Transportation Research Part F: Psychology and Behaviour 114 (2025) 919–932

Contents lists available at ScienceDirect

Transportation Research Part F: Psychology and Behaviour

journal homepage: www.elsevier.com/locate/trf

Investigating nighttime driver behaviors and interactions at pedestrian Hybrid Beacons

Xi Zhang, Alyssa Ryan *, Yao-Jan Wu

Civil Engineering and Environmental Engineering and Mechanics, 1209 East 2nd Street, University of Arizona, Tucson, AZ 85721, USA

ARTICLE INFO

Keywords:
Pedestrian hybrid beacons
Driver compliance
Social interactions
Nighttime driver behavior
Peer influence

ABSTRACT

Pedestrian safety remains a critical concern globally and in the United States. Pedestrian Hybrid Beacons (PHBs) at marked crosswalks have been effective in increasing driver-yielding rates and reducing pedestrian crashes. However, nighttime driver behaviors and social interactions at PHBs, e.g., imitating the behavior of peer drivers, have remained understudied in the post-pandemic context. This study investigates nighttime driver behaviors and explores empirical evidence of social interactions at PHBs following the pandemic. Driver behaviors are collected from videos from four PHB locations in Pima County, Arizona. Descriptive analysis and logistic regression models are used to reveal drivers' non-compliance rates and interactions with pedestrians and peer vehicles at PHBs at night. Results indicate that 94% to 97% of drivers stopped during the steady red phase of PHBs at night and compliance dropped further to 53% during the flashing red phase. Compared to initial drivers in a platoon approaching during the steady red phase, those approaching during the flashing red phase were approximately 3.6 times more likely to fail to stop. Among leading-following pairs in a platoon (excluding the first vehicles), 50% to 83% of following drivers mimicked the leading vehicle's behavior, even when the leading driver violated traffic laws. At intersections with a speed limit of 25 mph, 41.7% of drivers resumed travel during the flashing red phase, even when pedestrians were in the crosswalk. These findings provide critical insights into nighttime driver behaviors and social interactions at PHBs. The results can inform improvements in PHB design, implementation, and pedestrian crossing treatments.

1. Introduction

Pedestrians and cyclists are among the most vulnerable road users (Haque et al., 2025; Mahmood et al., 2024). Their safety is an escalating concern across the United States, with pedestrian deaths rising by 66 %, reaching over 7,400 annually between 2011 and 2021 (Caggiano et al., 2025; Hu & Cicchino, 2018; NHTSA, 2023). Nighttime conditions, with reduced visibility, a greater likelihood of impaired driving, and additional blind spots, contribute significantly to these fatalities (FHWA, 2025; Mikoski et al., 2019). From 2011 to 2020, pedestrian fatalities during dark conditions in the United States showed an increasing trend, with approximately 5,000 deaths recorded in 2020 (FHWA, 2022). Pedestrians are roughly five times more likely to be killed at night compared to daytime (Ferenchak et al., 2022). The National Highway Traffic Safety Administration (NHTSA, 2023) reports that about 77 % of pedestrian fatalities occur during nighttime.

* Corresponding author.
E-mail address: alyssaryan@arizona.edu (A. Ryan).

https://doi.org/10.1016/j.trf.2025.07.011
Received 8 February 2025; Received in revised form 7 July 2025; Accepted 8 July 2025
Available online 12 July 2025
1369-8478/

The Pedestrian Hybrid Beacon (PHB), previously known as the High-Intensity Activated CrossWalK (HAWK), is a traffic control device designed to enhance pedestrian safety at midblock crossings and uncontrolled intersections (MUTCD, 2023), both during the day and at night. The PHB was first developed and implemented in Tucson, Arizona in the late 1990s and was later included in the Manual on Uniform Traffic Control Devices (MUTCD) in its 2009 edition. As of 2019, 41 states had installed PHBs statewide. Arizona led in adoption, with more than 190 installations statewide (DeLorenzo et al., 2019; Zhang et al., 2024).

The PHB consists of a circular yellow signal in the center, flanked by two horizontally aligned circular red signals above it. The PHB remains dark until actuated. Pedestrians press a pushbutton to actuate the PHB signal. Upon actuation, the PHB initiates a flashing yellow signal, followed by a steady yellow signal to alert drivers to prepare to stop. Next, two solid red indications illuminate steadily during the all-red and pedestrian walk interval. This is followed by alternating flashing red indications during the pedestrian clearance interval. The PHB returns to its dark state once the pedestrian clearance interval concludes (MUTCD, 2023). Drivers should begin to slow down and prepare to stop during the flashing yellow stage. During the steady yellow stage, they are required to stop if it is safe to do so. Drivers must come to a complete stop during the steady red stage, regardless of the pedestrians' location in the crosswalk. During the flashing red stage, drivers must stop when approaching the PHB and may proceed with caution after stopping only once the crosswalk is clear (Fitzpatrick & Park, 2021; MUTCD, 2023). This study observed a transition phase in which the signal changes from steady red to flashing red as a vehicle approaches the PHB. In such cases, drivers should stop at the stop line and may proceed with caution if they are in the flashing red phase as they continue through the crosswalk.

1.1. Safety effectiveness of PHBs

Previous research has demonstrated the safety benefits of PHBs by evaluating drivers' yielding rates to pedestrians (Arhin & Noel, 2010; Fitzpatrick et al., 2016; Fitzpatrick et al., 2014; Fitzpatrick et al., 2006), assessing changes in crash rates following PHB installation (Eapen, 2014; Fitzpatrick & Park, 2010), and identifying factors influencing pedestrian crashes at PHBs (Fitzpatrick et al., 2021; Pulugurtha et al., 2018; Zhang et al., 2024). Some studies have indicated that drivers tended to yield to pedestrians at activated PHBs, based on data from video footage collected between 2004 and 2020 (Arhin & Noel, 2010; Fitzpatrick et al., 2016; Fitzpatrick et al., 2014; Fitzpatrick et al., 2019; Fitzpatrick et al., 2006; Godavarthy & Russell, 2016). Yielding rates reported in these studies varied from 75 % to 97 %. Fitzpatrick & Park (2021) found similar yielding rates during the day (97 %) and night (96 %), and concluded that PHBs were highly effective during both daytime and nighttime.

Fitzpatrick & Park (2010) conducted a before-after study using crash data from 1999 to 2007, which indicated that total crashes and pedestrian crashes decreased by 29 % and 69 %, respectively. In a later study, Fitzpatrick et al. (2021) performed a cross-sectional analysis of 186 PHB locations in Arizona using crash data from 2007 to 2017. The authors concluded that crash frequencies increased with more traffic lanes and shorter distances between traffic control signals and PHBs. However, features such as bike lanes, raised medians, and pedestrian refuge islands were associated with reductions in total crashes. Pulugurtha et al. (2018) used Pearson correlation tests on crash data (2011–2014) from 13 PHB locations in North Carolina. They concluded that higher crash rates were associated with high traffic volume, high speeds, wide roads, and proximity to office, multi-family, retail, and vertical mixed land-use areas. Zhang et al. (2024) conducted Bayesian multilevel Poisson-Lognormal regression analyses using crash data from 2018 to 2021. Their findings indicated that regions with a greater proportion of White individuals and higher household incomes were associated with fewer crashes near PHBs.

1.2. Challenges of PHBs and research gaps

Despite the demonstrated safety effectiveness of PHBs, one of the challenges identified in previous research is the occurrence of non-compliant driver behaviors in response to PHBs. Fitzpatrick et al. (2016) analyzed driver behaviors in response to PHBs using daytime footage collected in 2014 at eight study sites in Texas and in 2015 at 12 study sites in Arizona. The authors observed that when a queue of vehicles was present during the flashing red indication, approximately half of the crossing actuations included at least one driver who did not come to a complete stop before entering the crosswalk. Additionally, about 5 % of the PHB actuations involved at least one driver who stopped during the flashing red stage and remained stopped until the signal terminated. This observation aligns with a recent study in Massachusetts (Caggiano et al., 2025), which surveyed driver comprehension of PHB intervals and found that drivers had the most difficulty understanding the meaning and required actions during the flashing yellow and flashing red stages. Later, Fitzpatrick et al. (2019) examined driver behaviors in response to PHBs using daytime footage from 2018 at ten high-speed sites (with speed limits of 45–50 mph) in Arizona. They found that while 90 % of drivers stopped and remained stopped during the steady red stage, about 59 % of drivers rolled through the intersection without fully stopping during the flashing red stage. These non-compliant driver behaviors in response to PHBs violate the law and may be strongly associated with pedestrian-involved crashes (Bella & Silvestri, 2015; Kong et al., 2021).

