NEW JERSEY DEPARTMENT OF TRANSPORTATION
Rowan University
RUTGERS
Edward J. Bloustein School of Planning and Public Policy

New Jersey Bicycle & Pedestrian Resource Center: Emerging Countermeasures for Pedestrian Safety

Authors:

Dr. Mohammad Jalayer, Rowan University

Anahita Kakhani, Rowan University

Parisa Hosseini, Rowan University

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ABSTRACT

In 2021, more than 7,340 pedestrians were killed in the United States, a 13% increase over 2020's already historically high number (NHTSA, 2023). Therefore, there is a need to develop effective safety countermeasures to reduce the frequency and severity of pedestrian-involved crashes. Over the past decade, many transportation agencies across the nation have proposed and tested a variety of safety countermeasures, ranging from conventional strategies such as enhanced crosswalk lighting, signage, and markings, to more advanced strategies, which are mainly based on Intelligent Transportation Systems (ITS) technologies to reduce these types of crashes. ITS-based pedestrian safety systems show improvements in pedestrian safety and collision avoidance. However, there is a lack of comprehensive documentation bringing together various emerging pedestrian safety countermeasures in one place, which can serve as a reference for transportation agencies when selecting suitable solutions to achieve targeted outcomes for their existing problems. The main objective of this project is to provide a comprehensive overview of ITS-based technologies and various case studies that aim to provide transportation practitioners, engineers, and decision-makers with a good understanding of emerging countermeasures for pedestrian safety.

EXECUTIVE SUMMARY

According to the National Highway Traffic Safety Administration (NHTSA), a pedestrian is defined as "any person on foot, walking, running, jogging, hiking, sitting, or lying down who is involved in a motor vehicle traffic crash." Based on the data provided by the NHTSA, 6,516 pedestrians were killed and 54,769 were injured in traffic crashes in 2020, indicating about one pedestrian death every 81 minutes and one pedestrian injury every 10 minutes. In New Jersey alone, 173 pedestrians were killed in traffic crashes, accounting for 29.6% of all traffic fatalities in the state (NHTSA, 2022).

In recognition of the magnitude of this problem, improving pedestrian safety has become a primary concern of policymakers on the federal, state, and local levels, with an increased focus on supporting different projects and programs to enhance pedestrian safety. For instance, the Federal Highway Administration (FHWA) sponsored a project in multiple states, including California, Florida, and Nevada, to install 18 combined pedestrian safety engineering and intelligent transportation systems (ITS)-based countermeasures to improve pedestrian crossings (Pécheux et al., 2009). Recently, research has been conducted on developing new and optimizing existing ITS-based countermeasures to enhance road users' safety, including pedestrian safety (FHWA, 2021). However, to the best of our knowledge, there is a lack of comprehensive documentation bringing together various emerging pedestrian safety countermeasures to serve as a reference for transportation agencies. This project seeks to fill this gap by providing a comprehensive overview of ITS-based technologies and various case studies to help transportation practitioners, engineers, and decision-makers understand emerging countermeasures for pedestrian safety.

This project also provides a summary of each safety countermeasure's effectiveness and cost. Overall, 11 ITS-based countermeasures are discussed in detail, which fall into four main categories: signal-based countermeasures, sign-based countermeasures, in-pavement countermeasures, and pedestrian warning systems. Signal-based countermeasures included the Pedestrian Hybrid Beacon (PHB), Leading Pedestrian Interval (LPI), Pedestrian Countdown Signal (PCS), Responsive Push Buttons, and Puffin Crossings. Sign-based countermeasures include the Rectangual Repid Flashing Beacon (RRFB), Flashing LED Signs, Speed-Monitoring

Trailer, and Speed Display Signs. An In-Pavement Flashing Light System was the single in-pavement countermeasure to be investigated in this study, and pedestrian warning systems included Automatic Pedestrian Detection Devices and Smart Lighting.

Pedestrian safety was significantly enhanced by most of the studied countermeasures, as evidenced by a reduction in pedestrian-vehicle crashes (CMF Clearing house, 2023) and an increase in the number of yielding drivers. For example, signal-based countermeasures such as Pedestrian Countdown Signals (PCS), Pedestrian Hybrid Beacons (PHB), and Leading Pedestrian Intervals (LPI), significantly reduced pedestrian crashes. PHB and LPO are both FHWA Proven Safety Countermeasures. PCS had the most significant impact, with a 70% reduction (CMF Clearing house, 2023). The sign-based countermeasure Rectangular Rapid Flashing Beacon (RRFB), which is also an FHWA Proven Safety Countermeasure, decreased the frequency of pedestrian collisions by 47% (CMF Clearing house, 2023).

It should be noted that this project had limitations due to a relatively small number of studies evaluating the effectiveness of certain countermeasures, including Puffin crossings and LED flashing lights. To overcome this limitation, future studies can be conducted to evaluate the effectiveness of these and other existing ITS-based countermeasures, such as crosswalk illuminators and overhead lighting. In addition, before-and-after studies can be conducted on an inventory of New Jersey locations where pedestrian safety countermeasures have been implemented to identify the effectiveness of these measures in improving pedestrian safety.

CHAPTER ONE: Emerging Countermeasures for Pedestrian Safety

Background

Over the past several years, different emerging countermeasures for pedestrian safety have been proposed, implemented, and tested, by the public and private sectors including (1) signal-based countermeasures, (2) sign-based countermeasures, (3) in-pavement countermeasures, and (4) pedestrian warning systems. The following section provides more detailed information on these safety countermeasures and their effectiveness in mitigating pedestrian-involved crashes.

Signal-Based Countermeasures

Traffic signals are designed to provide gaps in traffic flow and enable pedestrians to safely cross at locations where they would otherwise experience excessive delay, difficulties crossing the street, or safety issues. The following section describes and explores the effectiveness of the introduced ITS signal-based countermeasures on pedestrian safety, including pedestrian hybrid beacon (PHB), leading pedestrian interval (LPI), responsive push buttons, pedestrian countdown signal (PCS), and puffin crossings.

Pedestrian Hybrid Beacon (PHB)

The Pedestrian Hybrid Beacon (PHB), also known as the High Intensity Activated Crosswalk (HAWK), was developed in the late 1990s in Tucson, Arizona, to provide a safer experience for pedestrians crossing major arterials at minor street intersections. In 2009, the PHB was included in the Manual on Uniform Traffic Control Devices (MUTCD) for the first time. According to MUTCD section 4F.01, a pedestrian hybrid beacon is a special type of hybrid beacon used to warn and control traffic at an unsignalized location to assist pedestrians in crossing a street or highway at a marked crosswalk (MUTCD, 2009). According to MUTCD section 4F.02, the PHB consists of two red lenses over a single yellow lens (MUTCD, 2009). Based on MUTCD section 4F.03, the lenses remain dark until a pedestrian activates the unit by pressing a push button. when the button is pressed, the yellow lens starts flashing, and after a set amount of time, the device displays solid yellow to warn the drivers that a pedestrian is going to cross. Then the red lenses show a steady red light for drivers and a symbol of a person walking for the pedestrians. The device then alternates flashing red lights and a flashing raised hand, supplemented with a countdown to pedestrians indicating the pedestrian Clearing interval. Upon termination of the pedestrian Clearing interval, the pedestrian signal heads shall revert to a steady UPRAISED HAND (symbolizing DONT WALK) signal indication. (MUTCD, 2009). Figure 1 demonstrates the sequence for a PHB system.

