Guidelines and Toolbox for Reducing Pedestrian Crashes with Turning Vehicles at Signalized Intersections

Final Report

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Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the authors and are not necessarily those of the Florida Department of Transportation.

Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

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This report details the development of guidelines and a toolbox aimed at reducing pedestrian conflicts with turning vehicles at signalized intersections. The guidelines and toolbox are based on a comprehensive literature review, interviews with 14 transportation professionals, and pilot testing at seven intersections across Tampa Bay and Sarasota.

The pilot testing covered individual and combined countermeasures, including Leading Pedestrian Intervals (LPI), "No Turn on Red" (NTOR) blank-out signs, the omission of permissive left turns during pedestrian phases in a protected and permitted left-turn operation, and automated pedestrian detection (APD). Results showed LPI to be highly effective, especially when paired with NTOR signs. Omission of permissive left turns was highly effective in eliminating or reducing the conflict between pedestrians and left-turning vehicles. Despite some limitations, automated pedestrian detection systems have proven to be highly beneficial and show outstanding promise for improving safety and performance, especially when paired with other countermeasures.

Recommendations include combining multiple treatments—such as LPI, NTOR signs, omission of permissive left turns, and APD for implementations. For a greater impact, deploy APD at intersections with pedestrian safety concerns, and reinforce education and enforcement strategies to improve compliance. The guidelines and toolbox developed from this project offer practical, site-specific guidance to help agencies implement proven safety measures, supporting broader Vision Zero goals and safer, more pedestrian-friendly urban environments.</td></tr>
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Executive Summary

Florida faces significant pedestrian safety challenges, particularly at signalized intersections where conflicts with turning vehicles are common. This report presents the development of guidelines and a toolbox to improve pedestrian safety at signalized intersections, focusing on reducing pedestrian crashes involving turning vehicles. The toolbox compiles best practices, recent research findings, expert insights, and results from pilot deployments.

The major project tasks included 1) a comprehensive literature review to identify the best practices and emerging technologies to reduce pedestrian crashes, injuries, and fatalities, 2) interviews with fourteen transportation professionals, 3) field testing of proposed countermeasures, and 4) development of guidelines and a toolbox. The tested countermeasures included integrating leading pedestrian intervals (LPIs), "No Turn on Red" blank-out signs, automated pedestrian detection (APD), and/or advanced traffic signal control operations that omit permitted left turns when a pedestrian phase is activated.

The pilot deployment included six signalized intersections in the Tampa Bay area and one in the City of Sarasota, selected for the implementation of individual and/or combined countermeasures at locations where significant conflicts had been identified. To assess the effectiveness of omitting left turns during a pedestrian phase, historical crash data were analyzed in a before-and-after study to evaluate the impact. Additionally, field data were collected and analyzed through a cross-sectional approach at sites featuring at least two of the proposed countermeasures.

The findings suggest that LPIs are a widely used and effective countermeasure among engineering solutions. LPIs provide pedestrians a head start of 3 to 10 seconds before vehicles are given a green signal, with longer intervals (7 to 10 seconds) demonstrating particular effectiveness at large or complex intersections. LPIs paired with "No Turn on Red" (NTOR) blank-out signs, which activate when pedestrian push-buttons are pressed or pedestrian presence is detected via APDs, can significantly improve driver compliance and reduce pedestrian-vehicle conflicts. Agencies have also reported success with the use of dual-message signs (e.g., "No Turn on Red" and "Turning Vehicles Yield to Pedestrians") and from the deployment of omissions of permitted left-turn phases during pedestrian intervals. In such cases, converting from five-section to four-section signal heads may be necessary, depending on structural load limits.