Three significant research gaps remain unaddressed in previous studies evaluating non-compliant driver behaviors in response to PHBs. First, prior research has not examined driver behaviors at PHBs in the post-pandemic era. Since the onset of the COVID-19 pandemic, studies have documented notable shifts in driver behavior, including increased speeding and other aggressive driving behaviors (NHTSA, 2022). Dong et al. (2022) found a significant rise in driver aggressiveness and inattentiveness following the pandemic. Similarly, Ghosh et al. (2024) reported increases in risky driving behaviors such as aggression, distraction, and driving under the influence of alcohol. Truelove et al. (2021) observed that average speeds rose by 20.6 % to 70.6 % on selected routes in Columbus, Ohio, with similar patterns in other major cities. According to Ansari et al. (2023), several post-pandemic behavioral changes are expected to persist and continue impacting transportation systems, particularly driver behavior, for years to come. These changes may also influence driver compliance at locations with traffic control devices such as PHBs. Therefore, it is important to investigate whether these post-pandemic behavioral shifts have affected driver compliance with PHBs.

Second, nighttime presents unique challenges to the performance of PHBs, as a recent study has found that pedestrian crashes are more likely to occur at night than during the day, even when PHBs are active (Zhang et al., 2024). The compounding effects of reduced visibility at night and limited driver compliance with PHBs, such as rolling stops, may contribute to this trend (Hassan & Abdel-Aty, 2011). Nighttime also coincides with an increased likelihood of driver impairment, fatigue, and drowsiness (FHWA, 2025; Mikoski et al., 2019; NSC, 2024), which can lead to delayed reaction times and more aggressive behaviors, thereby elevating crash risk. Despite these risk factors, driver behavior at PHBs during nighttime, particularly in the post-pandemic era, remains unexamined in the literature.

Third, it remains unclear how drivers interact socially when a platoon of vehicles is present during the flashing red stage. Specifically, it is unknown whether drivers tend to follow the actions of drivers ahead of them. Some studies have shown that drivers often mimic the actions of peer drivers, and this social influence can lead to behaviors such as speeding, accelerating, or not stopping at all (Bingham et al., 2016; Fleiter et al., 2010; Trogolo et al., 2022). Understanding these social interactions at PHBs, especially at night, can help transportation professionals in their decision-making to improve driver compliance and enhance pedestrian safety.

1.3. Study objectives

This study addresses the identified research gaps through two primary objectives: (1) to evaluate driver behaviors during the "steady red" and "flashing red" signal stages of PHBs at nighttime in the "new normal," and (2) to analyze the social interactions between leading and following vehicles at PHBs at night during the post-pandemic period. The study also developed a framework for extracting and validating driver behaviors from video footage to support these objectives, with the potential for application in similar studies by other agencies that aim to evaluate their own PHB compliance. Four PHB locations with low (25 mph) and high (40 mph) speed limits were selected for data collection. Logistic regression analysis was employed to identify factors influencing driver behaviors. Several variables, such as intersection types, speed limits, preceding vehicle behaviors, pedestrian locations within the crosswalk, and PHB signal phases, were included in the regression analysis.

The findings of this study offer critical insights into nighttime driver compliance at PHBs, assisting transportation agencies to better understand and address current safety challenges. By examining the social aspects of driver interactions, the study provides a new

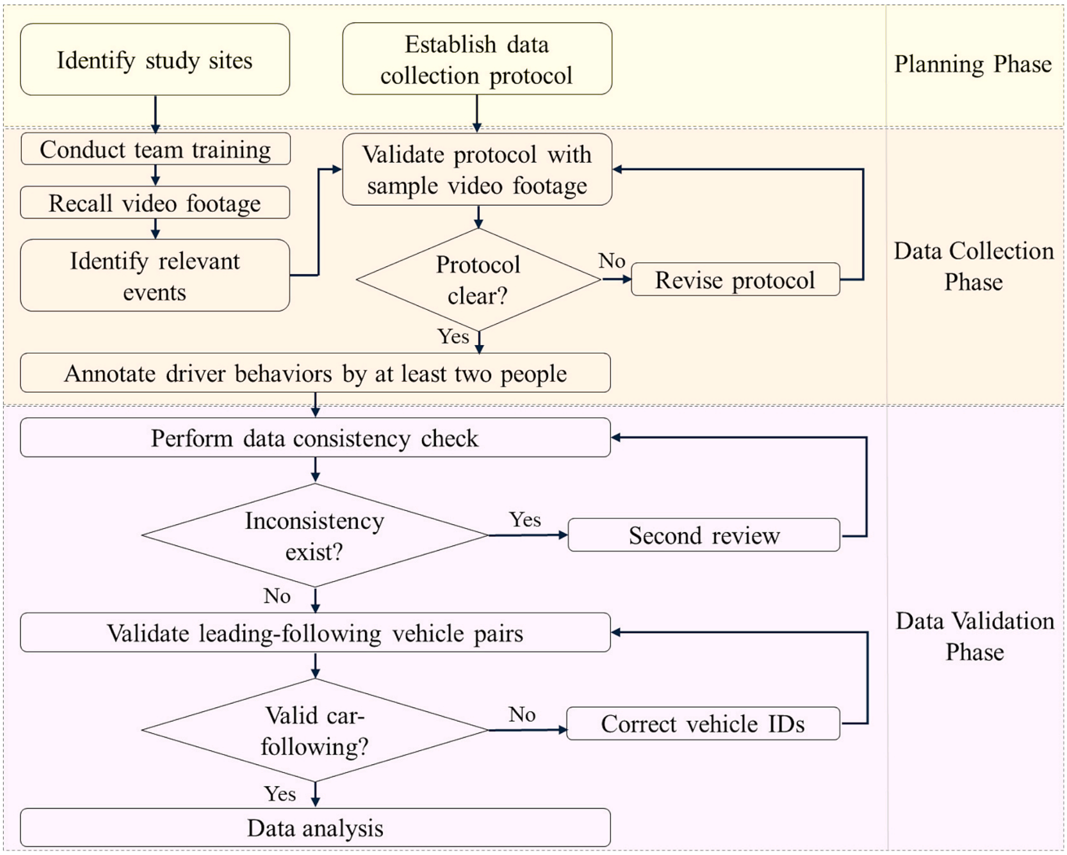

Fig. 1. Framework for data collection and validation.

perspective on how driver behavior patterns can influence overall crossing safety. These insights can guide improvements in PHB design and implementation strategies. They can also be used for optimizing other pedestrian crossing treatments, such as Rectangular Rapid Flashing Beacons (RRFBs), and help develop more effective driver education programs.

2. Methodology

Many studies have collected driver behavior and other relevant information by reducing video footage (Fitzpatrick et al., 2016; Fitzpatrick et al., 2019; Fitzpatrick & Park, 2021; Godavarthy & Russell, 2016). These were considered in the development of this study's methodology. Specifically, Fig. 1 illustrates a comprehensive framework encompassing the planning, data collection, and data validation phases necessary for conducting this observational study. The following sections provide an in-depth explanation of each phase, and the logistic regression model employed in this study to identify the influential factors affecting various driver behaviors.

2.1. Planning phase

2.1.1. Study Site selection

The selection of study sites involved several considerations, including but not limited to data collection efficiency and a diverse range of geometric configurations, to ensure comprehensiveness. In this study, a list of locations with PHBs and pre-installed Miovision video sensors (Miovision, n.d.) in Pima County, Arizona, was initially compiled. The study was limited to Pima County due to the prevalence of potential study sites in this region, as well as data access. To identify the most ideal study sites, several criteria were applied, including clear camera views to observe both driver and pedestrian behaviors, high pedestrian volumes at night to capture nighttime PHB actuations, varying speed limits, the number of lanes, and intersection types. Following this filtering process, four study locations were selected. Fig. 2 shows the geometry of the selected study sites. These sites featured speed limits ranging from 25 to 40 mph and varying numbers of lanes, with both three-leg and four-leg intersections. All of these sites were located within the jurisdiction of the Pima County Department of Transportation (PCDOT) in Arizona. A Miovision SmartView 360 camera was installed at each study location, marked by a star in Fig. 2. Each camera provides a 360-degree field of view, allowing coverage of most of the intersection with a single device and enabling the capture of approaching vehicles from distances of up to 500 feet (Miovision, n.d.).

2.1.2. Data collection protocol

The goal of the data collection protocol was to ensure the consistent collection of relevant information from video footage. Four categories were included in the protocol:

- Basic information:
  - o Study location, video name, and the time when the PHB actuation begins in the vide.
- Pedestrian data:
  - o Pedestrian moving direction (eastbound [EB], westbound [WB], southbound [SB], or northbound [NB]) and whether the pedestrian is on a bicycle.
- Vehicle data:
  - o Vehicle direction (EB, WB, SB, NB), lane position (inner, middle, outer), vehicle ID, and whether the vehicle is following the leading vehicle (i.e., traveling closely behind another vehicle in the same lane, maintaining a following distance rather than driving independently).

