*n* = 58)

Figure 10 shows response frequencies for the most common factors Group B named that would make them more likely to push the button at a similar crosswalk device in the future. These were heavier traffic (52%), faster cars (48%), and no factor (41%).

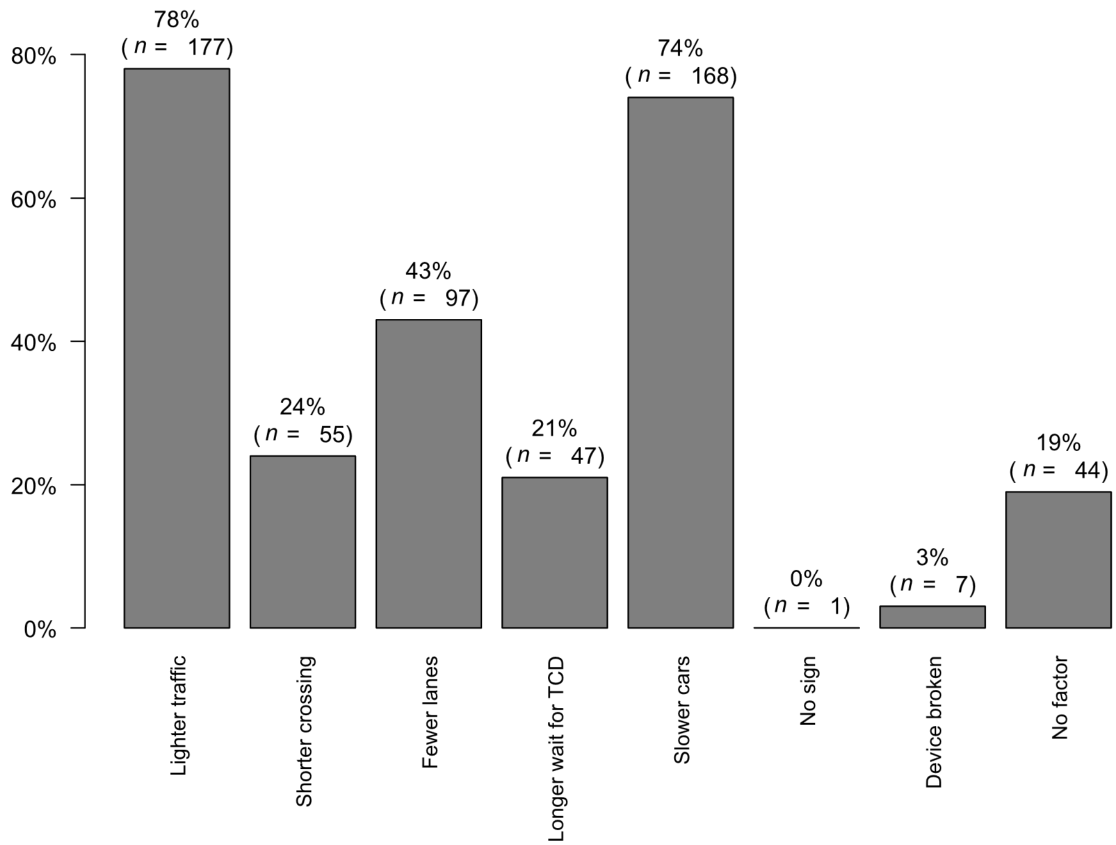

Figure 11. Stated factors that would reduce chances of actuation in Group A (*n* = 228)

figure 11 shows that for Group A, the most common factors named that would make them less likely to press the button at a similar device in the future were lighter traffic (78%), slower cars (74%), and either a shorter crossing or fewer lanes (67%).

ANALYSIS OF WAITING TIMES BY DEVICE TYPE

In the light of the survey responses indicating that not wanting to wait for the device was a top reason for non-actuation, we reviewed waiting times from the observational study to better understand the differences in observed actuation between devices. Waiting time is defined as the time between pedestrian arrival to the concrete staging area by the crosswalk and the moment they begin to walk into the travel lanes to cross.