APD systems are another promising technology, especially at intersections with high pedestrian, bicycle, or scooter activity or where pedestrians often fail to press the push-button to cross streets. These systems reduce reliance on manual activation and improve accessibility, but present challenges such as false triggers (especially at shared crosswalk corners), high costs, and maintenance requirements. Their effectiveness significantly increases when each crosswalk has a clearly defined waiting area. Technologies like fisheye cameras, LIDAR, thermal sensors, and AI-powered analytics are advancing pedestrian detection capabilities, potentially enabling

predictive behavior modeling and more adaptive signal timing. For nighttime safety, strategies such as increasing streetlight brightness when pedestrians are detected and promoting the use of reflective pavement marking materials were also recommended.

The qualitative benefits from the pilot study are shown below:

- Reducing right-turn conflicts by installing NTOR blank-out signs and LPIs at high-volume intersections.
- Reducing left-turn conflicts by omitting permissive turns, adding LPIs, and modifying existing Flashing Yellow Arrow (FYA) operations.
- Combining multiple countermeasures, such as LPIs, blank-out signs, and omitted FYAs, for greater effectiveness in reducing pedestrian-vehicle conflicts.
- Deploying APD systems at key intersections and using audible "push button locator tones" at locations without detection to maintain pedestrian compliance.

The quantitative benefits from the pilot study are shown below:

- The treatment (LPI + blank-out sign) significantly reduced unsafe behaviors among right-turning vehicles, such as conflicts or being too close to pedestrians. At a large-sized intersection, the treatment resulted in a 34% reduction in unsafe behaviors (48% improvement), while at a middle-sized intersection, the reduction reached 91% (a 100% improvement). Additionally, the treatment reduced right-turn vehicles' unyielding behaviors by 10% (24% improvement) at large-sized intersections and by 14% (100% improvement) at a middle-sized intersection.
- The treatment (O-FYA+LPI) reduced left-turn vehicles' unsafe behaviors (conflicts or too close to pedestrians) by 19% (83% improvement) and left-turn vehicles' unyielding behaviors by 13% (76% improvement).
- A simple crash comparison in Pinellas County using three years of pedestrian crash data before and after the O-FYA deployments shows that pedestrian crashes related to left-turn crashes were reduced by nearly 71% after implementing O-FYA. This finding supports the safety effects of O-FYA + LPI.
- The use of APD systems increased the rate of pedestrian crossings on the "WALK" signal indication by 24% and reduced the rate of crossing on the "RED" signal indication by 25%, which significantly improves pedestrian safety.

Education and enforcement are essential for ensuring the success of these treatments. Public awareness campaigns, driver education (including the integration of NTOR blank-out sign rules into licensing exams), and targeted law enforcement at problem intersections are all recommended to promote compliance and safe behavior. Educational outreach should emphasize the importance of crossing only during the "WALK" signal and understanding new signage and signal operations.

Finally, the project synthesized insights from the literature, expert interviews, and pilot evaluations into practical guidelines and a decision-support toolbox. This toolbox helps state and local transportation agencies in selecting appropriate treatments based on site-specific factors and known conflict types. These tools are intended to guide the effective deployment of innovative and evidence-based safety measures at signalized intersections across Florida and beyond.

Transportation agencies are encouraged to adopt the toolbox as a practical resource to guide safety improvements. This effort supports the broader goals of Vision Zero and pedestrian-friendly urban design.

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Abbreviations and Acronyms

AAA	American Automobile Association
AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
ALMS	Advanced Lighting Measurement System
APD	Automated Pedestrian Detection
APS	Accessible Pedestrian Signals
AZ	Arizona
CA	California
CADD	Computer-Aided Design and Drafting
CDC	Centers for Disease Control and Prevention
CFR	Code of Federal Regulations
CMF	Crash Modification Factor
CPFM	Continuous Pavement Friction Measurement
CRF	Crash Reduction Factor
CUTR	Center for Urban Transportation Research
CVPDP	Connected Vehicle Pilot Deployment Program
DOT	Department of Transportation
FDOT	Florida Department of Transportation's
FHWA	Federal Highway Administration
FL	Florida
FYA	Flashing Yellow Arrow
HFST	high friction surface treatment
I2P	Infrastructure to pedestrians
ICE	Intersection Control Evaluation
IL	Illinois
IRI	International Roughness Index
ITS	Intelligent Transportation System
LED	light-emitting diode
LPI	Leading Pedestrian Interval
LTTC	Left Turn Traffic Calming
MPH	mile per hour
MUTCD	Manual on Uniform Traffic Control Devices
NACTO	National Association of City Transportation Officials