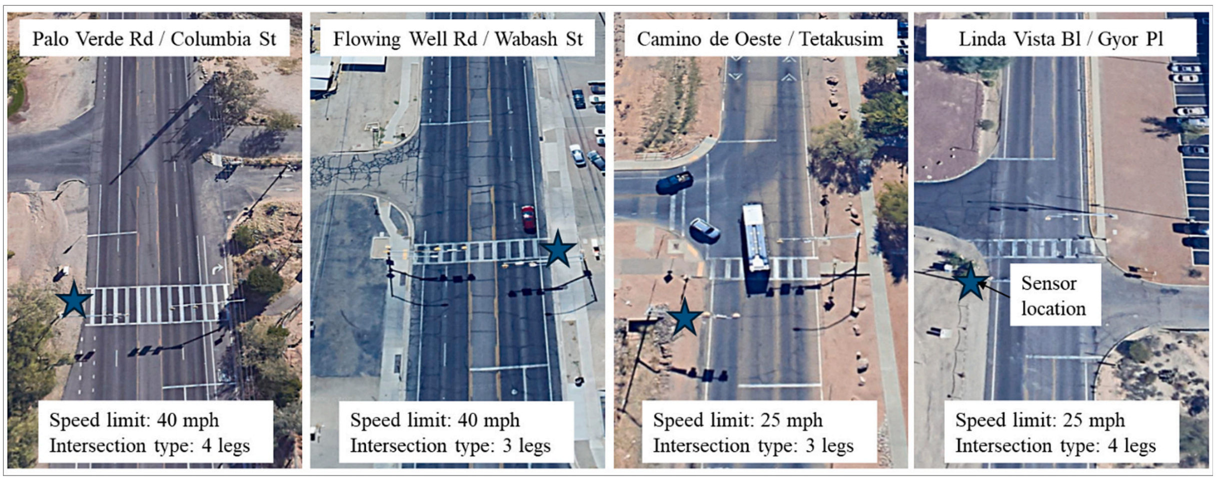

Fig. 2. Study sites (Google, n.d.).

- Driver behavior and pedestrian position relative to the crosswalk during the steady red, flashing red, and transition stages (with the transition stage being the steady red turning to flashing red as the vehicle approaches the PHB):
  - o Driver's behavior when approaching the PHB:
    - ■ Complete stop: drivers come to a complete stop.
    - ■ No stop: drivers roll through the intersection or do not slow down.
    - ■ Resume travel: drivers come to a complete stop during the steady red stage and resume travel during the flashing red stage.
  - o Pedestrian position in the crosswalk relative to the side where the pedestrian activates the PHB pushbutton, and as the vehicle approaches (i.e., not yet in the crosswalk, 1/3 of the way, halfway, 2/3 of the way, already crossed).

2.2. Data collection phase

Prior to data collection, training sessions were conducted by the senior researcher to prepare four trainee researchers for video reduction tasks. All four researchers were trained on the study's objectives and the use of the data collection protocol, including guidance on identifying driver behaviors, such as complete stops and no stops, with the help of sample videos. Additionally, two researchers received specific instructions on using the Miovision platform to review video footage. These two researchers were then tasked with identifying and documenting PHB actuations at night from the study locations. Meanwhile, the other two researchers tested the protocol using pilot videos to evaluate its clarity and usability. Revisions to the protocol were made based on training sessions and discussions with the senior researcher to ensure clarity of the data collection goals at hand. Once the protocol was finalized, and sufficient PHB actuations were documented, all relevant events were identified and categorized accordingly.

2.3. Data validation phase

After the trainee researchers completed the review in line with the protocol, the senior researcher was responsible for reviewing the results to ensure consistency and addressing any potential discrepancies in the results by revisiting the video footage. Additionally, one column included in the protocol was aimed at identifying scenarios where the leading vehicle had already left when the following vehicle approached the PHB. In such cases, the Vehicle ID of the following vehicle was relabeled to reflect the updated sequence. For example, if the following vehicle, originally labeled as Vehicle ID 4 in the middle lane traveling EB, was determined not to be strictly following Vehicle ID 3 in the same lane and direction, its ID was corrected to Vehicle ID 1. The IDs of subsequent vehicles were then adjusted accordingly to maintain consistency in the dataset. This ensured the vehicles were genuinely part of a platoon, with the following driver's behavior potentially influenced by the leading vehicle.

2.4. Logistic regression model

A multivariate logistic regression model was employed to analyze factors associated with an increased likelihood of law violations (i.e., no-stop behaviors) at PHBs. The binary outcome variable was defined as follows: 0 for drivers who adhered to the law by coming to a complete stop at PHBs and 1 for drivers who violated the law by not stopping at PHBs. The logistic regression model form for predicted probabilities was expressed as a natural logarithm of the odds (log-odds) (Boateng & Abaye, 2019):

$$\ln[\frac{P(Y)}{1-P(Y)}] = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \quad (1)$$

$$P(Y) = \frac{e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k}}{1 + e^{\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k}} \quad (2)$$

where $\ln[\frac{P(Y)}{1-P(Y)}]$ is the log (odds) of the outcomes; Y is the binary outcome; X_1 to X_k are the predictors, e.g., intersection types, speed limits, leading vehicle behaviors, driver position relative to pedestrians, and PHB signal phases; β_1 to β_k are the model coefficients, and β_0 is the intercept.

The odd ratio (OR) of each coefficient was expressed as below:

$$OR_k = e^{\beta_k} \quad (3)$$

ORs derived from logistic regression models are not reliable approximations for relative risk ratios (RRs) when the incidence of the outcome is not rare in the study population (i.e., greater than 10 %) (Hu et al., 2024; Zhang & Yu, 1998), which is the case for no-stop behaviors in this study, particularly during the flashing red stage. Therefore, the ORs were transformed into RRs using the Equation (4):

$$RR_k = \frac{OR_k}{(1-p) + (p \times OR_k)} \quad (4)$$

where p represents the proportion of vehicles that violated the law at PHBs, i.e. no-stop behaviors.

Confidence intervals (CIs) were calculated to assess the significance of the coefficients at the 95 % CI.

$$CI_k = \beta_k \pm Z_{\alpha/2} \times SE(\beta_k) \quad (5)$$

where $Z_{\alpha/2}$ is the critical value from the standard normal distribution for a 95 % confidence interval (approximately 1.96 for 95 % CI); $SE(\beta_k)$ is the standard error of the coefficient β_k.

McFadden pseudo R^2 was used to assess the goodness-of-fit of the models, as shown in Equation (6). McFadden pseudo R^2 from 0.2 to 0.4 is generally considered are considered good for social science or behavioral data (Domencich & McFadden, 1975; Mohammadi et al., 2021).

$$McFadden\,pseudo\,R^2 = 1 - \frac{LL_\theta}{LL_0} \tag{6}$$

where LL_θ is the log-likelihood at convergence, LL_0 is the log-likelihood of the constant-only model.

3. Results and Discussion

Video footage was recorded from October 2023 to January 2024, with a few recordings collected in November 2024. All PHB activations were recorded during dark sky conditions, with street lighting, and when the road surface was dry. The number of PHB activations ranged from 24 to 40 across the four study locations. A total of 424 drivers were analyzed for intersections with a speed limit of 40 mph, and 104 drivers were analyzed for intersections with a speed limit of 25 mph. This section examines drivers' compliance with PHBs, their social interactions with pedestrians and vehicles, and the factors influencing non-compliant driver behaviors at PHBs.

3.1. Driver behaviors during different PHB signal phases

Table 1 presents the statistics of driver behaviors when approaching PHBs during the steady red, flashing red, and transition stages.

Intersections with speed limits of 40 mph and 25 mph exhibited similar trends during the steady red stage. Although most drivers completely stopped when approaching PHBs displaying steady red indications, there were seven instances where drivers failed to stop despite the steady red. In three of these cases, pedestrians were already in the crosswalk. During the transition stage, most drivers opted to stop, though some still ran the red light. It is noted that red-light running is a frequent and often fatal issue. In 2022, crashes involving red-light running resulted in 1,149 fatalities, with half of the victims being pedestrians, bicyclists, or occupants of other vehicles hit by red-light runners (IIHS, 2024).

In the flashing red stage, 47 % of the initial drivers in a platoon failed to stop. Additionally, more than 80 % of the second, third, and fourth drivers in a platoon failed to stop at night at intersections with a 40 mph speed limit. Studies have demonstrated a strong correlation between darker conditions and more severe pedestrian injuries in crashes (Thomas et al., 2018; Zegeer & Bushell, 2012). Reduced visibility at night can make it difficult for drivers, especially these no-stop drivers, to detect pedestrians clearly, potentially increasing the risk of crashes and severe injuries (FHWA, 2025; Sanders et al., 2022).

3.2. Driver-Pedestrian interactions

Interpersonal interactions between drivers and pedestrians occur during crossing (Zafri et al., 2022). In this section, we examine driver behavior in relation to the position of pedestrians during the flashing red stage. The transition stage was also excluded due to a limited sample size. It is noted that 95.3 % of drivers who arrived during the steady red stage stopped completely, regardless of pedestrian positioning, while 2 % of the drivers failed to stop even when the pedestrians were in the crosswalk.

Table 2 illustrates the interactions between drivers and pedestrians for vehicles traveling on the same side as pedestrians who activated pushbuttons. Each of the four study locations has a road width of approximately 32 feet. At intersections with a 25 mph speed limit, approximately 75 % of drivers either resumed their travel or completed a stop after pedestrians had already crossed during the flashing red phase. In contrast, at intersections with a 40 mph speed limit, a statistically significant portion (46.8 %, 95 % CI: 39.7 % – 53.9 %) of drivers failed to stop, although pedestrians had already crossed the crosswalk. This difference could be attributed to lower vehicle speeds at 25 mph intersections, as a study has shown an inverse relationship between vehicle speeds and driver yielding rates

Table 1
Statistics of drivers' behaviors when approaching PHBs.