Figure 12 shows the waiting time distributions from the observational study including only pedestrians recorded as waiting for a gap in traffic to cross, as noted in the video reduction (waiting time rounded to the closest second). The waits were longer with PHB actuations (Panel c), compared with RRFB actuations (Panel a). Panels b and d show that both non-actuation distributions were similar.

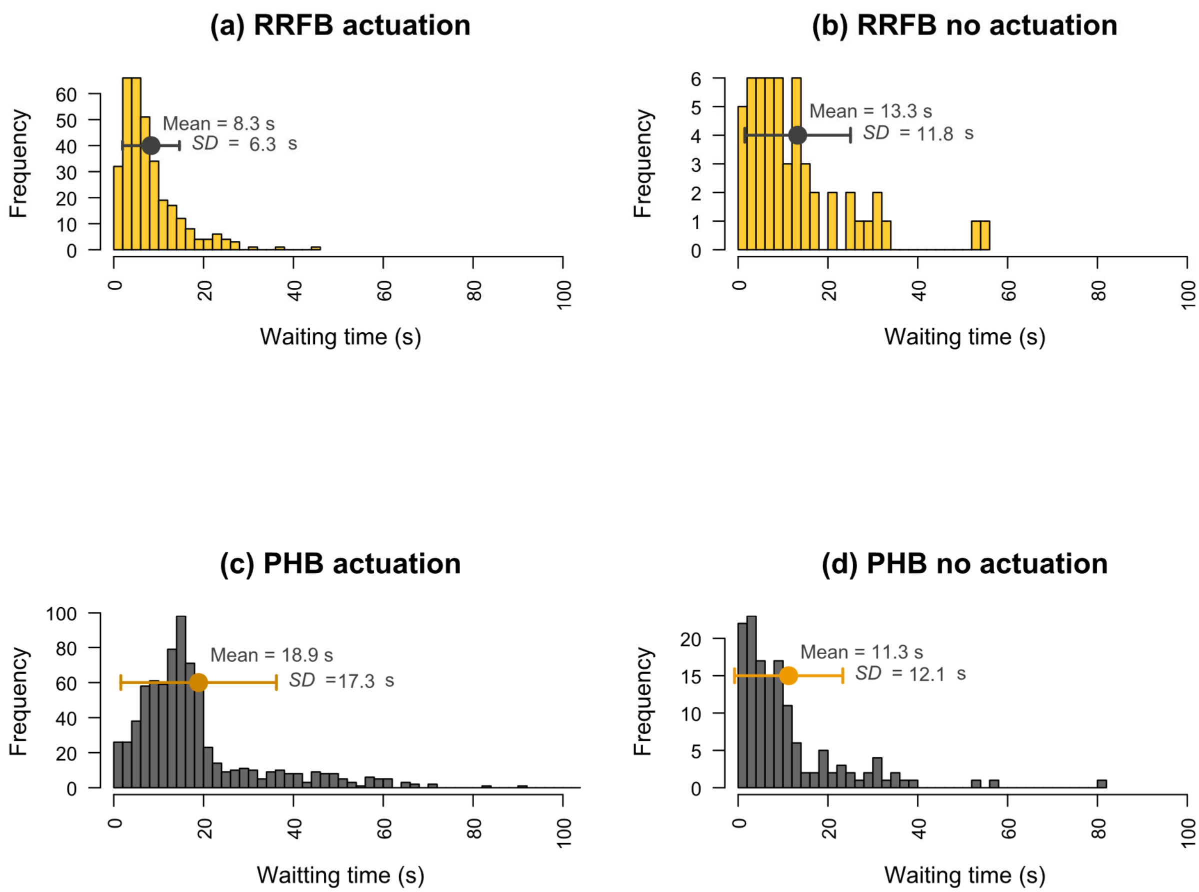

Figure 12. Marginal distributions for waiting times by device and actuation status

We noted that the mean and standard deviation in Panel a seem significantly smaller than Panel b, suggesting a reduced and more consistent waiting experience with actuated RRFBs compared with non-actuation, whereas the opposite is true for PHBs: longer and less reliable waits when actuated compared with not actuated, per Panels c and d.