NC	North Carolina
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Safety Administration
NY	New York
NYC	New York City
NYCDOT	New York City Department of Transportation
OBU	Onboard Unit
PCS	pedestrian countdown signals
PDO	property damage only
PHBs	Pedestrian Hybrid Beacon
PPLT	protected-permissive
PSEE	Project Suite Enterprise Edition
PSM	Personal Safety Message
PUFFIN	Pedestrian User-Friendly Intelligent
RCUT	Restricted Crossing U-Turn Intersections
RTOR	right-turn-on-red
SCRIM	Sideway-Force Coefficient Routine Investigation Machine
SHSP	Strategic Highway Safety Plan
SPF	Safety Performance Function
SSD	stopping sight distance
TEM	Traffic Engineering Manual
TRB	Transportation Research Board
UK	United Kingdom
US	United States
USDOT	United States Department of Transportation
USF	University of South Florida
V2I	Vehicle-to-infrastructure
V2V	Vehicle-to-vehicle
VMT	vehicle miles traveled
WYDOT	Wyoming Department of Transportation

1 Introduction

1.1 Project Background

Florida faces significant challenges regarding pedestrian safety. Four of the top ten most dangerous metro areas to walk in the United States (U.S.) are in Florida, according to the 2024 edition of Dangerous by Design [1]. The Tampa-St. Petersburg-Clearwater metro area is ranked 8th on this list and is the most dangerous major metropolitan area (population > 1M) for pedestrians in Florida. Considering the challenges, the Florida Department of Transportation's (FDOT) top priority has been to develop and implement effective countermeasures to significantly improve pedestrian safety.

Intersections, locations where the paths of various road users coincide, represent concentrated groupings of conflict points, leading to many safety challenges. In Florida, approximately 27% of fatal crashes and 36% of serious injury crashes that occurred between 2018 and 2023 were related to intersections. Considering the past three years (2021-2023), intersections accounted for 29% of fatalities and 37% of serious injury crashes. Figure 1-1 shows the trends of fatalities and serious injuries at intersections from 2018 to 2023. To reach the goal of "Vision Zero" [2, 3], intersections have been a national, state, and local road safety priority and a program focus area [4, 5].