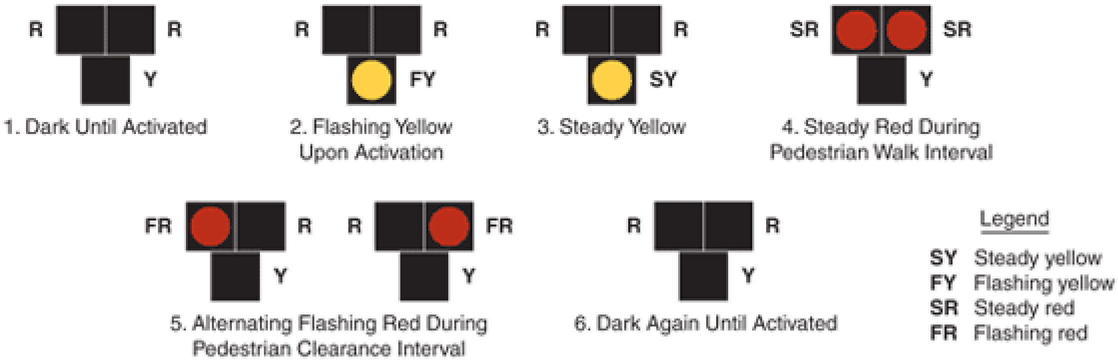

Figure 1. Sequence for a PHB (MUTCD, 2009)

In 2010, Fitzpatrick and Park conducted a before and after study to evaluate the effectiveness of PHBs on traffic safety at 21 PHB locations in Tucson, Arizona. Three years of crash data for both before and after the installation of the PHBs were collected at treated locations and nearby untreated locations. The results from the empirical Bayes method showed statistically significant reductions of 29% in total crashes, and 69% in pedestrian crashes. In 2021, they evaluated the effectiveness of the PHB, rectangular rapid flashing beacon (RRFB), and LED-embedded crossing warning sign (LED-Em), on drivers' yielding behavior during nighttime conditions. Video data were collected for 10 PHB sites, 12 RRFB sites, and 8 LED-Em sites. The collected data include the number of staged pedestrians and drivers during daytime and nighttime conditions. ANCOVA and logistic regression models were used to evaluate the effectiveness of each treatment. The results showed that the drivers' yielding rate was almost the same during daytime and nighttime at the PHB locations, while RRFBs and LED-Ems were found to be more effective on drivers' yielding rates in nighttime conditions. The findings also indicated that LED-Em should be used in locations with lower-speed operations, lower hourly volumes, or narrow lanes (Fitzpatrick and Park, 2010).

A study conducted by Pulugurtha and Self (2015) evaluated the effects of PHBs installed at three locations in Charlotte, North Carolina, on pedestrian and motorist behavior and analyzed their effectiveness on pedestrian safety. Vehicle speed data, as well as pedestrian and driver behavior data, were collected during different time periods, including before the installation and one, three, six, and twelve months after the installation during morning and evening peak hours, to assess the impact of time on pedestrian and motorist behavior. Results of the statistical analysis, including one-tail two-sample T-test and two-proportion Z-test, showed a statistically significant increase in drivers' yielding rate, a decrease in the number of trapped pedestrians, and a reduction in pedestrian-vehicle conflicts at one location. Moreover, it was concluded that the pedestrian and motorist behavior changes were more consistent three months after the installation of the pedestrian hybrid beacons, perhaps because it takes 2-3 months for them to adjust to new changes.

In 2019, another study evaluated the effectiveness of PHBs on pedestrian safety and driver yielding behavior on ten highways in Arizona. The study team selected 343 sites on roadways with higher-operating speed conditions (85th-percentile speed ranging between 44 and 54 mph) for further analysis, including 186 PHB sites along with 56 signalized intersections and 101 unsignalized intersections as comparison sites. The results of the empirical Bayes before and after study indicated that the number of pedestrians, severe, and severe rear-end crashes, reduced by 46%, 25%, and 29%, respectively. In addition, the average driver yielding was 97%, which was consistent with previous studies conducted on roadways with lower operating speeds (Fitzpatrick et al., 2019).

In 2014, the FHWA sponsored a project to analyze driver and pedestrian behavior at several locations with PHBs. More than 78 hours of video data were recorded at 20 locations in Austin, Texas, and Tucson, Arizona. The results indicated that the average driver yielding rate at the 20 locations was 96% after the installation. Only 6% of pedestrians (124 out of 1,979) crossed during the dark motorist signal indication, and in most cases, there were sufficient gaps for them to cross. The number of pedestrians who activated the push button was higher at locations with a speed limit of 45 mph, compared to those with a speed limit of 40 mph. Overall, 91% of pedestrians activated the push button, and none of the drivers stopped at a dark motorist signal indication–meaning they did not consider the dark PHB as a condition requiring a stop (Fitzpatrick and Pratt, 2016). Figures 2 and 3 are examples of installed PHBs.

Figure 2. A PHB installed at Maple Avenue, Plainfield, NJ (TAPINTO, 2019)

Figure 3. A PHB installed at Washington Street, Kokomo, IN (IUK, 2020)

Leading Pedestrian Interval (LPI)

An LPI gives pedestrians a head start by providing the WALK signal three to seven seconds before the green indication for adjacent vehicular movements. The head start allows pedestrians to establish their presence in the crosswalk, resulting in fewer conflicts between pedestrians and motorists (Fayish and Gross, 2010). In 2010, Fayish and Gross assessed the effectiveness of LPIs on pedestrian safety by conducting a before and after Empirical Bayesian study at 10 intersections with LPIs, and 14 stop-controlled intersections as the comparison group. Road characteristics, crash data, traffic volume, and pedestrian volume of the selected locations, were collected for further analysis. The study's results showed that the number of pedestrian-vehicle crashes was reduced by 58.7% at the treated sites, which was statistically significant at a 95% confidence level. The results of the economic analysis showed a benefit/cost ratio of 801. A benefit/cost ratio indicates the relationship between the relative costs and benefits of a proposed method. If the benefit/cost ratio is greater than 1, it is expected that the proposed method delivers a positive net present value (Investopedia, 2022). According to the results of the before and after study, the number of pedestrian-vehicle crashes was 14 with LPIs installed, whereas this number would have been 30.85 without LPIs.

In another study, Goughnour et al. (2018) evaluated the effectiveness of LPIs on pedestrian-vehicle crashes at 56 sites in Chicago, 42 sites in New York City, and seven sites in Charlotte. The researchers collected roadway data, vehicle volume, pedestrian volume, and crash data before and after the installation of the LPIs to conduct before and after Empirical Bayesian analysis. The results showed that the LPIs had a crash modification factor (CMF) of 0.87 in total crashes (13 percent reduction in total crashes), and a CMF of 0.81 in pedestrian-vehicle crashes (19 percent reduction in pedestrian-involved crashes) for all the cities combined. The researchers evaluated the economic benefit of the treatment, and the results showed a potential benefit/cost ratio range of 207/517.

In 2009, Pecheux et al. (2009) assessed the effectiveness of LPIs at two sites in Miami, Florida. Driver and pedestrian behavior were observed before and after the treatment installation. The results demonstrated a statistically significant increase in left-turning drivers yielding at the WALK phase from 40% to 58% at the first site and from 22% to 31% at the second site. Significant increases in pedestrian push button pressing (7% and 15%) were also observed at both locations. According to the results, a significant increase in the percentage of pedestrians crossing at the beginning of the WALK phase was observed at both locations (31% and 21%) because the leading pedestrian interval eliminates left-turning vehicles for the first few seconds of the WALK phase, reducing the number of pedestrians giving up the right of way to turning vehicles.

Figure 4. An intersection with LPI (ADOT, 2023)

Pedestrian Countdown Signal (PCS)

Pedestrian signals were first developed in the first half of the 20th century and had been changing since. In 2003, countdown timers were included in the MUTCD for the first time, and according to the most recent edition of the MUTCD, all signalized intersections where the pedestrian Clearing interval exceeds seven seconds shall use pedestrian countdown signals (Mead et al., 2014). These countermeasures are designed to start counting down at the beginning of the Clearing interval (flashing DON'T WALK).