We fitted a lognormal mixed-effects model on the median waiting time to check if these differences might be better explained by influential factors other than the device types (results in Table 5). We found that the differences by device and actuation status persist, having statistically significant coefficients even after controlling for random variations between blocks of aggregation (i.e., random effects including location, direction of travel, time of day, and day of week), number of pedestrians already in queue, speed limit, and number of vehicles observed during the crossing.

Table 5 Lognormal Mixed-Effects Regression of Pedestrian Waiting Time (n = 3,307)

Variable (Fixed effects)	Estimate	S*E*	Deg. of Fr.	*t* value	*p* value	Significance[a]
(Intercept)	1.3380	0.0834	15.82	16.04	<0.0001	***
Pedestrians in queue (max: 6)	−0.0344	0.0086	961.00	−4.002	<0.0001	***
45-mph speed limit	−0.2741	0.1253	13.98	−2.188	0.0462	*
Number of yielding vehicles	0.1132	0.0140	3199.00	8.07	<0.0001	***
Number of non-yielding vehicles	0.0707	0.0035	2990.00	20.406	<0.0001	***
Number of vehicles without enough stopping sight distance	0.0231	0.0030	3110.00	7.731	<0.0001	***
RRFB	−0.2513	0.1087	18.50	−2.312	0.0325	*
Actuation	0.7940	0.0436	3277.00	18.213	<0.0001	***
[RRFB] × [Actuation]	−0.4832	0.0616	3226.00	−7.848	<0.0001	***
Random effect standard deviation estimates						
Site	0.1383					
Direction at site	0.1230					
Weekday at direction	0.2085					
Hour at direction	0.1358					
Hour at weekday at direction	0.1502					
Residual	0.6788					

[a] Significance coded as follows:
* 0.010 < p-value < = 0.050;[
*** p-value < 0.001

Regarding other influential factors, this model indicates that median pedestrian waiting times tend to be shorter for crossings where larger groups of pedestrians are already in queue at arrival (3.4% shorter per additional pedestrian in queue, or −0.034 = exp(−0.0344) − 1) and 24.0% shorter at locations with posted 45-mph speed limits (−0.240 = exp(−0.2741) − 1).

As expected, median waiting times tended to increase with each additional vehicle observed at the crossing (i.e., because of the positive and statistically significant coefficients for the three types of vehicle classifications in the table). Regarding the devices and actuation status, median waiting time was 52.0% shorter for an actuated RRFB compared with an actuated PHB under the same crossing conditions ($-0.520 = \exp(-0.2513 - 0.4832) - 1$). Figure 13 shows the conditional distributions for a scenario involving a crossing with seven vehicles, for a fair comparison and illustration of the magnitude of the waiting time difference between devices.