Intersection Speed Limit (mph)	Vehicles in Platoon	Steady Red Stage		Flashing Red Stage		Transition Stage	
		Complete Stop	No Stop	Complete Stop	No Stop	Complete Stop	No Stop
		Count (%)	Count (%)	Count (%)	Count (%)	Count (%)	Count (%)
40	1st veh	100 (94.3 %)	6 (5.7 %)	61 (53.0 %)	54 (47.0 %)	20 (90.9 %)	2 (9.1 %)
	2nd veh	NA	NA	18 (16.8 %)	89 (83.2 %)	NA	NA
	3rd veh	NA	NA	10 (19.6 %)	41 (80.4 %)	NA	NA
	4th veh	NA	NA	3 (16.7 %)	15 (83.3 %)	NA	NA
25	1st veh	43 (97.7 %)	1 (2.3 %)	11 (52.4 %)	10 (47.6 %)	6 (75.0 %)	2 (25.0 %)
	2nd veh	NA	NA	13 (50.0 %)	13 (50.0 %)	NA	NA

Note: NA = Not applicable.

Table 2
Driver behaviors and pedestrian locations for vehicles on the same side as pedestrians who activated pushbuttons.

Intersection Speed Limit (mph)	Driver Behavior – Pedestrian Location	Count	Percentage (95 % CI)	Notes
40	Resume travel – 2/3 of the way	14	7.5 % (4.0 % – 11.0 %)	Risky behavior
	Resume travel – Already crossed	30	16.1 % (10.7 % – 21.5 %)	Safe behavior
	Complete stop – 2/3 of the way	5	2.7 % (0.4 % – 5.0 %)	Safe behavior
	Complete stop – Already crossed	40	21.5 % (15.5 % – 27.5 %)	Safe behavior
	Complete stop – Halfway	2	1.1 % (0.0 % – 2.6 %)	Safe behavior
	No stop – 2/3 of the way	8	4.3 % (1.3 % – 7.3 %)	Risky behavior
	No stop – Already crossed	87	46.8 % (39.7 % 53.9 %)	Risky behavior
25	Resume travel – 2/3 of the way	2	4.3 % (0.0 % – 10.1 %)	Risky behavior
	Resume travel – Already crossed	21	44.7 % (30.2 % – 59.2 %)	Safe behavior
	Complete stop – Already crossed	12	25.5 % (13.0 % – 38.0 %)	Safe behavior
	No stop – Already crossed	12	25.5 % (13.0 % – 38.0 %)	Risky behavior

toward pedestrians (Zafri et al., 2022).

The pattern at the larger intersections aligns with previous research on daytime driver behaviors at PHBs, which found that most rolling stops occurred during queue discharge after pedestrians had completed their crossing (Fitzpatrick et al., 2019). However, this study revealed that at night, 4.3 % of drivers did not stop even when pedestrians were in the crosswalk. Overall, 7.5 % of drivers resumed their travel during the flashing red phase, following a complete stop during the steady red, even when pedestrians were two-thirds of the way across the road on the crosswalk.

In most cases, pedestrians had already crossed when many drivers failed to stop as required during the flashing red stage. This is noteworthy nonetheless, as this behavior raises concerns about the potential for other pedestrians to approach the crosswalk and/or begin crossing during this phase, as this is allowed. For example, a pedestrian may trail just behind a leading pedestrian and enter the crosswalk during the flashing phase. Drivers who fail to stop may not detect or react to these trailing pedestrians in time, especially at night, when visibility is lower and the risk of impaired or drowsy driving increases (FHWA, 2025; Mikoski et al., 2019).

Table 3 presents the interactions between drivers and pedestrians for vehicles traveling on the opposite side of the road from where pedestrians activated the pushbuttons. The trend of risky driver behaviors is similar to that observed for vehicles traveling on the same side at large intersections. However, a significant risky behavior was observed at an intersection with a 25 mph speed limit, where 41.7 % (95 % CI: 30.5 % – 52.9 %) of drivers resumed their travels during the flashing red phase after coming to a complete stop during the steady red, even when pedestrians were in the crosswalk. This behavior occurred statistically significantly more often than the safe behavior "Complete stop – Already crossed" (2.1 %, 95 % CI: 0.0 % – 5.0 %). This observation could be because of the geometry of the road, which can influence drivers' risk perception (Yao et al., 2019). As some studies have shown, a greater number of lanes and higher vehicle speeds are associated with an increased risk of pedestrian crashes and greater injury severity (Anciaes et al., 2020; Schneider et al., 2021; Thomas et al., 2020). Drivers may feel overly confident in their ability to navigate lower-speed intersections because these environments seem less complex or threatening, causing them to overlook the presence of pedestrians.

3.3. *Driver-Driver interactions*

This section presents how drivers' behaviors were influenced by their peers, i.e., leading vehicles in this study, during the flashing red stage of PHBs at intersections with a 40 mph speed limit.

Fig. 3 shows the social interactions between drivers for vehicles traveling on the same side of the road from where pedestrians activated the pushbuttons. Among all leading-following vehicle pairs for the first two vehicles in a platoon, when the leading vehicle resumed travel from a complete stop during the steady red phase, 62 % (95 % CI: 49.9 % – 76.0 %) of the following vehicles tended not to stop during the flashing red stage. These vehicle pairs were statistically significantly more common than other types. These followers may have approached the leader during either the steady red or flashing red phase. In 11 % of all leading-following vehicle pairs, when

Table 3
Driver behaviors and pedestrian locations for vehicles on the opposite side as pedestrians who activated pushbuttons.

Intersection Speed Limit (mph)	Driver Behavior – Pedestrian Location	Count	Percentage (95 % CI)	Notes
40	Resume travel – 2/3 of the way	1	0.5 % (0.0 % – 1.6 %)	Risky behavior
	Resume travel – Already crossed	56	26.9 % (21.1 % – 32.7 %)	Safe behavior
	Complete stop – 2/3 of the way	13	6.3 % (3.0 % – 9.6 %)	Safe behavior
	Complete stop – Already crossed	32	15.4 % (10.5 % – 20.2 %)	Safe behavior
	Complete stop – Halfway	1	0.5 % (0.0 % – 1.6 %)	Safe behavior
	No stop – 2/3 of the way	1	0.5 % (0.0 % – 1.6 %)	Risky behavior
	No stop – Already crossed	104	50.0 % (43.3 % – 56.7 %)	Risky behavior
25	Resume travel – 2/3 of the way	20	41.7 % (30.5 % – 52.9 %)	Risky behavior
	Resume travel – Already crossed	13	27.1 % (14.7 % – 39.4 %)	Safe behavior
	Complete stop – Already crossed	1	2.1 % (0.0 % – 5.0 %)	Safe behavior
	No stop – Already crossed	14	29.2 % (16.4 % – 42.0 %)	Risky behavior

Note: Pedestrians at "2/3 of the way" are closer to vehicles traveling on the opposite side of the road from those who activated the pushbuttons.

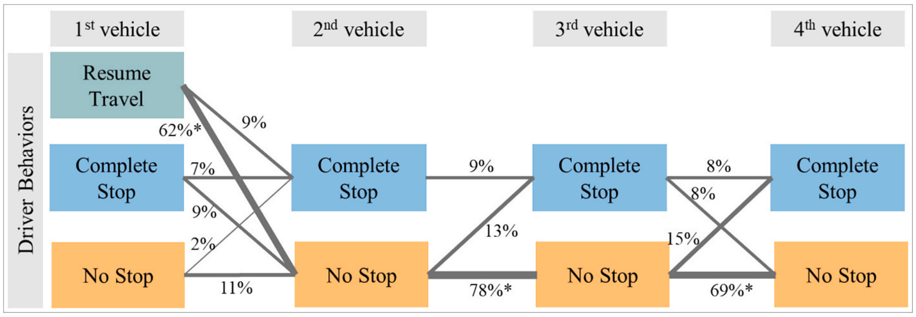

Fig. 3. Drivers' social interactions on the same side of the road as pedestrians who activated the pushbuttons (*indicates the percentage is statistically different at the 95% confidence level).

the leading vehicle did not stop, the followers also did not stop. However, if the leading vehicle came to a complete stop, about half of the followers stopped, while the other half did not. For the second and third vehicles or third and fourth vehicles in a platoon, 69 % (95 % CI: 46.6 % – 91.4 %) to 78 % (95 % CI: 62.0 % – 94.0 %) of these pairs showed that when the leading vehicle did not stop, the followers also did not stop. These patterns were statistically significantly more common than other vehicle pair behaviors. These findings indicate that following drivers tended to mimic the behavior of their leading vehicles, even when the leading vehicles violated traffic laws. This "imitative behavior," which relies on observing the actions of other drivers at PHBs, aligns with findings from other studies that suggest drivers often follow and imitate the actions of their peers (Fleiter et al., 2010; Mohammadi et al., 2021).