In 2014, Huitema et al. Huitema et al. (2014) evaluated the effects of pedestrian countdown signals (PCSs) on pedestrian crashes throughout a large-scale study in Detroit, Michigan, by using a time-series intervention analysis to focus on the historical time-series crash data. Monthly pedestrian crash data from 2001 to 2010 were collected at 449 sites in Detroit. 362 of the selected sites received a PCS, and the remaining 87 sites were considered control sites. After analyzing the data, it was concluded that the number of pedestrian-vehicle monthly crashes reduced by 70% by the end of the 10-year study period at the treated sites, whereas little evidence of change was observed in the control units. In another study, Pulugurtha et al. (2010) conducted a before and after study to determine the effects of PCSs on pedestrian-vehicle crashes and vehicle-vehicle crashes. Three years of crash and traffic volume data were collected at 106 signalized intersections equipped with PCSs in Charlotte, North Carolina. The results indicated a 13% decrease in pedestrian-involved crashes and a 21% decrease in all crashes, including pedestrian-vehicle crashes and vehicle-vehicle crashes, following the installation of PCSs.

Vasudevan et al. (2011) evaluated the effectiveness of the PCS with animated eyes installed at an intersection in Las Vegas, Nevada. An animated eyes symbol may be added to pedestrian signal head to encourage pedestrians to look for vehicles before crossing an intersection (MUTCD, 2022). Researchers studied different pedestrian and driver measures of effectiveness (MOEs) by observing pedestrian and driver behavior before and after the treatment installation. The result of the two-proportion Z-test analysis indicated that the percentage of pedestrians who looked for vehicles before beginning to cross during the WALK phase increased by 7%, which was significant at a 95% confidence interval, indicating an overall improvement in pedestrian behavior.

Figure 5. An intersection with PCS (PEDSAFE, 2013)

Figure 6. A PCS installed in Long Beach, CA (Longbeach, 2022)

Responsive Push Buttons

In 2006, Van Houten et al. (2006) evaluated the effectiveness of pedestrian behavior of push buttons that provide visual and audible feedback after being pressed. The treatment was installed at two locations in Miami Beach, Florida. Pedestrian behavior data was collected before and after the installation. After analyzing the data using a two-proportion Z-test, it was concluded that the proportion of pedestrians pushing the button and the percentage of pedestrians waiting for the walk sign after pressing the button increased significantly to 58.1% and 86%, respectively. Moreover, a significant decrease in the percentage of trapped pedestrians was observed after the treatment installation. Therefore, it has been suggested that replacing old standard call buttons at the end of their life with newer push buttons that provide call confirmation can be a cost-effective method of increasing pedestrian safety at intersections, especially for visually-impaired pedestrians.

Pecheux et al. (2009) also assessed the effectiveness of pedestrian safety of call buttons that provide confirmation after being pressed. This countermeasure was deployed at two locations in Miami, Florida, and one location in Las Vegas, Nevada. Data was collected before and after the treatment installation to assess different measures of effectiveness. The results showed that the percentage of signal cycles in which the call button was pressed when pedestrians were present increased to 24.3% at the Miami sites. The percentage of pedestrians disregarding signals decreased to 17.8% at the Miami sites and 5% at the Las Vegas site. The number of pedestrians who begin to walk during the WALK phase increased significantly to 21.3% at the Miami locations. There was a minor decrease in the percentage of trapped pedestrians: 2.3% for the Miami locations and 1.6% for the Las Vegas location. Moreover, Vasudevan et al. (2011) evaluated the effectiveness of three signal-based countermeasures, one of which was pedestrian-activated call buttons that light up to confirm the activation of pedestrian safety system. The countermeasure was installed at an intersection in Las Vegas. Driver and pedestrian behavior were observed before and after the treatment installation. The results of the two-proportion Z-test showed that pedestrian-activated call buttons that light up to confirm activation reduced the number of trapped pedestrians by 11% and the number of pedestrians disregarding the signal significantly by 38%. Moreover, the percentage of signal cycles in which the call button was pushed in the presence of pedestrians increased by 53.7%.

Figure 7. A responsive push button in Newark, NJ (PEDSAFE, 2013)

Puffin Crossings

The PUFFIN crossing, short for "Pedestrian User-Friendly Intersection," is an updated version of the older Pelican crossing device and was first introduced in the United Kingdom in the 1990s. The Puffin crossing enables pedestrians to call a WALK phase and extends the signal when necessary (Maed et al., 2014). At a Puffin crossing, if a pedestrian is detected to be on the crossing area (through sensors mounted on the traffic light pole) after the initial "WALK" phase has elapsed, the "DON'T WALK" phase is delayed, allowing more time for the pedestrian to finish crossing the road. This feature is particularly beneficial for slower pedestrians, such as the elderly or disabled. A limited number of sources have evaluated the effectiveness of this countermeasure. In a 2010 study by Maxwell and Kennedy, 50 sites (40 mid-block crossings and 10 signalized intersections) were selected in the United Kingdom for further analysis. All of the selected sites had been converted from either Pelican or farside facilities to Puffin crossings in order to evaluate the impact of Puffin crossings on pedestrian safety. Crash data were collected three years before and after the treatment installation to compare crash frequencies at the treated sites. The results showed that pedestrian crashes and vehicle crashes were reduced significantly by 24% and 16%, respectively, following the treatment installation.

Figure 8. A Puffin crossing (Shale-Hester, 2020)

Sign-Based Countermeasures

Traffic signs provide essential information by letting people know what to expect, which may improve their reactions and behavior. For example, warning drivers regarding an upcoming pedestrian crossing in advance will give the drivers a chance to modify their speed and perform better reactions as they approach the crossing. Hence, it is crucial to develop and implement effective sign-based countermeasures to improve pedestrian safety. The following section will elaborate on several commonly-used ITS signed-based pedestrian safety countermeasures, including RRFB, flashing LED signs, and a speed-monitoring trailer.

Rectangular Rapid Flashing Beacon (RRFB)

Rectangular Rapid Flashing Beacons (RRFBs) are used to enhance pedestrian crossings at mid-blocks and unsignalized intersections by drawing drivers' attention to crossing signs. RRFBs can be activated by pedestrians or pedestrian detection systems. The RRFB was given interim approval by the FHWA in 2008; however, it has not been included in the MUTCD (Maed et al., 2014). In 2017, Zegeer et al. conducted a study to develop CMFs for four pedestrian safety countermeasures, including RRFBs, PHBs, pedestrian refuge islands (RIs), and advance yield or stop markings and signs (AS). The researchers collected traffic, roadway features, pedestrian crashes, and other crash type data from 499 treatment sites and 476 comparison sites in 14 cities in the U.S. In order to identify the impact of each treatment on crashes, the researchers developed cross-sectional regression models and before and after Empirical Bayesian analysis. The results of the study showed that all the countermeasures were effective in reducing pedestrian crashes. The CMFs for PHBs, RRFBs, RIs, and ASs were 0.45, 0.53, 0.68, and 0.75, respectively. The CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure (CMF Clearing house, 2022), indicating that all the studied countermeasures reduced pedestrian crashes.