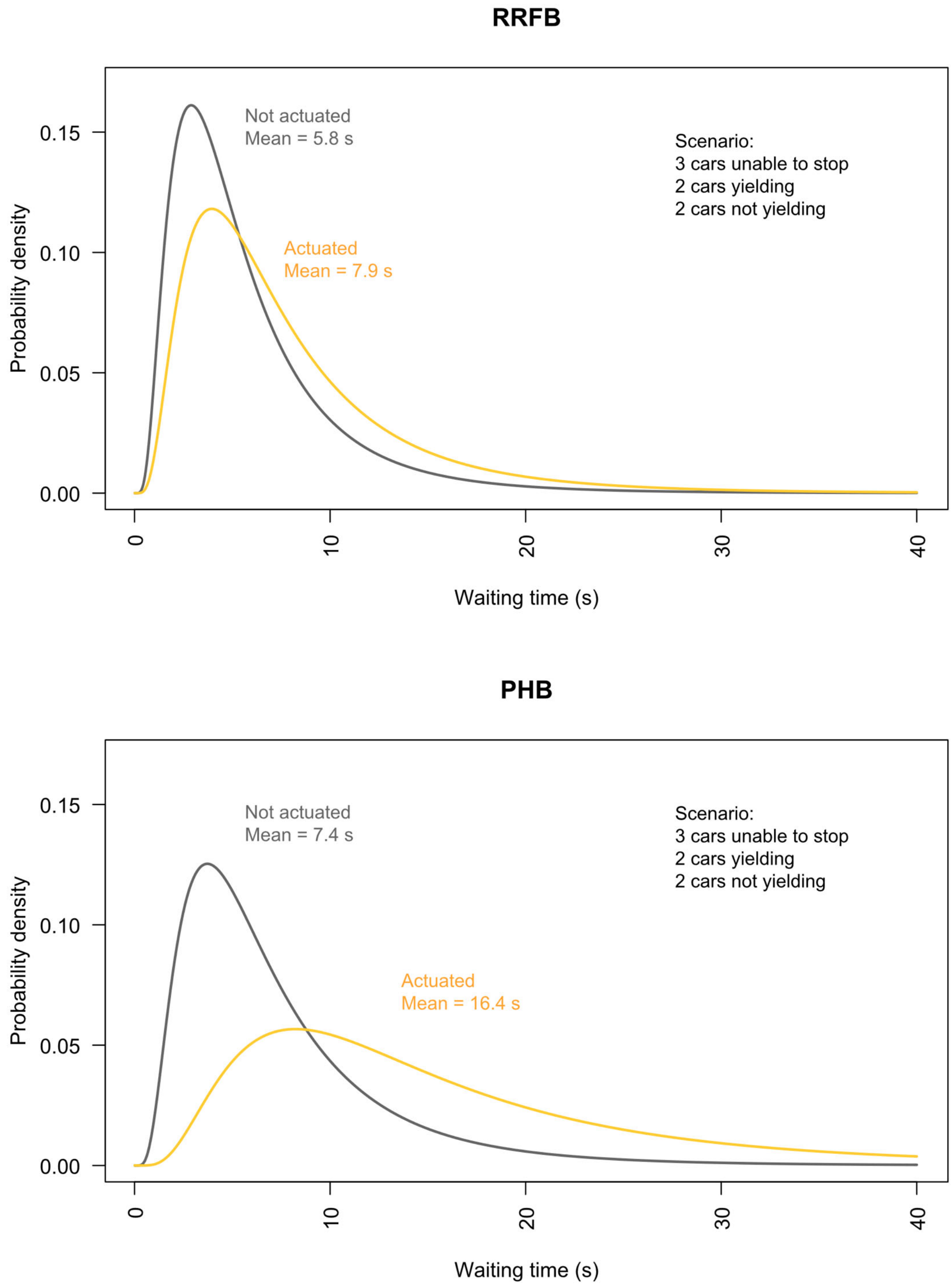

Figure 13. Waiting time by device and actuation status for a scenario with seven vehicles

Figure 13 shows that while the difference in waiting time between the actuation and non-actuation conditions is minimal for RRFBs (2.1 s longer with actuation on average), it is substantial for PHBs (waiting time more than doubling, up 9.0 s with actuation on average).

Figure 14 shows the difference between actuated devices, given a specific number of vehicles interacting with the pedestrian in a given crossing. The mean waiting time is, in this case, longer by 14.3 s with an actuated PHB compared with an actuated RRFB.