Similar trends in drivers' social interactions were observed among drivers traveling on the opposite side of the road from where pedestrians activated the pushbuttons, as shown in Fig. 4. A notable difference is the slightly higher proportion (17 %) of leading-following pairs for the first two vehicles in a platoon where, if the leading vehicle resumed travel, the following vehicle would stop, compared to 9 % for vehicles traveling on the same side. Additionally, a slightly higher proportion of pairs involving the second and third vehicles in a platoon showed that 21 % of these pairs came to a complete stop when the leading vehicle did not stop, compared to 13 % for drivers traveling on the same side. This could be because pedestrians were closer to vehicles traveling on the opposite side as these vehicles were discharged from the intersection during the flashing red stage. The reduced distance and increased immediacy may have triggered a stronger sense of urgency and responsibility in drivers.

3.4. Regression results

Logistic regression models were used to identify the factors influencing the likelihood of law violations at PHBs, i.e., no-stop behaviors. The binary outcome variable was coded as 1 for drivers who did not stop at PHBs when activated (law violation), and 0 for those who came to a complete stop (law compliance).

Two scenarios were examined: one focused on factors influencing the likelihood of law violations at PHBs for initial vehicles in a platoon, and the other for following vehicles during the flashing red stage.

Explanatory variables considered in both scenarios included intersection type, speed limits, number of lanes, the presence of pedestrians on bikes, pedestrian locations within the crosswalk, and whether vehicles were on the same side as the pedestrian who pressed the pushbutton. In the first scenario, PHB signal phases when vehicles approached PHBs were considered, while in the second scenario, the vehicle preceding the study vehicle's behavior and the PHB signal phase when the preceding vehicle approached the PHB were taken into account. These variables were selected based on prior research (e.g., Pulugurtha et al., 2018; Fitzpatrick et al., 2021), which identified several of these factors as being associated with pedestrian-related crashes at PHBs. They are also directly aligned with this study's focus on driver compliance behavior.

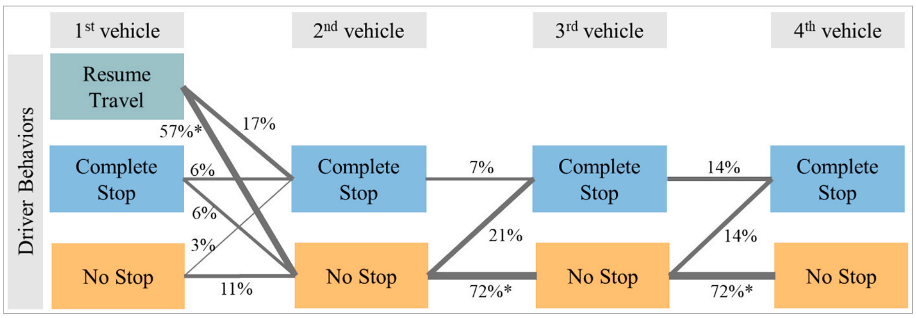

Fig. 4. Drivers' social interactions on the opposite side of the road as pedestrians who activated the pushbuttons (*indicates the percentage is statistically different at the 95% confidence level).

Multicollinearity among the explanatory variables was assessed using the Variance Inflation Factor (VIF). Predictors with VIF values greater than four, an acceptable threshold in previous transportation-related studies (Almasi; & Behnood, 2022; Zhang et al., 2025b), were excluded from the models. Interaction terms were not included in the final models due to sample size limitations, increased AIC values when interactions were added, and to preserve model interpretability.

Intersection type, speed limits, and whether vehicles were on the same side as the pedestrian who pressed the pushbutton were included in the modeling of both scenarios. For the first scenario, which modeled initial vehicles' behavior, two models were developed: one included pedestrian locations within the crosswalk, and the other included PHB signal phases when vehicles approached PHBs. These two variables were found to be collinear but were both of interest in this study, and thus, an interest in understanding their contribution together was of interest. In the second scenario, modeling the behavior of the following vehicles, the preceding vehicle's behavior and the PHB signal phase when the preceding vehicle approached the PHB were included in the model. Table 4 shows the relative risks and 95 % confidence intervals for each predictor in the model.

3.4.1. *Initial vehicle in Platoon's behaviors at PHBs*

The results of the two logistic regression models indicate statistically significant associations between the likelihood of law violations (i.e., no-stop behaviors of the initial vehicles) and two key variables: pedestrian locations within the crosswalk and PHB signal phases when the initial vehicles approached.

Specifically, initial drivers were 2.66 times more likely to be associated with a law violation if pedestrians were "2/3 of the way" into the crosswalk, compared to when pedestrians had not yet entered the crosswalk (95 % CI: 1.40–3.72). Similarly, drivers were 3.61 times more likely to be associated with a law violation if pedestrians had "Already crossed" the crosswalk, compared to when pedestrians had not yet entered the crosswalk (95 % CI: 2.86–4.02). These results suggest that the likelihood of law violations by drivers increased as pedestrians progressed further in the crosswalk, with the highest risk observed when pedestrians had already crossed.

Initial drivers who approached the PHBs during the flashing red stage were 3.58 times more likely to be associated with a law violation compared to those who approached during the steady red stage (95 % CI: 3.07–3.92). Initial drivers who approached the PHBs during the transition stage were 2.1 times more likely to be associated with a law violation compared to those who approached during the steady red stage. This result was statistically significant at the 90 % confidence level. The results suggest that initial drivers were more likely to come to a complete stop during the steady red stage compared to other signal phases. Practitioners may consider increasing the duration of the steady red stage to further enhance driver compliance and potentially improve pedestrian safety.

Table 4
Model estimates.

Predictors	Initial Vehicle in Platoon		Following Vehicle in Platoon
	Model 1	Model 2	Model 3
	RR (95 % CI)	RR (95 % CI)	RR (95 % CI)
Intercept	0.04 (0.01, 0.13)**	0.07 (0.02, 0.19)**	0.11 (0.03, 0.32)**
Behaviors of the vehicle preceding the study vehicle when approaching PHBs			
Complete stop[1]	–-	–-	
No stop	–-	–-	1.20 (1.17, 1.79)**
PHB signal phases faced by the vehicle preceding the study vehicle when approaching PHBs			
Steady red stage[1]	–-	–-	
Flashing red stage	–-	–-	2.00 (1.65, 2.19)**
Transition stage	–-	–-	1.60 (0.81, 2.09)
Pedestrian locations within the crosswalk			
Not yet in the crosswalk[1]			
1/3 of the way	1.17 (0.20, 2.97)	–-	–-
Halfway	0.53 (0.03, 2.26)	–-	–-
2/3 of the way	2.66 (1.40, 3.72)**	–-	–-
Already crossed	3.61 (2.86, 4.02)**	–-	–-
PHB signal phases when the initial vehicle in the platoon approaches PHBs			
Steady red stage[1]			
Flashing red stage	–-	3.58 (3.07, 3.92)**	–-
Transition stage	–-	2.10 (0.83, 3.27)*	–-
Speed limits			
25[1]			
40	1.34 (0.77, 2.12)	1.02 (0.55, 1.74)	1.79 (1.27, 2.12)**
Intersection types			
3-leg[1]			
4-leg	1.23 (0.77, 1.81)	0.78 (0.46, 1.24)	1.44 (1.04, 1.78)**
Sides of vehicles relative to pedestrians who pressed the pushbutton			
Same side[1]			
Opposite side	1.01 (0.63, 1.54)	0.99 (0.61, 1.51)	0.93 (0.59, 1.32)
McFadden pseudo R^2	0.34	0.34	0.35

Note: RR = Relative risk; **= Results are statistically significant at 95 % confidence interval; *= Results are statistically significant at 90 % confidence interval; [1] = Reference category.

3.4.2. Following vehicles in Platoon's behaviors at PHBs during the flashing red stage

If the preceding vehicles failed to stop, the following vehicles were 1.2 times more likely to fail to stop during the flashing red stage, compared to when the preceding vehicle came to a complete stop. This statistically confirms that the behavior of the preceding vehicle influences the likelihood of the following vehicle stopping or not stopping. Following vehicles were twice as likely to fail to stop when the preceding vehicle encountered a flashing red stage, compared to when the leading vehicle faced a steady red. This may be because the following vehicles tend to imitate the behavior of the preceding vehicles (Fleiter et al., 2010), which often stop at a steady red but not at a flashing red (Fitzpatrick et al., 2019). Speed limits also played a role, with following vehicles at 25 mph PHBs being 1.79 times more likely to violate the law compared to those in 40 mph PHBs. Furthermore, following vehicles at 4-leg intersections were 1.44 times more likely to violate laws than those at 3-leg intersections.

3.5. Summary

A higher likelihood of driver impairment and drowsiness occurs at night compared to daytime (FHWA, 2025; Mikoski et al., 2019; NSC, 2024). These factors can lead to aggressive driving behaviors and significantly increase crash risks for pedestrians (Chai & Zhao, 2016; Foster et al., 2015; Su et al., 2023). Research also indicates that drivers' yielding behavior plays a crucial role in pedestrian safety at controlled intersections (Zafri et al., 2022). To ensure crash-free interactions, both drivers and pedestrians must exercise careful attention and strict compliance with traffic rules (Krizsik & Sipos, 2024).