In 2009, Shurbutt et al. conducted a comprehensive study of three experiments on the effects of RRFBs on driver yielding behavior at 18 uncontrolled pedestrian mid-block crossings in Saint Petersburg, Florida. In the first experiment, the effectiveness of two-beacon systems (two sets of RRFBs on both sides of the crosswalk) and four-beacon systems (four sets of RRFBs on the median island and both sides of the crosswalk) was measured and compared. The comparison showed that the average driver yielding rate increased from 18.5% (baseline) to 81.2% at two-beacon system sites and 88% at four-beacon system sites, indicating 63% more yielding over the baseline for the two-beacon treatment and 69.6% more for the four-beacon treatment. The second experiment compared the operation of a standard round, overhead yellow flashing beacon and a standard round, side-mounted yellow beacon with two-beacon and four-beacon RRFBs at two locations. The analysis results showed that the driver yielding rate increased by 4.6% at the traditional overhead beacon location, whereas two-beacon and four-beacon RRFB systems increased the yielding rates by 70.6% and 77.8%, respectively. The driver yielding rate increased by 11.48% at the side-mounted beacon location, while the two-beacon RRFB system increased the yielding rate by 63.4%. The third experiment evaluated the effect of RRFBs on the yielding rate over time. Data was collected seven days, 30 days, 60 days, and a year after the installation. The researchers concluded that the average yielding rate at the 18 locations was 2% before the treatment, 86% 60 days after the treatment installation, and approximately 80% a year after the treatment installation.

Another study by Van Houten et al. (2008) evaluated the effect of RRFBs (referred to as "stutter-flash LED beacons") on driver behavior. Driver yielding rate, vehicle-pedestrian conflicts, trapped pedestrians, and motorist yielding distance, were recorded before and after the installation of RRFBs at two multilane crosswalks in Miami-Dade County, Florida. The results of the ANOVA analysis showed that the driver yielding rate increased from 0% and 1% to 65% and 92% at the two locations. Moreover, there was a reduction in vehicle-pedestrian conflicts, the number of trapped pedestrians, and motorist yielding distance after the installation of the RRFBs, resulting in improved pedestrian safety at the multilane crosswalks. Later on, Hunter et al. (2012) conducted a before and after study to evaluate the effect of an RRFB on pedestrian and bicyclist safety at a street crossing of Florida's Pinellas Trail. A video camera was installed beside the trail and several hundred feet from the trail crossing. The results of the Chi-square tests indicated that the average trail user's delay before starting to cross decreased from 10.1 seconds to 5.2 seconds after installation. In addition, pedestrian and bicyclist yielding rates to drivers reduced significantly from 19% to 9%, and 78% to 56%, following treatment installation. In addition, driver yielding increased significantly from 2% to 35%, and the number of trapped trail users decreased from 18% to 6% after the treatment was installed.

In 2012, Brewer and Fitzpatrick developed a before and after study at a school zone crosswalk in the city of Garland, Texas, to investigate the effects of RRFBs on driver compliance during school zone and non-school zone conditions. For the non-school zone condition, a staged pedestrian protocol was used to collect driver yielding behavior. Data was collected both manually and by video recording. The analysis of the before and after data showed that driver compliance increased significantly from less than 1% to approximately 80% in the non-school zone condition. However, there were no changes in driver yielding rates in the school zone condition. Fitzpatrick et al. (2014) investigated the impacts of the traffic control signal (TCS), PHB, and RRFB on drivers yielding to pedestrians in Texas. In this study, one of the researchers acted as a staged pedestrian based on Texas protocols, and another research member recorded drivers yielding behavior. Seven TCS sites, 22 RRFB sites, and 32 PHB sites were observed in this study. The researchers also developed a logistic regression model to predict whether a particular driver would stop or not. The results showed that the highest rate of drivers yielding belonged to TCS sites, with an average of 98%. RRFBs and PHBs led to 86% and 89% yielding rates, respectively. The findings were compared with national findings, indicating that the yielding rate for TCSs was similar to national findings. However, the rate for RRFBs was higher in Texas, and the researchers assumed the reason might be due to the closeness of this treatment to "School Crossing" signs in Texas. Finally, the yielding rate for PHBs was lower in Texas than in Tucson. It was also concluded that as the drivers become more familiar with the treatments over time, yielding rates increase.

Figure 9. A Rectangular Rapid Flashing Beacon (RRFB) (Carmanah, 2022)

Flashing LED Signs

A 2014 report by Ellis and Tremblay provided the results of a project carried out by the Vermont Agency of Transportation (VTrans) in 2008 in which they intended to mitigate pedestrian and motorist conflicts by installing BlinkerSigns® produced by Tapco. Driver yielding rates were collected two months before the installation and one year and four years after the installation. The result of the analysis showed that the yielding rate increased from 56% to 80% one year after the installation, then decreased to 64% four years after the installation, meaning that the yielding rate increased by 8% four years following the installation.

Figure 10. Flashing LED sign (TAPCO, 2022)

Speed-Monitoring Trailer

Speed-monitoring trailers are placed on the side of the road, displaying the speed of an approaching vehicle to enhance enforcement efforts directed at speed compliance. They are best used in residential areas (PEDBIKESAFE, 2022).

In the report provided by Pecheux et al. (2009), different measures of the effectiveness of portable radar speed trailers were evaluated. The treatment was installed at a mid-block location in both Miami and Las Vegas and four mid-block locations in San Francisco. The evaluated MOEs in this study were: vehicle speed, percentage of drivers yielding to pedestrians, percentage of cycles where a pedestrian was trapped in the roadway, percentage of pedestrian-vehicle conflicts, and pedestrian delay, which refers to the time that a pedestrian starts to cross, but has to wait for a traffic gap to start crossing. The results of the analysis showed an up to 21.7% increase in driver yielding rate at the San Francisco site and a 23% decrease at the Las Vegas site. Pedestrian delay decreased up to 4.1 % in San Francisco sites.

Dangeti et al. (2010) assessed the effectiveness of different ITS-based countermeasures implemented in Las Vegas, Nevada, including portable speed trailers on pedestrian safety. Field observations were collected before and three weeks after the installation of the treatment at two locations in Las Vegas. The following MOEs were then collected: drivers yielding to pedestrians, the pedestrian delay, the time that a pedestrian is trapped in the street after they start crossing, and vehicle speed. The results did not show a significant increase in driver yielding rate, or a decrease in pedestrian delay after the installation. Overall, the portable speed trailer decreased vehicle speeds and increased driver yielding rates, indicating that the countermeasure is effective in increasing pedestrian safety; however, the effect disappeared when the speed-monitoring trailer was removed.

Figure 11. A speed-monitoring trailer (PEDSAFE, 2013)

Speed Display Signs

Reducing vehicle speeds has been identified as one of the contributing factors to improving traffic safety for different types of areas and road users (Adminaité-Fodor and Jost, 2019). Speed display signs are one of the countermeasures that can be used to reduce vehicle speeds. These are interactive signs which display the speed of approaching vehicles.

Flynn et al. (2020) conducted a meta-analysis, reviewing 43 publications to assess the effectiveness of speed display signs on speed reduction in different contexts, such as school and work zones, and for different vehicle types. The results of the meta-analysis showed that overall, the speed display signs caused a 4 mph reduction in passenger car speed and a 2-4 mph reduction in speed for different vehicle types in different contexts. Also, it was concluded that a speed reduction of 4 mph for vehicles traveling 30-35 mph decreased fatal pedestrian strike probability by 40% (Flynn, et al., 2020). It was also noted that this countermeasure was practically significant in school and work zones.

In 2020, Malin and Luoma conducted a before and after study with control sites to determine the effects of speed display signs on vehicle speed reduction at pedestrian crossings on low-speed (40 km/h or 24.85 mph) urban streets. The researchers selected two busy and two quiet sites to install the countermeasure and one busy and one quiet site to assess as control sites. Driver speed data were collected one week before installation, as well as one week, one month, three months, and five months after installation, and one week after removal. The results of the ANOVA test showed that the mean speed decreased by 0.5-2.9 km/h (0.31-1.8 mph), which would cause a 4-22% reduction in pedestrian fatality probability (Malin and Luoma, 2020). Moreover, it was concluded that the driving speeds stayed lower over time, indicating the long-term effect of the countermeasure. Furthermore, the countermeasure had a higher effect on speed reduction in quiet sites.