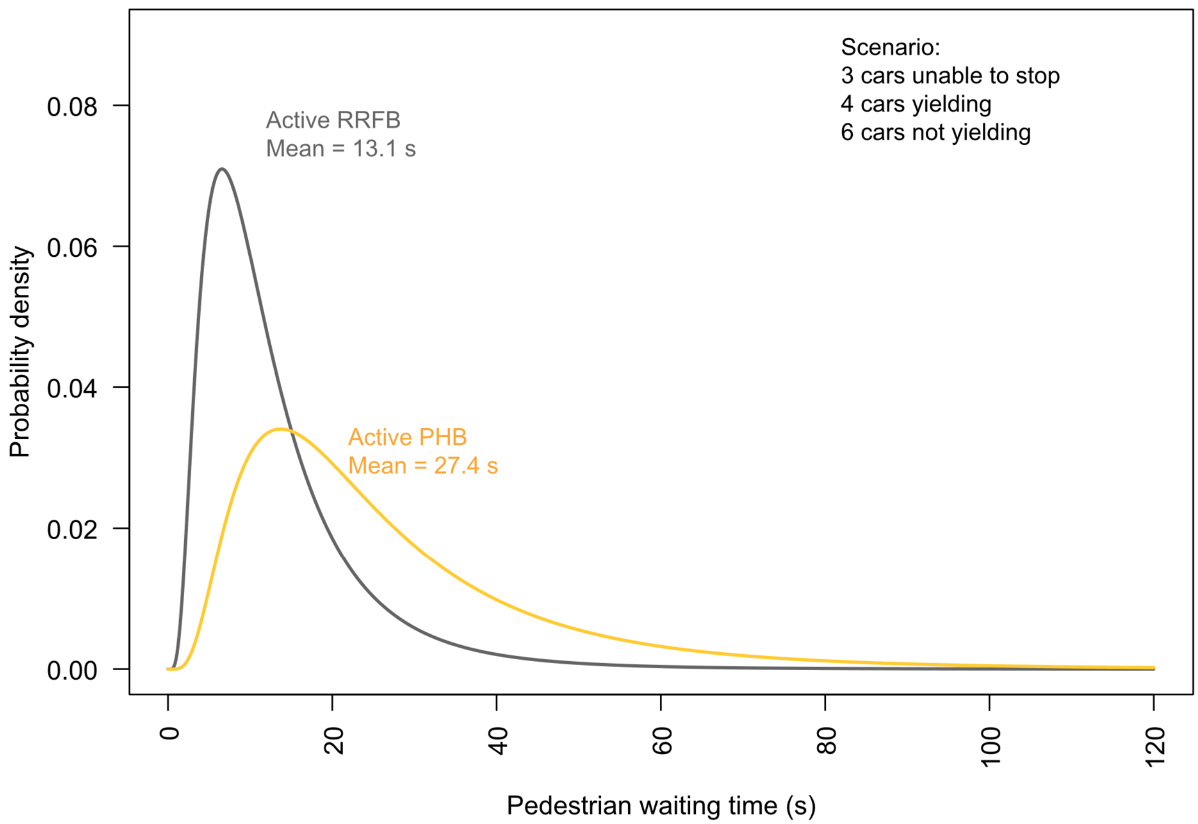

Figure 14. Waiting times for active devices and scenario with 13 vehicles

The long right tail of the distributions in these figures should be noted. Even though the mean waiting times are shorter than a minute, waiting times can be expected to exceed 60 s in the case of crossing with a PHB, but not for an RRFB in the illustrated scenario.

We noted in the survey that 41 out of 170 Group A respondents at RRFB sites (24.1%) reported being less likely to actuate the device if the wait for activation were longer, compared with 6 out of 58 (10.3%) at PHB sites. A Pearson's homogeneity test provides statistical evidence against this difference being just chance ($X^2 = 4.207$, $df = 1$, $p = 0.0403$). This finding is not surprising, given the differences in waiting time from the observational study. Perhaps this reflects that RRFB users assume (correctly) that they will experience a short, acceptable waiting time when actuating RRFBs compared with PHB users who might (correctly) assume longer perhaps unacceptable waiting times, per Figure 12.

If PHB users have the expectation of longer waits when actuating these devices, as shown in Figure 12, it should be unsurprising that a larger percentage of Group B pedestrians surveyed at PHB sites (19 out of 42 responses, 45.2%) reported not having actuated the device because they did not want to wait, compared with 5 out of 16 (31.3%) pedestrians at RRFB sites. This trend would suggest longer waits at PHBs might be steering more pedestrians not to actuate and crossing without the aid of these devices. However, this difference in proportions was not statistically significant ($X^2 = 0.0447$, $df = 1$, $p = 0.504$).