Drivers' attitudes and behaviors are critical to ensuring safety for both themselves and pedestrians (Bener et al., 2017). They are encouraged to make independent, law-abiding decisions rather than being influenced by their peers. Educational campaigns may be crucial to raising driver awareness, given that a significant proportion of drivers failed to stop during the flashing red phase of PHBs. This study found that, on average, approximately 66 % of drivers did not stop during the post-COVID-19 nighttime period. Specifically, about 47 % of lead drivers in a platoon failed to stop, and more than 80 % of following vehicles at intersections with a 40 mph speed limit did not stop. Following drivers frequently mimicked the behavior of lead vehicles, even when that behavior involved violating traffic laws. Notably, similar non-stopping behavior was also observed before the COVID-19 pandemic during daytime conditions. For example, Fitzpatrick et al. (2019) examined driver behavior in response to PHBs using 2018 daytime footage from ten high-speed locations (45–50 mph) in Arizona. They found that about 59 % of drivers rolled through the intersection without fully stopping during the flashing red phase. However, that study did not specify whether these statistics applied to lead or following vehicles.

Drivers must yield to pedestrians, especially when they are in the crosswalk. As evidenced in this study, many drivers resumed traveling during the flashing red phase after coming to a complete stop at the steady red, even when pedestrians were still in the crosswalk. Drivers' understanding that the flashing red phase requires them to yield to pedestrians until the crosswalk is completely clear of pedestrians is critical for safety improvement. Failure to do so compromises pedestrian safety and undermines the effectiveness of PHBs. Promoting driver awareness of these responsibilities is essential to reduce risky behaviors and ensure safe interactions between drivers and pedestrians.

4. Conclusion

Pedestrian safety is a growing concern in the United States, with pedestrians more likely to be fatally injured at night. Pedestrian Hybrid Beacons (PHBs) effectively encourage drivers to yield during both day and night and reduce pedestrian crashes. However, studies have highlighted significant non-compliance among drivers in response to PHBs, which may be strongly associated with pedestrian-related crashes.

This study examined driver behavior at PHBs during nighttime conditions in the post-pandemic era, focusing on how drivers interacted socially with pedestrians and their leading vehicles in a platoon. A comprehensive data collection and validation framework was developed to extract and validate driver behaviors through video footage. Descriptive and logistic regression analyses were conducted to evaluate driver behaviors across different PHB signal phases, driver-pedestrian interactions, and driver-driver interactions. The findings revealed that most drivers fully stopped when approaching PHBs during the steady red phase. Compared to initial platoon drivers approaching during the steady red phase, those approaching during the flashing red phase were 3.58 times more likely to not stop, and those during the transition phase were 2.1 times more likely to not stop.

During the flashing red phase at intersections with a 25 mph speed limit, approximately 75 % of drivers resumed travel or completed a stop after pedestrians had already crossed when traveling on the same side as the pedestrian activating the pushbutton. In contrast, for vehicles traveling on the opposite side of the road, a different pattern was identified: 41.7 % of drivers resumed travel even when pedestrians were still in the crosswalk. At intersections with a 40 mph speed limit, during the flashing red phase, about 47 % of initial drivers and more than 80 % of following drivers in the platoon did not stop. Additionally, approximately 50 % of drivers did not stop after pedestrians had fully completed their crossing. Regression analysis results indicated that initial drivers in a platoon were 2.66 and 3.61 times more likely to exhibit no-stop behaviors when pedestrians were "2/3 of the way" across the crosswalk or had "already crossed," respectively, compared to when pedestrians had not yet entered the crosswalk.

In the analysis of leading-following vehicle pairs in a platoon, when the leading vehicle resumed travel during the flashing red phase, 57 % to 62 % of the following vehicles did not stop. In 11 % of cases where the leading vehicle failed to stop, the following vehicle also did not stop. For the following vehicles in the platoon, 69 % to 78 % failed to stop when the leading vehicle did not stop. Regression analysis further suggested that if the preceding vehicle failed to stop, the following vehicles were 1.2 times more likely to fail to stop compared to situations where the leading vehicle came to a complete stop.

Overall, the findings of this study suggest that drivers tended to stop during the steady red phase but not consistently during the flashing red phase at night in the post-pandemic period. Most followers in a platoon tended not to stop during the flashing red and often imitated the leaders' behavior, even if leaders violated the law. This provides insight into car-following travel behavior, where following drivers mimic the behavior of drivers ahead of them, regardless of whether it is the correct decision or not. Transportation agencies may consider studying the effectiveness of an extended steady red phase at high pedestrian volume locations, particularly at night, to increase pedestrian protections. Educational campaigns could also be implemented to assist drivers in understanding the risks of imitating leading vehicle behaviors and raise awareness of the associated dangers. Lastly, increased enforcement may assist in encouraging drivers to abide by the law at PHBs.

In addition to PHBs, several other pedestrian traffic control devices, such as mid-block pedestrian signals (MPSs) and rectangular rapid flashing beacons (RRFBs), have been deployed across the United States and shown to be effective in improving pedestrian safety (Ahsan et al., 2025a). These devices have demonstrated safety benefits by increasing driver-yielding rates and reducing pedestrian crashes at mid-block crossings (Ahsan et al., 2025b; Fitzpatrick et al., 2023; Zhang et al., 2025a; Zhang et al., 2024). A recent study reported comparable crash rate distributions between MPSs and PHBs (Fitzpatrick et al., 2023). MPSs have been found to enhance safety by encouraging more gradual vehicle speed reductions, while PHBs and RRFBs have raised concerns about potential sudden braking behaviors (Ahsan et al., 2025b). However, PHBs can be used for three- and four-leg intersections, whereas MPSs are generally applied at two-leg crossings (Fitzpatrick et al., 2023). PHBs have been shown to outperform RRFBs in terms of safety effectiveness, despite their higher installation costs (Anwari et al., 2025; Ugan et al., 2022).

Outside the United States, similar devices have also been implemented. In the United Kingdom, the PUFFIN (Pedestrian User-Friendly Intelligent) crossing was introduced in the 1990 s as an upgrade to the older Pelican crossings. Maxwell et al. (2011) evaluated 50 sites that had been converted from Pelican or far side facilities to PUFFIN crossings. The results showed significant reductions in pedestrian and vehicle crashes, by 24 % and 16 %, respectively, following the installation.

Despite these encouraging findings, a limited number of studies have assessed the effectiveness of these countermeasures in terms of driver behavior. Future research could apply the evaluation framework developed in the present study to better understand driver responses to other pedestrian traffic control devices, both in the United States and internationally.

This study acknowledges several limitations, which should be considered in future studies: daytime evaluations during the post-pandemic period were not possible due to camera angle constraints. Interaction terms may also be considered in future studies which have increased sample size to explore additional relationships. Furthermore, when analyzing driver interactions, the sample size limited the ability to evaluate different scenarios based on the PHB signal phases when the leading vehicle arrived. While vehicle speeds and driver demographic information could offer additional insights into driver interactions, this data was unavailable. Moreover, the impact of vehicles in other lanes was not evaluated. Future studies can focus on these aspects to further understand driver behavior and contribute to pedestrian safety.

CRediT authorship contribution statement

Xi Zhang: Writing – original draft, Methodology, Conceptualization. **Alyssa Ryan:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Yao-Jan Wu:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to gratefully acknowledge the Pima County Department of Transportation for providing access to the Miovision video sensors. Special thanks to trainee researchers Isabel Rei Zann Wee, Ryan Cassity, Sofia Iliev, and Ela Aldrete for their efforts in reducing the video footage.

Appendix

Appendix:. Summary of variables' descriptive statistics

Variables		Count (proportion) Initial Vehicle in Platoon	Following Vehicle in Platoon
Behaviors of the vehicle preceding the study vehicle when approaching PHBs	Complete stop	–-	169 (54.3 %)
	No stop	–-	142 (45.7 %)
PHB signal phases faced by the vehicle preceding the study vehicle when approaching PHBs	Steady red stage	–-	142 (64.5 %)
	Flashing red stage	–-	60 (27.3 %)
	Transition stage	–-	9 (4.1 %)
Pedestrian locations within the crosswalk	Not yet in the crosswalk	67 (21.1 %)	15 (7.1 %)
	1/3 of the way	36 (11.4 %)	15 (7.1 %)
	Halfway	44 (13.9 %)	35 (16.6 %)
	2/3 of the way	49 (15.5 %)	21 (10.0 %)
	Already crossed	121 (38.2 %)	125 (59.2 %)
PHB signal phases when the initial vehicle in the platoon approaches PHBs	Steady red stage	151 (54.0 %)	–-
	Flashing red stage	136 (48.6 %)	–-
	Transition stage	30 (10.7 %)	–-
Speed limit (mph)	25	73 (23 %)	31 (14.7 %)
	40	244 (77.0 %)	180 (85.3 %)
Intersection types	3-leg	137 (43.2 %)	79 (37.4 %)
	4-leg	180 (56.8 %)	132 (62.6 %)
Sides of vehicles relative to pedestrians who pressed the pushbutton	Same side	148 (46.7 %)	97 (46.0 %)
	Opposite side	169 (53.3 %)	114 (54.0 %)
Presence of pedestrians on bikes	Yes	16 (5.0 %)	10 (4.7 %)
	No	301 (95.0 %)	201 (95.3 %)

Data availability

The authors do not have permission to share data.