In another study by Karimpour et al. (2021), the authors evaluated the effectiveness of three speed management countermeasures, including speed display signs (referred to as speed feedback signs) on driver speed and compliance. Nine locations were selected in Pima County, Arizona, to collect speed data prior to treatment zones, at the treatment zones, and downstream of the treatment zones. The results of the T-test showed that all the countermeasures were effective in decreasing drivers' mean speed and the proportion of drivers exceeding the speed limit. The researchers suggested that adding periodic law enforcement to speed display signs increases its effectiveness.

Figure 12. A speed display sign (Karimpour et al., 2021)

Other Countermeasures

Several sign-based countermeasures have been installed in various locations to enhance pedestrian safety, including crosswalk illuminators (Figure 13), overhead lighting (Figure 14), and flashing LED “state law - stop for pedestrians within crosswalk” signs (Figure 15). The crosswalk illuminator consists of a floodlight that illuminates the approach area of the crosswalk and a beam light projecting outward, illuminating the middle of the crosswalk (TAPCO, 2022). Overhead lighting increases visibility at mid-block crossings with a directional, compliant, and efficient LED light (Carmanah, 2022). Flashing LED "state law stop for pedestrian" crosswalk signs consist of a system that employs a set of synchronized high-intensity LEDs that extend the range of visibility of the sign during the day or night in all weather conditions (Solar Traffic Systems, 2022). However, there are no available studies that evaluate the effectiveness of these countermeasures on pedestrian safety improvement.

Figure 13. A crosswalk illuminator (TAPCO, 2022)

Figure 14. An overhead lighting (Carmanah, 2022)

Figure 15. A Flashing LED "state law - stop for pedestrians within crosswalk" sign (Solar Traffic Systems, 2022)

In-Pavement Countermeasures

In-pavement countermeasures, including in-pavement flashing light systems, are used at uncontrolled locations to draw drivers' attention to the crossing. These countermeasures include, but are not limited to, lights embedded in the pavement at both sides of a crosswalk that can be activated either by a pedestrian push button or a pedestrian detection system and are proven to help enhance driver compliance with pedestrians (Maed et al., 2014). This category of countermeasures may be expanded with new innovations in intelligent transportation systems.

In-Pavement Flashing Light System

Patella et al. (2020) assessed the effects of LED-illuminated crosswalks on driver behavior and pedestrian safety during nighttime. Vehicle speeds were captured using a TRUSPEED telelaser in two cases. The two cases included the presence and absence of pedestrians for both LED switched-on and LED switched-off conditions at a crosswalk in Rome, Italy. For each case, 100 observations were carried out for the illuminated and non-illuminated conditions. The analysis results for the first case (presence of pedestrians) showed that for the LED-off condition, the vehicle mean speed did not change significantly from 65 m (213.25 ft.) before the crosswalk to the crosswalk, but there was a minor decrease of 4.3%. However, for the LED-on condition, the mean vehicle speed decreased from 50.2 km/h (31.19 mph) at 65 m before the crossing to 39.9 km/h (24.79 mph) at the crosswalk, indicating a 20.6% reduction. For the second case at the same location (absence of pedestrians), the analysis showed that in the non-illuminated condition, the mean speed of vehicles 65 m before the crossing was 50.7 km/h (31.50 mph), which decreased to 40.2 km/h (24.98 mph) at the crossing, resulting in a 20.7% reduction. During the LED-on condition, the speed was 49.4 km/h (30.69 mph), 65 m before the crossing and 32.4 km/h (20.13 mph) at the crossing, showing a 34.4% reduction in mean speed.

Karkee et al. (2010) conducted a before and after study on a relatively low-volume roadway to evaluate the MOEs of in-pavement flashing light systems. The investigated MOEs include motorist yielding behavior, vehicle speeds, and yielding distance from the crosswalk. Data was collected two weeks before and one month after the treatment installation during morning and evening peak hours. The results showed up to a 3% increase in motorist yielding rate, which was significant at the 95% confidence level. Moreover, vehicle speeds decreased significantly by 4.7 mph when pedestrians were waiting to cross. The yielding distance increased by about 2.7 m (9 ft.) in the eastbound direction. However, the yielding distance in the westbound direction was reduced by about 6.1 m (20 ft.).

Van Derlofske et al. (2003) provided the report of a study conducted at an uncontrolled intersection in Denville, New Jersey, selected by the Department of Transportation to improve pedestrian safety at the location. The study consisted of a sequence of before and after studies comparing the effectiveness of striped crossings with high visibility markings and an in-pavement flashing and warning lights system. The results of the study showed that high visibility markings increased the visibility of the crosswalk, and decreased the conflicts between pedestrians and drivers. Moreover, adding an in-pavement flashing warning light system decreased the mean speed of vehicles approaching the crosswalk, and the mean number of drivers failing to yield to waiting pedestrians.

Figure 16. An in-pavement flashing light system (TAPCO, 2022)

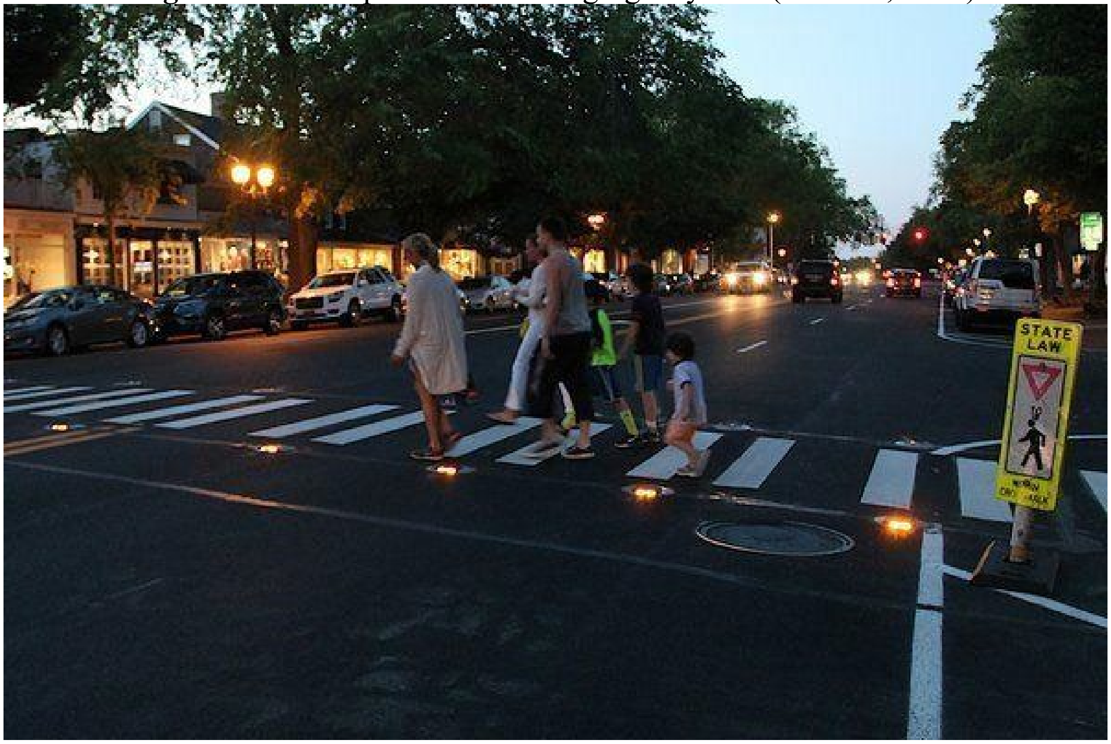

Figure 17. An in-pavement flashing light system (Light Guard System, 2019)

Pedestrian Warning Systems

Pedestrian warning systems, including automatic pedestrian detection devices, utilize ultrasonic or microwave radar to detect pedestrians. These devices are installed at crosswalks to reduce pedestrian-vehicle conflicts by warning the drivers regarding the presence of pedestrians, extending pedestrian intervals at signalized intersections, and increasing crosswalk illumination with the help of smart lighting (Nambisan et al., 2009).