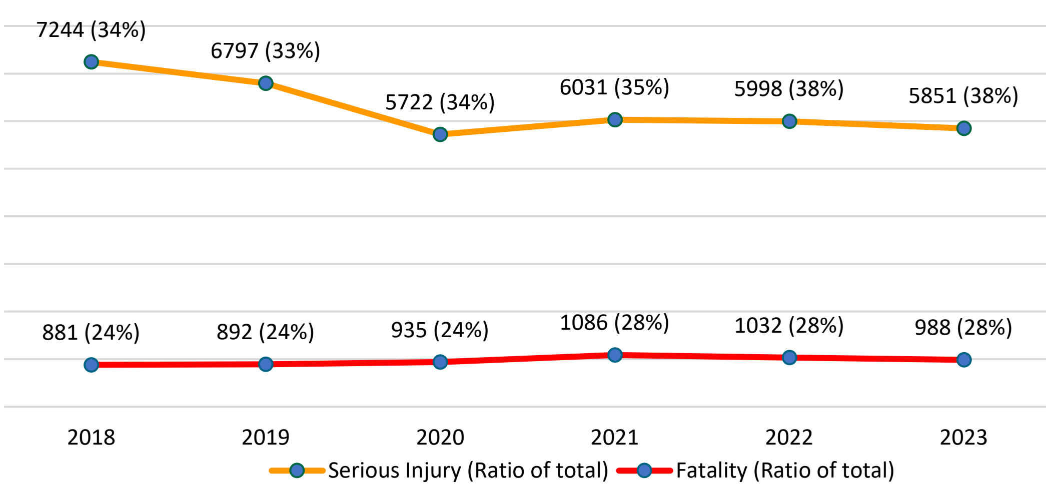


Figure 1-1. Historical intersection-related traffic fatal and serious injury crashes in Florida

It is evident from the data that pedestrian crashes at intersections need to be reduced. The historical distribution of the total number and severity of intersection-related pedestrian crashes in Florida over the past six years (2018-2023) is shown in Figure 1-2 and Figure 1-3, respectively.