References

Ahsan, M. J., Abdel-Aty, M., & Abdelrahman, A. S. (2025). Can mid-block pedestrian signals (MPS) provide greater safety benefits than other mid-block pedestrian crossings? *Accid. Anal. Prev., 218*, Article 108105. https://doi.org/10.1016/j.aap.2025.108105

Ahsan, M. J., Abdel-Aty, M., Anwari, N., & Barbour, N. (2025). Evaluating drivers' braking behavior at mid-block pedestrian crosswalks using video data and a mixed logit model with heterogeneity in the means. *Transp. Res. Interdiscip. Perspect., 31*. https://doi.org/10.1016/j.trip.2025.101380

Almasi; S. A., & Behnood, H. R.. (2022). Exposure based geographic analysis mode for estimating the expected pedestrian crash frequency in urban traffic zones; case study of Tehran. *Accid. Anal. Prev., 168*.

Anciaes, P., Di Guardo, G., & Jones, P. (2020). Factors explaining driver yielding behaviour towards pedestrians at courtesy crossings. *Transport. Res. F: Traffic Psychol. Behav., 73*, 453–469. https://doi.org/10.1016/j.trf.2020.07.006

Ansari, S., Du, H., Naghdy, F., & Sattar, A. (2023). Impact of Post-Covid-19 on driver behaviour: A perspective towards pandemic-sustained transportation. *J. Transp. Health, 28*, Article 101563. https://doi.org/10.1016/j.jth.2022.101563

Anwari, N., Abdel-Aty, M., & Ahsan, M. J. (2025). Comparative evaluation of vehicle delays at midblock rectangular rapid flashing beacon and pedestrian hybrid beacon pedestrians' crossings. *Journal of Transportation Engineering, Part A: Systems, 151*(2), Article 10.1061/jtepbs.Teeng-8400.

Arhin, S., & Noel, E. C. (2010). *Evaluation of HAWK signal at Georgis avenue and Hemlock Street. NW in the District of Columbia*. DDOT-PPSA-HAWK-001.

Bella, F., & Silvestri, M. (2015). Effects of safety measures on driver's speed behavior at pedestrian crossings. *Accid. Anal. Prev., 83*, 111–124. https://doi.org/10.1016/j.aap.2015.07.016

Bener, A., Yildirim, E., Özkan, T., & Lajunen, T. (2017). Driver sleepiness, fatigue, careless behavior and risk of motor vehicle crash and injury: Population based case and control study. *Journal of Traffic and Transportation Engineering (English Edition), 4*(5), 496–502. https://doi.org/10.1016/j.jtte.2017.07.005

Bingham, C. R., Simons-Morton, B. G., Pradhan, A. K., Li, K., Almani, F., Falk, E. B., Shope, J. T., Buckley, L., Ouimet, M. C., & Albert, P. S. (2016). Peer passenger norms and pressure: Experimental effects on simulated driving among teenage males. *Transport. Res. F: Traffic Psychol. Behav., 41*(A), 124–137. https://doi.org/10.1016/j.trf.2016.06.007

Boateng, E. Y., & Abaye, D. A. (2019). A review of the logistic regression model with emphasis on medical research. *Journal of Data Analysis and Information Processing, 07*(04), 190. https://doi.org/10.4236/jdaip.2019.74012

Caggiano, A., Pamarthi, J., Zafian, T. M., Deng, M. Y., Johnson, K., Tainter, F., & Knodler, M. (2025). An evaluation of driver comprehension of the Pedestrian Hybrid Beacon. *J. Saf. Res., 92*, 181–191. https://doi.org/10.1016/j.jsr.2024.11.001

Chai, J., & Zhao, G. (2016). Effect of exposure to aggressive stimuli on aggressive driving behavior at pedestrian crossings at unmarked roadways. *Accid. Anal. Prev., 88*, 159–168. https://doi.org/10.1016/j.aap.2015.12.026

DeLorenzo, S., Jiang, M., & Attalla, M. (2019). DeLorenzo, S. S., Jiang, M., & Attalla, M. (2019). Current policies throughout the nation for Pedestrian Hybrid Beacon (PHB) installation. *FHWA-ICT-19-010*.

Domencich, T., & McFadden, D. L. (1975). *Urban travel demand: A behavioral analysis*. DOi: North-Holland Publishing Co. https://eml.berkeley.edu/~mcfadden/travel.html.

Dong, X., Xie, K., & Yang, H. (2022). How did COVID-19 impact driving behaviors and crash severity? a multigroup structural equation modeling. *Accid. Anal. Prev., 172*, Article 106687. https://doi.org/10.1016/j.aap.2022.106687