Automatic Pedestrian Detection Devices and Smart Lighting

Nambisan et al. (2009) provided the results of a study in which they evaluated the effectiveness of an automated pedestrian detection device and a smart lighting system on pedestrian safety at a mid-block crossing in Las Vegas, Nevada. The researchers collected field observation data before and three weeks after the installation to assess the impacts of the countermeasures on pedestrian and motorist behavior. The results of the analysis showed that the percentage of diverted pedestrians–pedestrians who would walk some additional distance to use the mid-block crossing with installed safety countermeasures –increased by 17% after the installation. In addition, a 15% decrease in the percentage of trapped pedestrians was observed. Moreover, the driver yielding rate increased from 22% to 35%. Overall, the researchers concluded that installing these devices helped increase pedestrian safety.

Dangeti et al. (2010) evaluated the effectiveness of the ITS-based countermeasures installed in Las Vegas, Nevada, as a pedestrian safety improvement project sponsored by FHWA. The evaluated countermeasures include "No Turn on Red" signs, pedestrian detection devices and smart lighting, and portable speed trailers. Researchers evaluated the effectiveness of the pedestrian detection devices at mid-block crossings by measuring the number of pedestrians who looked for vehicles before and while crossing the street, driver yielding rate, driver yielding distance, pedestrian delay, and vehicle speed before and after the installation of the countermeasure. Data was collected during the morning and evening peak hours of weekdays before and three weeks after the installation. The results from the statistical tests and field observations showed a significant increase in the proportion of diverted pedestrians (16.7%) and a significant decrease in the proportion of trapped pedestrians (15.2%). Moreover, the proportion of drivers yielding to pedestrians at 10 to 20 ft from the crosswalk increased by 28%.

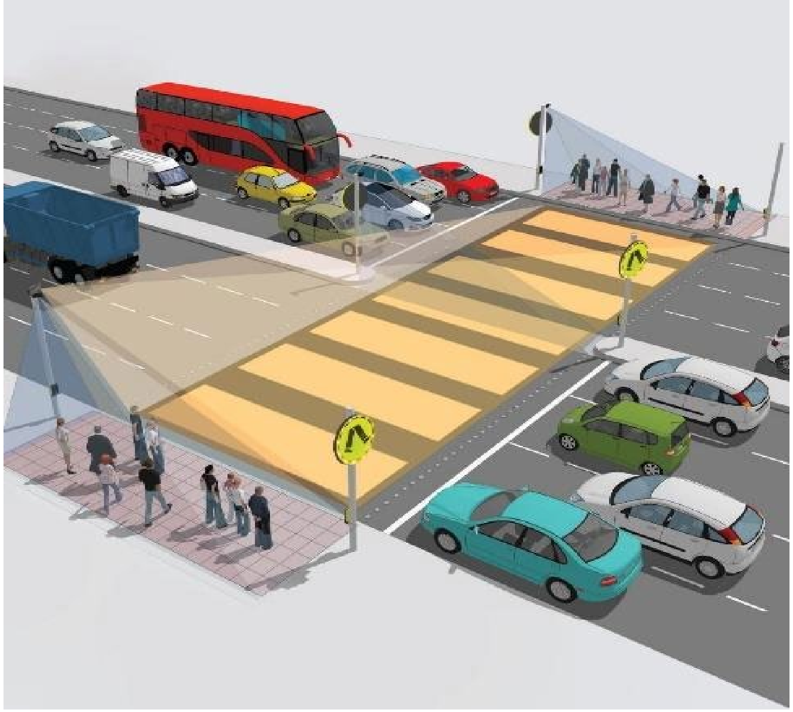

Figure 18. Pedestrian detection system scheme (HI-VIS, 2022)

Table 1 summarizes the description, the level of effectiveness, and the cost of installing the discussed ITS-based pedestrian safety countermeasures.

Table 1. List of ITS-based pedestrian safety countermeasures

Category	ITS-based Countermeasure	Description	Estimated Installation Cost (PEDBIKE, 2013)	CMF (CMF Clearing house, 2022)	FHWA proven safety countermeasures (FHWA, 2022)	Installation location/ Urban- Rural (Cited in this research)	Site Characteristics	Effectiveness/ Results	Reference
Signal-based countermeasures	Pedestrian Hybrid Beacon	• Consists of two horizontally-arranged red lenses above a single yellow lens • Dark until activated • Flashing and steady yellow upon activation • Steady red during pedestrian crossing • Alternating flashing red • Dark again	$21,000-$128,000	0.31	Yes	Tucson, AZ Urban	• Intersection • Number of lanes: 4,6 • Speed limit: 30, 35, 40 mph	• 69 % reduction in pedestrian crashes • 29 % reduction in total crashes • 15 % reduction in severe crashes	(Fitzpatrick and Park, 2010)
						Arizona, Urban, rural	• Intersection and mid-block • Number of lanes: 2,4,5 • Speed limit: 45,50 mph	• 25% reduction in severe crashes • 46% reduction in pedestrian crashes • 29% reduction in severe rear-end crashes • 97% average driver yielding at the 10 highways	(Fitzpatrick et al., 2019)
						Austin, TX and Tucson, AZ Urban	• Intersection and mid-block • Number of lanes: 4,6 • Speed limit: 35,40, 45 mph	• Average driver yielding rate of 96% at the 20 locations • Only 6% of the pedestrians left during the dark indication • 91% of the pedestrians activated the pushbutton	(Fitzpatrick and Pratt, 2016)
						Charlotte, NC Urban	• Mid-block	• Increased driver yielding rate • Decreased the number of trapped pedestrians • Decreased pedestrian-vehicle conflicts	(Pulugurtha and Self, 2015)
						Austin, TX Urban	• Intersection and mid-block • Number of lanes: 2,4,5 • Speed limit: 30,35,40,45 mph	• Almost the same driver yielding rate during daytime and nighttime at PHB locations	(Fitzpatrick and Park, 2021)

Category	ITS-based Countermeasure	Description	Estimated Installation Cost (PEDBIKE, 2013)	CMF (CMF Clearing house, 2022)	FHWA proven safety countermeasures (FHWA, 2022)	Installation location/ Urban- Rural (Cited in this research)	Site Characteristics	Effectiveness/ Results	Reference
	Leading Pedestrian Interval	• Allows pedestrians to enter a crosswalk in an intersection 3-7 seconds before the vehicle's green signal • Helps pedestrians establish their presence before vehicles have priority to turn right or left	$0-$3,500	0.41	Yes	State College, PA Urban	• Intersection • Number of lanes: 2 • Speed limit: 25 mph	• Reduced pedestrian-vehicle crashes by 58.7%	(Fayish and Gross, 2010)
						Chicago, IL NYC, NY Charlotte, NC Urban	• Intersection • Number of lanes: 3,4	• Caused a CMF of 0.87 in total crashes • Caused a CMF of 0.81 in pedestrian-vehicle crashes	(Goughnour et al., 2018)
						Miami, FL Urban	• Intersection • Number of lanes: 4 • Speed limit: 35 mph	• Increased left-turning drivers yielding at the walk phase • Increased pedestrian push button pressing • Increased the percentage of pedestrians crossing at the beginning of the WALK phase	(Pécheux et al., 2009)
	Rectangular Rapid Flishing Beacon	• Enhances pedestrians crossing at mid-blocks and unsignalized intersections by drawing attention to crossing signs	$4,500-$52,000	0.53	Yes	14 cities in the U.S. Urban	• Intersection • Number of lanes: 4 or more	• RRFBs caused a CMF of 0.53	(Zegeer et al., 2017)
						Miami–Dade, FL Urban	• Intersection • Number of lanes: 2 • Speed limit: 35,40 mph	• Driver yielding rate increased up to 92% • Vehicle-pedestrian conflicts, the number of trapped pedestrians, and motorist yielding distance decreased	(Van Houten et al., 2008)
						St. Petersburg, FL Urban	• Intersection • Number of lanes:2,3,4 • Speed limit: 35,40 mph	• The average driver yielding rate increased up to 88%	(Shurbutt et al., 2009)
						Pinellas, FL Urban	• Street crossing	• The average trail user's delay before starting to cross decreased from 10.1 s to 5.2 s	(Hunter et al., 2012)