CONCLUSIONS AND RECOMMENDATIONS

RRFBs and PHBs are effective countermeasures to increase yielding to pedestrians, but to optimally influence driver behavior pedestrians need to actuate them. This research examined pedestrian and driver behavior around midblock crossings in Raleigh and Charlotte, NC. We collected observational and survey data from a random sample of locations representing conditions equally likely to have either RRFBs or PHBs and a survey of pedestrians from a subset of these locations. In our sample, 80.3% of pedestrians actuated RRFBs and 56.1% actuated PHBs. This trend remained after analyzing the complete actuation dataset and controlling for other influential factors. In that analysis we found the odds of pedestrians actuating RRFBs were 2.409 times the odds of actuating PHBs.

From the subset of the observational data that allows estimating yielding rates (those with observed vehicles with enough sight distance to yield), we initially found higher yielding at RRFBs (see Table 2). However, that trend inverted when we used the complete dataset in a statistical model to control for other influential aspects of each crossing and site (as implied by Parameter 33 in Table 3 and seen in Figure 6 and Figure 7 for various scenarios). From our analysis of yielding behavior, we estimate that increasing actuation to 100% would raise the probability of drivers yielding by 13.2% at RRFBs and by 54.8% at PHBs when holding other conditions equal.

Key Findings

One of the main findings from our research is that pedestrians' inclination to actuate any of the devices in this study is sensitive to their perception of friction or hazard at their intended crossing. Our analyses consistently showed a link between actuation rates and variables that would signal increased friction or crossing hazards. Surveyed pedestrians who crossed after actuating reported that "heavy traffic," "fast cars," and "long crossing" were their main reasons for having actuated. Non-actuators reported similar answers when asked what factors would make them more likely to be actuators in the future. Additionally, the observational study documented behaviors consistent with these types for factors being associated with increased rates of actuation (higher odds of actuation at wider crossings, when more vehicles are present, and at night).

The results from our deeper examination of waiting times provide insights worth discussing. We found statistically significantly longer waiting times after actuation at PHBs compared with RRFBs. This extended wait at PHBs probably explains—to a large extent—why fewer pedestrians were observed actuating these devices. However, longer waiting times at PHBs should not be a surprise. A typical PHB cycle requires an initial flashing phase to alert drivers they will need to stop soon before signaling a mandatory stop to drivers. This flashing period is preceded in some cases by an additional period of wait for pedestrians to allow coordination with nearby signals in order to preserve traffic progression. In contrast, RRFBs entail no additional wait, starting to flash warning lights to upcoming vehicles immediately after activation. Future research should investigate systematic ways to reduce or keep the waiting times low at sites with PHBs. In our estimation, these devices have the larger potential to improve their yielding rates (as shown in Figure 9), if pedestrians who are currently disinclined to actuate the devices could be encouraged to actuate more often.

Our observational study results clearly show a duality of behaviors around the two types of devices studied: on the one hand, drivers are more inclined to yield at actuated PHBs; on the other hand, pedestrians are less likely to actuate those devices. Each of these features is consistent with past findings by Fitzpatrick et al. (*11*) and Kutela and Teng (*17*), respectively. However, a caveat for our findings is that the studied locations represent conditions where cross sections and vehicle volumes are such that RRFBs are equally likely to be deployed. This is an important distinction to make because NCDOT—similar to other agencies—outlines different criteria to select which of the two devices to deploy (*21*). Figure 1 reflects the outcome of the different criteria in the statewide distributions: PHBs are reserved for locations with larger cross sections, heavier traffic, and higher pedestrian volumes. Considering all these points, we are careful not to recommend one device over the other in a general sense, as AADT and crossing-distance ranges at the PHBs in our study do not cover the statewide range of the application of those devices. We note that in light of our results, it makes sense to reserve PHBs for more challenging crossing conditions. Pedestrians at those types of locations should perceive an increased crossing friction and, thus, should be more motivated to actuate the devices and tolerate longer waiting times, according to responses to our survey.