Eapen, A. (2014). Evaluation of PHB mid-street crossing system in Las Vegas. *Nevada-pedestrian.* perspectives.
Ferenchak, N. N., Gutierrez, R. E., & Singleton, P. A. (2022). Shedding light on the pedestrian safety crisis: An analysis across the injury severity spectrum by lighting condition. *Traffic Inj. Prev., 23*(7), 434–439. https://doi.org/10.1080/15389588.2022.2100362
FHWA. (2022). *Lighting for Pedestrian Safety*. https://safety.fhwa.dot.gov/roadway_dept/night_visib/docs/Lighting_for_Pedestrian_Safety_2pager.pdf.
Fhwa. (2025). *Nighttime Visibility for Safety*. Retrieved January from https://www.fhwa.dot.gov/innovation/everydaycounts/edc_7/nighttime_visibility.cfm.
Fitzpatrick, K., Avelar, R., Pratt, M., Brewer, M. A., Robertson, J., Lindheimer, T., & Miles, J. (2016). *Evaluation of pedestrian hybrid beacons and rapid flashing beacons, No. FHWA-HRT-16-040.* Turner-Fairbank Highway Research Center.
Fitzpatrick, K., Brewer, M. A., & Avelar, R. (2014). Driver yielding at traffic control signals, pedestrian hybrid beacons, and rectangular rapid-flashing beacons in Texas. *Transportation Research Record: Journal of the Transportation Research Board, 2463*(1), 46–54. https://doi.org/10.3141/2463-06
Fitzpatrick, K., Cynecki, M. J., Pratt, M. P., Park, E. S., & Beckley, M. E. (2019). *Evaluation of pedestrian hybrid beacons on Arizona highways* (No. FHWA-AZ-19-756). Arizona. Department of Transportation.
Fitzpatrick, K., Geedipally, S., Kutela, B., & Koonce, P. (2023). Midblock pedestrian signal safety effectiveness. *Transportation Research Record: Journal of the Transportation Research Board, 2678*(4), 243–256. https://doi.org/10.1177/03611981231184196
Fitzpatrick, K., & Park, E. S. (2010). *Safety effectiveness of the HAWK pedestrian crossing treatment* (No. FHWA-HRT-10-042). United States. Federal Highway Administration. Office of Safety Research and Development.
Fitzpatrick, K., & Park, E. S. (2021). Nighttime effectiveness of the pedestrian hybrid beacon, rectangular rapid flashing beacon, and LED-embedded crossing sign. *Journal of Safety Research, 79*, 273–286. https://doi.org/10.1016/j.jsr.2021.09.009
Fitzpatrick, K., Park, E. S., Cynecki, M. J., Pratt, M. P., & Beckley, M. (2021). Investigation of crashes at pedestrian hybrid beacons: Results of a large-scale study in Arizona. *Journal of Safety Research, 78*, 59–68. https://doi.org/10.1016/j.jsr.2021.04.001
Fitzpatrick, K., Turner, S., Brewer, M., Carlson, P., Ullman, B., Trout, N., Park, E. S., Whitacre, J., Lalani, N., & Lord, D. (2006). *Improving pedestrian safety at unsignalized crossings.*. https://doi.org/10.17226/13962
Fleiter, J. J., Lennon, A., & Watson, B. (2010). How do other people influence your driving speed? Exploring the 'who' and the 'how' of social influences on speeding from a qualitative perspective. *Transportation Research Part F: Traffic Psychology and Behaviour, 13*(1), 49–62. https://doi.org/10.1016/j.trf.2009.10.002
Foster, S., Gmel, G., Estevez, N., Bahler, C., & Mohler-Kuo, M. (2015). Temporal patterns of alcohol consumption and alcohol-related road accidents in young swiss men: Seasonal, weekday and public holiday effects. *Alcohol and Alcoholism, 50*(5), 565–572. https://doi.org/10.1093/alcalc/agv037
Ghosh, S., Hernandez, S., & Al-Bdairi, N. S. S. (2024). Understanding the role of the COVID-19 pandemic on risky driving behavior and injury severity of drivers: Embracing heterogeneity in means and variances. *International Journal of Transportation Science and Technology*. DOi 10.1016/j.ijtst.2024.09.002.
Godavarthy, R. P., & Russell, E. R. (2016). Study of pedestrian hybrid beacon's effectiveness for motorists at midblock pedestrian crossings. *Journal of Traffic and Transportation Engineering (English Edition), 3*(6), 531–539. https://doi.org/10.1016/j.jtte.2016.01.007
Google. (n.d.). *Aerial view of the study location in Pima County, Arizona [Google Earth]*. Retrieved January from https://earth.google.com.
Haque, F., Kidwai, F. A., Haq, M. F., & u.. (2025). A systematic review of proactive approach for pedestrian safety at intersections. *Transportation Research Part F: Traffic Psychology and Behaviour, 109*, 792–808. https://doi.org/10.1016/j.trf.2025.01.013
Hassan, H. M., & Abdel-Aty, M. A. (2011). Analysis of drivers' behavior under reduced visibility conditions using a Structural Equation Modeling approach. *Transportation Research Part F: Traffic Psychology and Behaviour, 14*(6), 614–625. https://doi.org/10.1016/j.trf.2011.07.002
Hu, W., & Cicchino, J. B. (2018). An examination of the increases in pedestrian motor-vehicle crash fatalities during 2009-2016. *Journal of Safety Research, 67*, 37–44. https://doi.org/10.1016/j.jsr.2018.09.009
Hu, W., Houten, R. V., Cicchino, J. B., Engle, J., & Shomaly, L. A. (2024). *Effects of crosswalk illuminators and rectangular rapid flashing beacons on speed reductions and yielding to pedestrians at night.* https://www.iihs.org/api/datastoredocument/bibliography/2310#:~:text=Results%3A%20The%20study%20found%20that,as%20speed%20reductions%20became%20larger.
Iihs. (2024). *Red light running.* Retrieved January from: Insurance Institute for Highway Safety. https://www.iihs.org/topics/red-light-running.
Kong, X., Das, S., Zhang, Y., & Xiao, X. (2021). Lessons learned from pedestrian-driver communication and yielding patterns. *Transportation Research Part F: Traffic Psychology and Behaviour, 79*, 35–48. https://doi.org/10.1016/j.trf.2021.03.011
Krizsik, N., & Sipos, T. (2024). The effect of driver and pedestrian distraction factors on giving priority at designated pedestrian crossings. *Transportation Research Part F: Traffic Psychology and Behaviour, 104*, 109–117. https://doi.org/10.1016/j.trf.2024.05.013
Mahmood, K., Pang, J., Shahriar Ahmed, S., Yu, G., Sarwar, M. T., Benedyk, I., Anastasopoulos, Ch., & P.. (2024). Lessons learned from naturalistic driving data processing in a secure data enclave: Preliminary discoveries from analyzing dash camera videos. *Transportation Research Part F: Traffic Psychology and Behaviour, 106*, 135–149. https://doi.org/10.1016/j.trf.2024.08.012
Maxwell, A., Kennedy, J., Routledge, I., Knight, P., & Wood, K. (2011). Puffin pedestrian crossing accident study. *TRL published project reports, 2011*(PPR507), 1–62.
Mikoski, P., Zlupko, G., & Owens, D. A. (2019). Drivers' assessments of the risks of distraction, poor visibility at night, and safety-related behaviors of themselves and other drivers. *Transportation Research Part F: Traffic Psychology and Behaviour, 62*, 416–434. https://doi.org/10.1016/j.trf.2019.01.011
Miovision. (n.d.). *TrafficLink video detection*. Retrieved January from https://miovision.com/trafficlink/video-detection/.
Mohammadi, S., Arvin, R., Khattak, A. J., & Chakraborty, S. (2021). The role of drivers' social interactions in their driving behavior: Empirical evidence and implications for car-following and traffic flow. *Transportation Research Part F: Traffic Psychology and Behaviour, 80*, 203–217. https://doi.org/10.1016/j.trf.2021.04.002
Mutcd. (2023). *Manual on Uniform Traffic Control Devices* (11th Edition.).
Nhtsa. (2022). *NHTSA launches new campaign to remind drivers speeding wrecks lives*. Retrieved August 30 from https://www.nhtsa.gov/press-releases/nhtsa-launches-new-campaign-remind-drivers-speeding-wrecks-lives.
Nhtsa Pedestrian traffic safety facts 2023 2021 data.
Nsc. (2024). *Driving at night.* Retrieved January from: National Safety Council. https://www.nsc.org/road/safety-topics/driving-at-night.
Pulugurtha, S. S., Kukkapalli, V. M., & Mane, A. S. (2018). Pedestrian hybrid beacon signals: Identifying characteristics associated with negative consequences to reduce danger at mid-block locations. *Journal of Transport & Health, 10*, 225–235. https://doi.org/10.1016/j.jth.2018.05.015
Sanders, R. L., Schneider, R. J., & Proulx, F. R. (2022). Pedestrian fatalities in darkness: What do we know, and what can be done? *Transport Policy, 120*, 23–39. https://doi.org/10.1016/j.tranpol.2022.02.010
Schneider, R. J., Sanders, R., Proulx, F., & Moayyed, H. (2021). United States fatal pedestrian crash hot spot locations and characteristics. *Journal of Transport and Land Use, 14*(1), 1–23. https://doi.org/10.5198/jtlu.2021.1825
Su, Z., Woodman, R., Smyth, J., & Elliott, M. (2023). The relationship between aggressive driving and driver performance: A systematic review with meta-analysis. *Accident Analysis & Prevention, 183*, Article 106972. https://doi.org/10.1016/j.aap.2023.106972
F.D. Thomas A. Berning J. Darrah L.A. Graham R.D. Blomberg C. Griggs M. Crandall C. Schulman R. Kozar M. Neavyn K.W. Cunningham J. Ehsani J.C. Fell J. Whitehill K. Babu J.S. Lai M. Rayner Drug and alcohol prevalence in seriously and fatally injured road users before and during the COVID-19 public health emergency 2020 https://rosap.ntl.bts.gov/view/dot/50941.
Thomas, L., Sandt, L., Zegeer, C., Kumfer, W., Lang, K., Lan, B., Horowitz, Z., Butsick, A., Toole, J., & Schneider, R. J. (2018). *Systemic pedestrian safety analysis.*. https://doi.org/10.17226/25255
Trogolo, M. A., Ledesma, R., Medrano, L. A., & Dominguez-Lara, S. (2022). Peer pressure and risky driving: Development of a new scale. *Journal of Safety Research, 82*, 48–56. https://doi.org/10.1016/j.jsr.2022.04.005
Truelove, V., Watson-Brown, N., Parker, E., Freeman, J., & Davey, J. (2021). Driving through a pandemic: A study of speeding and phone use while driving during COVID-19 restrictions. *Traffic Injury Prevention, 22*(8), 605–610. https://doi.org/10.1080/15389588.2021.1980213
Ugan, J., Abdel-Aty, M., & Cai, Q. (2022). Estimating effectiveness of speed reduction measures for pedestrian crossing treatments using an empirically supported speed choice modeling framework. *Transportation Research Part F: Traffic Psychology and Behaviour, 89*, 276–288. https://doi.org/10.1016/j.trf.2022.07.002

Yao, Y., Carsten, O., Hibberd, D., & Li, P. (2019). Exploring the relationship between risk perception, speed limit credibility and speed limit compliance. *Transportation Research Part F: Traffic Psychology and Behaviour, 62*, 575–586. https://doi.org/10.1016/j.trf.2019.02.012

Zafri, N. M., Tabassum, T., Himal, M. R. H., Sultana, R., & Debnath, A. K. (2022). Effect of pedestrian characteristics and their road crossing behaviors on driver yielding behavior at controlled intersections. *Journal of Safety Research, 81*, 1–8. https://doi.org/10.1016/j.jsr.2022.01.001

Zegeer, C. V., & Bushell, M. (2012). Pedestrian crash trends and potential countermeasures from around the world. *Accident Analysis & Prevention, 44*(1), 3–11. https://doi.org/10.1016/j.aap.2010.12.007

Zhang, J., & Yu, K. F. (1998). *What's the Relative Risk? A method of correcting the odds ratio in cohort studies of common outcomes., JAMA(280(19))*, 1690–1691. https://doi.org/10.1001/jama.280.19.1690

Zhang, X., Haule, H., & Wu, Y.-J. (2025a). Investigating the impact of Pedestrian Hybrid Beacons on the effectiveness of adaptive traffic control systems. *Journal of Transportation Engineering, Part A: Systems*. DOi 10.1061/JTEPBS/TEENG-8661.

Zhang, X., Haule, H., & Wu, Y.-J. (2025). Leveraging probe data to assess left-turn driver behaviour under varying permissive signals. *Transportmetrica A: Transport Science, 1–24*. https://doi.org/10.1080/23249935.2025.2514664

Zhang, X., Ryan, A., & Wu, Y.-J. (2024). Influential factors of pedestrian and bicycle crashes near Pedestrian Hybrid Beacons: Observing trends through an applied analysis. *Journal of Transportation Safety & Security, 1–24*. https://doi.org/10.1080/19439962.2024.2325399