Category	ITS-based Countermeasure	Description	Estimated Installation Cost (PEDBIKE, 2013)	CMF (CMF Clearing house, 2022)	FHWA proven safety countermeasures (FHWA, 2022)	Installation location/ Urban- Rural (Cited in this research)	Site Characteristics	Effectiveness/ Results	Reference
								• Pedestrian and bicyclist yielding rate reduced • Driver yielding increased significantly from 2% to 35% • The number of trapped trail users decreased from 18% to 6%	
						Garland, TX Urban	• Intersection • Number of lanes: 4 • Speed limit: 35 mph	• Driver compliance increased from less than 1% to approximately 80% in non-school zone • No change in driver yielding rate during the school zone period	(Brewer et al., 2012)
						Texas Urban	• Intersection and mid-block • Number of lanes: 4,5,6 • Speed limit: 30,35,45	• 86% driver yielding rates • The yielding rate at RRFB sites in Texas was higher than the nationwide rate	(Fitzpatrick et al., 2014)
	Pedestrian Countdown Signal	• Designed to begin counting down at the beginning of the Clearing (flashing DON'T WALK) • Can be on fixed-time or push button operation	$190 -$1930	0.3	No	Detroit, MICH Urban	• Intersection	• 70% reduction in pedestrian-vehicle crashes from the baseline to the end of the 10-year study period	(Huitema et al., 2014)
						Charlotte, NC Urban	• Intersection • Speed limit: 35 and 40 mph	• A 13% decrease in the number of pedestrian-vehicle crashes • A 21% decrease in the number of all crashes including pedestrian-vehicle crashes and vehicle-vehicle crashes	(Pulugurtha et al. 2010)

Category	ITS-based Countermeasure	Description	Estimated Installation Cost (PEDBIKE, 2013)	CMF (CMF Clearing house, 2022)	FHWA proven safety countermeasures (FHWA, 2022)	Installation location/ Urban- Rural (Cited in this research)	Site Characteristics	Effectiveness/ Results	Reference
						Las Vegas, NV Urban	• Intersection • Speed limit: 35 and 45 mph	• Increased the percentage of pedestrians who looked for vehicles before beginning to cross and beginning to cross during the WALK phase	(Vasudevan et al., 2011)
	Puffin crossing	• Enables pedestrians to call a WALK phase and extends the signal when necessary	\$80,000-\$150,000	0.76	No	The United Kingdom Urban	• Intersection and mid-block	• 24% reduction in pedestrian crashes • 16% reduction in vehicle crashes	(Maxwell and Kennedy, 2010)
	Responsive Push Buttons	• Gives audible and visible response when pressed	\$800-\$1200	N/A	No	Miami Beach, FL Urban	• Intersection	• Increased the proportion of pedestrians pushing the button and the percentage of pedestrians who waited for the walk sign after pressing the button • Decreased the proportion of trapped pedestrians	(Van Houten et al., 2006)
						Miami, FL Las Vegas, NV Urban	• Intersection • Speed limit: 25 mph	• Increased the percentage of signal cycles in which the call button was pressed when pedestrians were present • Decreased the percentage of pedestrians disregarding signal • Increased the number of pedestrians who begin to walk during the WALK phase • Decreased the percentage of	(Pécheux et al., 2009)

Category	**ITS-based Countermeasure**	**Description**	**Estimated Installation Cost (PEDBIKE, 2013)**	**CMF (CMF Clearing house, 2022)**	**FHWA proven safety countermeasures (FHWA, 2022)**	**Installation location/ Urban- Rural (Cited in this research)**	**Site Characteristics**	**Effectiveness/ Results**	**Reference**
								trapped pedestrians	
						Las Vegas, NV Urban	• Intersection • Speed limit: 25 mph	• Reduced the number of trapped pedestrians • Reduced the number of pedestrians disregarding the signal	(Vasudevan et al., 2011)
Sign-based countermeasures	Flashing LED signs	• A traffic control device used at pedestrian crossings	$1,000-$1,825	N/A	No	Hartford, VT Urban	• Number of lanes: 4 • Speed limit: 35 mph	• Yielding compliance increased from 56% to 80% one year after the installation • 20% increase in the number of motorists who reduced their speed as they approached the crosswalk	(Ellis and Tremblay, 2014)
	Speed-Monitoring Trailer	• Displays the speed of an approaching vehicle to enhance enforcement efforts directed at speed compliance	$7,000-$18,000	N/A	No	Miami, FL Las Vegas, Nevada San Francisco, CA Urban	• Mid-block • Speed limit: 25, 30, 45 mph	• Increased driver yielding rate • Decreased pedestrian delay	(Pécheux et al., 2009)
						Las Vegas, NV Urban	N/A	• Decreased the vehicle speeds • Increased driver yielding rate	(Pulugurtha et al. 2010)
	Speed Display Sign	• Displays the speed of an approaching vehicle to enhance enforcement efforts directed at speed compliance	$2,000-$3900	N/A	No	N/A	N/A	• Decreased passenger car speed by 4 mph • Decreased different types of vehicle speed by 2-4 mph • Practically significant at school and work zones	(Flynn et al., 2020)

Category	ITS-based Countermeasure	Description	Estimated Installation Cost (PEDBIKE, 2013)	CMF (CMF Clearing house, 2022)	FHWA proven safety countermeasures (FHWA, 2022)	Installation location/ Urban- Rural (Cited in this research)	Site Characteristics	Effectiveness/ Results	Reference
						Lahti and Tampere, Finland Urban	• Mid-block • Speed limit: 40 km/h • Number of lanes: 2	• Decreased vehicle speed by 0.5-2.9 km/h • Decreased pedestrian fatality risk by 22% • Effective over time • More effective at quiet sites	(Malin and Luoma, 2020)
						Pima County, AZ Urban	• Speed limit: 40,45,50 mph	• Decreased vehicle speed • Decreased the proportion of drivers exceeding speed limit	(Karimpour et al., 2021)
Pedestrian Warning System	Automatic Pedestrian Detection Device and Smart Lighting	• Uses ultrasonic or microwave radar to detect pedestrians • Increases crosswalk illumination with the help of smart light	$10,000-$70,000	N/A	No	Las Vegas, NV Urban	• Mid-block • Number of lanes: 4 • Speed limit: 35 mph	• 17% increase in the percentage of diverted pedestrians • 15% reduction in the percentage of the trapped pedestrian • 13% increase in driver yielding rate	(Nambisan et al., 2009)
						Las Vegas, NV Urban	• Mid-block • Number of lanes: 4 • Speed limit: 35 mph	• 16.7% increase in the percentage of diverted pedestrians • 15.2% reduction in the percentage of the trapped pedestrians • 28% increase in the percentage of drivers yielding to pedestrians within 10-20 ft of the crosswalk	(Dangeti et al., 2010)
In-pavement Countermeasures	In-Pavement Flashing Light System	• Consists of lights embedded in the	$12,000-$20,000	N/A	No	Denville, NJ Urban	• Intersection	• Increased the visibility of the crosswalk	(Van Derlofske et al., 2003)