Recommendations

From our survey, we did not find any non-actuators indicating not knowing how the devices work. Therefore, education about the devices should not be a high priority in efforts aiming to increase actuation rates.

We recommend further research into modifying the time plans for PHBs (even considering passive pedestrian detection), given our finding that these devices are underutilized and present the most potential for safety improvement. Future work should explore alternatives and find ways to avoid extending waiting times unnecessarily, especially in situations where coordination with adjacent signals is an important factor to consider.

Regarding other actionable factors by transportation agencies —geometry interventions and considerations for new deployments—we offer additional insights that might improve actuation and yielding rates. First, we notice that pedestrian crossings near intersections tended to engage in undesired behaviors (i.e., more crossing out of the crosswalk and fewer actuations). This observation suggests that PHBs and RRFBs should preferably be deployed at midblock locations, keeping some distance from intersections. Another recommendation for future deployments is the preferred consideration of RRFBs over PHBs at trails or shared path crossings where the traffic and crossing distance allow. This policy would result in increased actuation rates according to our examination of counterfactuals, all else being equal.

One potential intervention we identify from this work is the construction of sidewalks at both sides of locations having or planning to have pedestrian crossings with active TCDs. We found higher chances of unwanted pedestrian behaviors (i.e., more instances of crossing out of the crosswalk and lower chances of actuation) at locations lacking a sidewalk on one side of the crossing.

Recommending the construction of pedestrian refuges at locations with sufficient space for that purpose is probably the intervention with most potential we identified from this work. We found significantly improved performance both by pedestrians (slightly higher actuation odds and lower odds of crossing out of the crosswalk) and drivers (significantly higher yielding odds) regardless of the TCD type present at locations with this geometric element. This is consistent with Zeeger et al. who found this geometric element beneficial by itself (*4*).

Limitations

Although we consider our analyses comprehensive and our sample sizes robust regarding the number of observed pedestrians (over 3,000 for the observational study, and over 300 for the survey), we would like to acknowledge the small number of sites represented (15 sites) as the main limitation of this study. Future research based on a larger sample should confirm some of the insights we present that were supported by a small number of study sites. For example, only two study sites had a sidewalk absent on one side of the crossing, only two were posted at 25 mph, and only three were posted at 45 mph.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Raul Avelar and Jessica Cicchino; data processing and preparation: Raul Avelar; analysis: Raul Avelar; interpretation of results: Raul Avelar and Jessica Cicchino; draft manuscript preparation: Raul Avelar and Jessica Cicchino. Both authors reviewed the results and approved the final version of the manuscript.

REFERENCES

[1] Blackburn, L., C. Zegeer, and K. Brookshire. Guide for Improving Pedestrian Safety at Uncontrolled Crossing Locations. Report No. FHWA-SA-17-072. Federal Highway Administration, 2017.

[2] Carter, D., W. Hunter, C. Zegeer, R. Stewart, and H. Huang. Pedestrian and Bicyclist Intersection Safety Indices: Final Report. Report No. FHWA-HRT-06-125. Turner-Fairbank Highway Research Center, 2006.

[3] Zegeer, C., D. Nabors, P. Lagerwey, C. Sundstrom, D. Lovas, T. Huber, R. Eldridge, and M. Bushell. Pedsafe 2013. Pedestrian Safety Guide and Countermeasure Selection System. Federal Highway Administration, 2013.

[4] Zegeer, C., R. Srinivasan, B. Lan, D. Carter, S. Smith, C. Sundstrom, N. Thirsk, J. Zegeer, C. Lyon, E. Ferguson, and R. Houten. Nchrp Research Report 841: Development of Crash Modification Factors for Uncontrolled Pedestrian Crossing Treatments. Transportation Research Board, 2017.