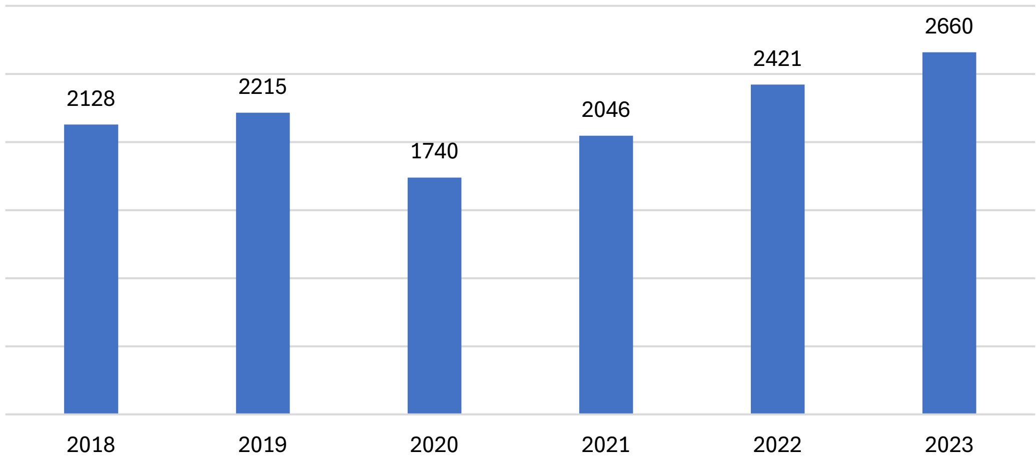


Figure 1-2. Historical intersection-related pedestrian crashes in Florida

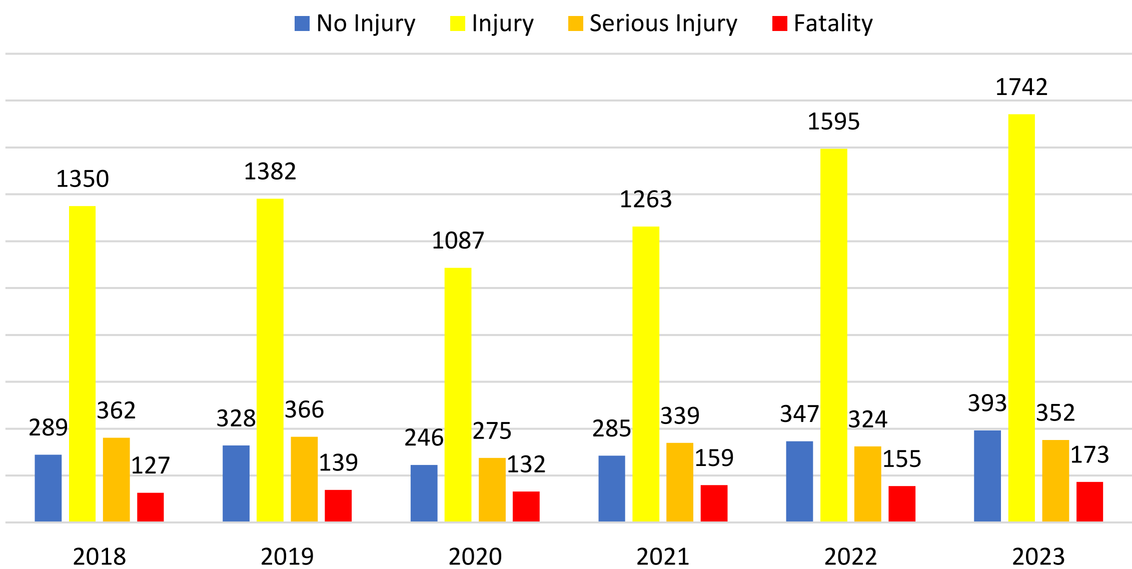


Figure 1-3. Historical intersection-related pedestrian crash severity in Florida

Based on Figure 1-2 and Figure 1-3, the following observations can be made:

- Over the past six years, an average of 14% of pedestrian crashes with no injuries, 64% of pedestrian crashes with injuries, 15% of pedestrian crashes with serious injuries, and 7% of pedestrian crashes resulting in fatalities were associated with intersections.
- Compared to 2021, the total number of pedestrian crashes related to intersections increased by 375 in 2022 and significantly increased by 614 in 2023.
- The number of pedestrian fatalities related to intersections decreased by four in 2022 and increased by 14 in 2023 compared to 2021.

- The total number of intersection-related serious injuries decreased by 33 in 2022 and by 180 in 2023 compared to 2021. However, the number of intersection-related pedestrian serious injuries increased by 13 in 2023 compared to 2021.
- In contrast to 2021, the number of no-injury pedestrian crashes related to intersections increased by 62 in 2022 and by 108 in 2023.

According to FDOT's Pedestrian and Bicycle Crash Typing project conducted by the Center for Urban Transportation Research (CUTR), approximately 10% of fatal and 43% of severe pedestrian crashes at intersections were associated with turning vehicles. In addition, nearly 55% of possible and no-injury pedestrian crashes were associated with turning vehicles. Many conflicts, near misses, and non-yielding behaviors occur between turning vehicles and pedestrians at signalized intersections. The potential causes of pedestrian crashes with turning vehicles at signalized intersections include, but are not limited to, the following:

- When right-turning vehicles and pedestrians on the same approach receive concurrent green and WALK indications, drivers either do not yield to pedestrians or do not see pedestrians due to a blockage of their view.
- When right-turn-on-red (RTOR) is permitted, right-turning drivers look to their left side to find a gap to make right turns and never see the pedestrians or bicyclists on their right side.
- When RTOR is permitted, a significant percentage of drivers do not come to a full stop before turning right on red, which is a traffic violation and causes a potential safety hazard for pedestrians and bicyclists.
- When drivers make permitted left turns with their focus on finding gaps to turn, they either do not see pedestrians crossing streets or cannot react in time to prevent striking pedestrians.
- Drivers hit pedestrians at night, dusk, and dawn due to visibility, impairment, and speeding.
- Drivers and/or pedestrians do not comply with traffic laws at signalized intersections.
- Drivers' speeding causes fatalities and serious injuries to pedestrians.
- Pedestrians do not press a pedestrian push button to activate a pedestrian call.

A number of engineering countermeasures have been developed and implemented to mitigate the conflicts between pedestrians and turning motor vehicles by spatial or temporal separation or via innovative approaches to warn drivers and/or pedestrians of the potential or immediate conflict between them. Based on recent and current practices and research, there is a number of promising pedestrian crash prevention countermeasures available, being studied or in the process of pilot implementation, including:

- Installing proper key pedestrian feature static signs (i.e., No Turn on Red, Right Turn on Red After Stop, Turning Vehicles Yield to Pedestrians, and Stop Here on Red).