Category	ITS-based Countermeasure	Description	Estimated Installation Cost (PEDBIKE, 2013)	CMF (CMF Clearing house, 2022)	FHWA proven safety countermeasures (FHWA, 2022)	Installation location/ Urban- Rural (Cited in this research)	Site Characteristics	Effectiveness/ Results	Reference
		pavement at both sides of the crosswalk						• Decreased the mean speed of vehicles approaching the crosswalk • Decreased the mean number of drivers failing to yield to waiting pedestrians	
						Las Vegas, NV Urban	• Intersection • Number of lanes: 2 • Speed limit: 35 mph	• Increased motorist yielding rate • Vehicle speeds decreased when pedestrians were waiting to cross and when they were crossing	(Karkee et al., 2010)
						Rome, Italy Urban	• Street crosswalk • Speed limit: 50 km/h	• Decreased mean vehicle speed	(Patella et al., 2020)

CHAPTER TWO: Conclusions and Recommendations

In response to the growing number of pedestrian crashes in recent years, transportation agencies have proposed and implemented various engineering, education, and enforcement countermeasures. Engineering countermeasures include, but are not limited to, lane narrowing and lane reduction (road diet)–which improve roadway design, lighting and illumination, crossing islands, and curb extensions–which are implemented at crossing locations. In addition to these, many agencies have implemented ITS-based safety countermeasures to enhance pedestrian safety. However, there is a lack of comprehensive documentation that gathers information regarding different aspects of ITS-based countermeasures, such as their effectiveness and cost of installation. This project reviewed the effectiveness of several ITS-based countermeasures deployed by transportation agencies to improve pedestrian safety and divided them into four major categories based on their application: signal-based countermeasures, sign-based countermeasures, in-pavement countermeasures, and pedestrian warning systems.

The majority of the evaluated countermeasures showed noticeable improvement in pedestrian safety in terms of pedestrian-vehicle crash reduction and an increase in drivers' yielding rate. Among the discussed countermeasures, PCS has the greatest effect on reducing the frequency of pedestrian crashes, followed by PHBs (FHWA proven) and LPIs (FHWA proven), which are all signal-based countermeasures. On the other hand, RRFBs, a sign-based countermeasure that is an FHWA proven safety countermeasure, reduced pedestrian crash frequency by 47%, according to the results of Zegeer et al. (2017). In terms of improving driver yielding rate, PHBs, RRFBs, and flashing LED signs resulted in the highest percentages of driving yielding rates, 97%, 92%, and 80%, respectively, according to the results of the reviewed studies.

Some of the evaluated countermeasures improved pedestrian and driver behaviour. For instance, installing LPIs, PCSs, and responsive push buttons resulted in an increase in the percentage of pedestrians who waited for the beginning of the walk phase before starting to cross crosswalks. In addition, speed monitoring trailers, speed display signs, and in-pavement flashing light systems reduced driver speed approaching crosswalks. Several of the reviewed safety countermeasures–including PHBs, RRFBs, responsive push buttons, automatic pedestrian detection devices, and smart lighting–resulted in a reduced percentage of trapped pedestrians. Due to the widespread development of transportation technologies, it is expected that ITS-based pedestrian safety countermeasures will have a significant impact on reducing and mitigating pedestrian crashes.

In the reviewed studies, each countermeasure was installed at locations with different characteristics regarding the type of crossing (intersection vs. mid-block), speed limit, number of lanes, traffic volume, and pedestrian volume. Therefore, it is recommended that transportation agencies refer to previous experiments and their results to select the most suitable countermeasure for the particular problem they are seeking to solve. Figure 19 provides information regarding the locations where different types of countermeasures were implemented according to previous studies. In this diagram, locations are categorized as either intersection and mid-block, and each is divided into two categories based on their speed limit (less than 40 mph and equal to or more than 40 mph).

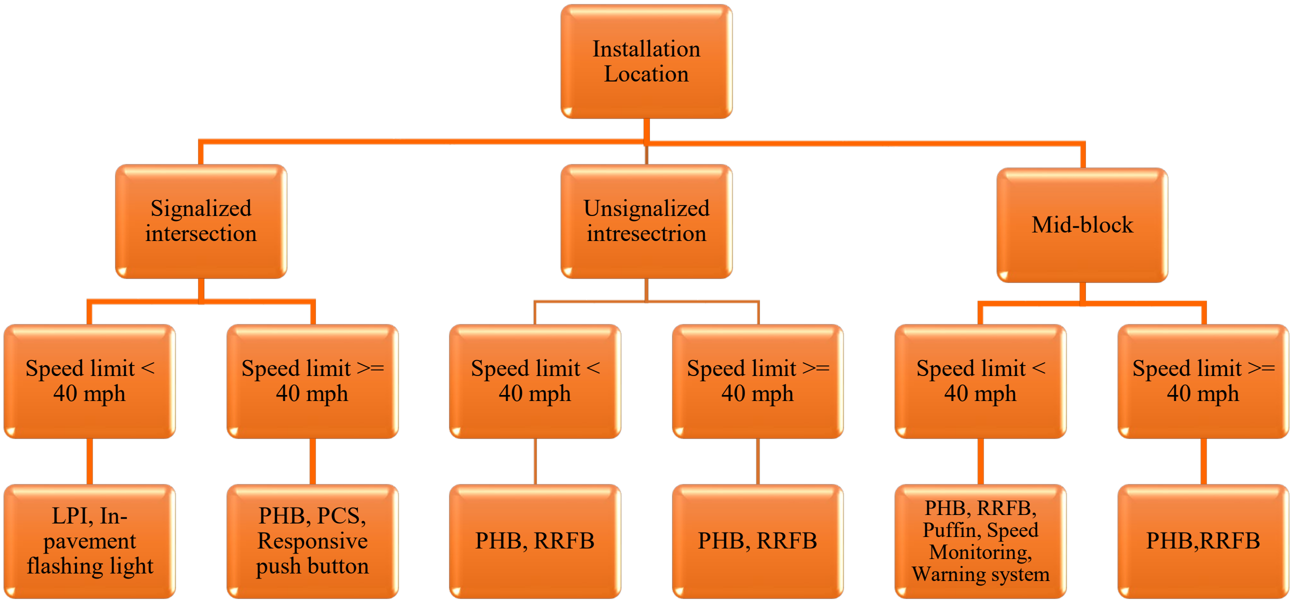

Figure 19. Type of pedestrian safety countermeasures according to installation locations

It is important to note that one of the limitations of this project was the relatively small number of studies evaluating the effectiveness of some of the countermeasures, including Puffin crossings and LED flashing lights. In the future, several studies can be conducted to evaluate the effectiveness of these countermeasures as well as other existing ITS-based countermeasures, including crosswalk illuminators and overhead lighting. Moreover, with access to an inventory of New Jersey locations where pedestrian safety countermeasures have been implemented, before-and-after studies can be conducted to identify the effectiveness of these countermeasures on enhancing pedestrian safety. Overall, the list of actionable next steps includes but is not limited to:

- Develop and track NJDOT ITS inventory to provide agencies with a more comprehensive resource.
- Conduct before-and-after studies to evaluate the effectiveness of ITS-based countermeasures.
- Identify locations for further targeted implementation of ITS-based countermeasures.
- Develop materials for future training and webinars on ITS-based countermeasures and identify opportunities to present at events such as NJDOT’s Tech Transfer Lunch and Learn.
- Host internal discussions at NJDOT to determine how best to implement ITS-based countermeasures more often.

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