[5] Zegeer, C. V., D. T. Nabors, D. Gelinne, N. Lefler, and M. Bushell. Pedestrian Safety Strategic Plan: Recommendations for Research and Product Development. Federal Highway Administration, 2010.

[6] Fitzpatrick, K., and E. Park. Safety Effectiveness of the Hawk Pedestrian Crossing Treatment. Report No. FHWA-HRT-10-042. Federal Highway Administration, 2010.

[7] Fitzpatrick, K., E. Park, M. Cynecki, M. Pratt, and M. Beckley. Investigation of Crashes at Pedestrian Hybrid Beacons: Results of a Large-Scale Study in Arizona. Journal of Safety Research, Vol. 78, 2021, pp. 59–68.

[8] Fitzpatrick, K., I. Potts, M. Brewer, and R. Avelar. Comparing Rectangular and Circular Rapid Flashing Beacons in an Open-Road Setting, 2014.

[9] Ross, J., and D. Serpico. Assessment of Driver Yielding Rates Pre- and Post-RRFB Installation, Bend, Oregon. Oregon Department of Transportation, Salem, OR, 2011.

[10] Fitzpatrick, K., R. Avelar, J. Robertson, and J. Miles. Comparison of Driver Yielding for Three Rapid-Flashing Patterns Used with Pedestrian Crossing Signs. FHWA-TechBrief-HRT-15-041. Federal Highway Administration, 2015.

[11] Fitzpatrick, K., M. Brewer, and R. Avelar. Driver Yielding to Traffic Control Signals, Pedestrian Hybrid Beacons, and Rectangular Rapid Flashing Beacons in Texas. Transportation Research Record, Vol. 2463, No. 1, 2014, pp. 46–54.

[12] Brewer, M., and K. Fitzpatrick. Before-and-after Study of the Effectiveness of Rectangular Rapid-Flashing Beacons Used with School Sign in Garland, Texas. Transportation Research Board 4th Urban Street Symposium, Chicago, IL, 2012.

[13] Al-Kaisy, A., G. Miyake, J. Staszcuk, and D. Scharf. Motorists' Voluntary Yielding of Right of Way at Uncontrolled Midblock Crosswalks with Rectangular Rapid Flashing Beacons. Journal of Transportation Safety and Security, Vol. 10, No. 4, 2018, pp. 303–317.

[14] Rowangould, D., J. Sullivan, and P. Pezeshknejad. Effectiveness of Rectangular Rapid Flashing Beacons (Rrfbs) in Small and Rural Communities. Report No. VTRC 20-3. University of Vermont Transportation Research Center, 2023.

[15] Bradbury, K., J. Stevens, L. Boyle, and S. Rutherford. To Go or Not to Go. Pedestrian Behavior at Intersections with Standard Pedestrian Call Buttons. Transportation Research Record, Vol. 2299, 2012, pp. 174–179.

[16] Zhang, X., A. Ryan, and Y. Wu. Influential Factors of Pedestrian and Bicycle Crashes near Pedestrian Hybrid Beacons: Observing Trends through an Applied Analysis. Journal of Transporation Safety & Security, Vol. 16, No. 11, 2024, pp. 1307–1330.

[17] Kutela, B., and H. Teng. Evaluating the Influential Factors for Pushbutton Utilization at Signalized Midblock Crosswalks. Safety Science, Vol. 122, 2020, pp. 1–8.

[18] Li, F., K. Morgan, and A. Zaslavsky. Balancing Covariates Via Propensity Score Weighting. Journal of the American Statistical Association, Vol. 113, No. 521, 2018, pp. 390–400.

[19] American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*. Washington, DC, 2019.

[20] R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2024.

[21] North Carolina Department of Transportation. NCDOT Pedestrian Crossing Treatment Evaluation Guidance [Flowchart]. Raleigh, NC, 2015. https://connect.ncdot.gov/resources/safety/Teppl/TEPPL%20All%20Documents%20Library/FlowChart.pdf