- Installing blank-out signs displaying “No Turn on Red” during red signal indications when a pedestrian call is active, and “Yield to Pedestrians” during green and yellow signal indications.
- Installing a “Turning Vehicles Stop for Pedestrians” blank-out sign instead of a “No Right Turn” sign and being illuminated for a long time during the green signal indication.
- Deploying FHWA-proven safety countermeasures for pedestrians at signalized intersections, such as Crosswalk Visibility Enhancements or Leading Pedestrian Intervals (LPIs).
- Eliminating or reducing conflicts between pedestrians and left-turning vehicles: For protected and permitted left-turn operations, only the protected left-turn phase is displayed; the permitted flashing left-turn arrow will be omitted if a pedestrian presses the button to cross the street.
- Constructing proper geometric improvements at signalized intersections, such as adding pedestrian islands.
- Implementing appropriate speed limits near signalized intersections.
- Implementing automated pedestrian detection to place or cancel a pedestrian call to cross a signalized intersection.
- Detecting the presence of pedestrians and providing a warning or an alert to drivers that the crosswalk is being used (California project currently underway (MUTCD Request to Experiment 4(09)-62) that adds yellow LED borders on pedestrian signals to help draw motorist attention to the crosswalk signal).
- Enhancing nighttime visibility at signalized intersections by improving lighting level and uniformity.
- Implementing High Friction Surface Treatment (HFST) to stop turning vehicles before hitting pedestrians.
- Constructing a tighter right-turn lane radius that reduces turning radii to slow turning speeds, reduce crosswalk length, improve pedestrian visibility, improve sight distance, decrease the angle of driver head turning, and reduce right-of-way impacts.
- Applying automatic pedestrian detection technology integrated with advanced traffic controllers to automatically place or remove a pedestrian call at a signalized intersection.
- Applying connected vehicle technologies to alert nearby drivers that a crosswalk is activated.

1.2 Research Objectives

This research project aims to investigate methods and conduct pilot deployments to recommend effective countermeasures for reducing pedestrian fatalities, injuries, and crashes involving turning vehicles to significantly improve pedestrian safety at signalized intersections. Findings will be incorporated into guidelines and a toolbox for FDOT and local transportation agencies. The major project objectives include:

- Understand and document the best practices, proven safety countermeasures, and innovative technologies to reduce pedestrian fatalities, serious injuries, and crashes involving turning vehicles at signalized intersections via a comprehensive literature review.
- Obtain experience, suggestions, and recommendations from agency experts, consultants, researchers, and technology vendors to reduce or eliminate the conflicts between pedestrians and turning vehicles at signalized intersections via in-depth interviews.
- Conduct pilot deployment and evaluation of recommended countermeasures at identified signalized intersections to reduce or eliminate conflicts between pedestrians and turning vehicles.
- Develop guidelines and a toolbox to support state and local transportation agencies for reducing pedestrian fatalities, injuries, and crashes involving turning vehicles to significantly improve pedestrian safety at signalized intersections.

1.3 Report Organization

This report is organized as follows: Chapter 2 summarizes the literature review on contributing factors to pedestrian crashes involving turning vehicles at signalized intersections. It highlights best practices and safety treatments, including engineering, enforcement, and education. It assesses their effectiveness in reducing such crashes, along with innovative technologies and methods aimed at eliminating pedestrian–vehicle conflicts. Chapter 3 presents findings from in-depth interviews with fourteen transportation professionals, offering insights into real-world challenges and solutions. Chapter 4 describes the pilot deployment of selected countermeasures, including implementation strategies and observations. Chapter 5 outlines the development of the pedestrian safety toolbox, providing guidance on countermeasure selection and detailed instructions for its use. Finally, Chapter 6 concludes the report with key findings and actionable recommendations to support agencies in enhancing pedestrian safety at signalized intersections.

2 Literature Review

This chapter provides a comprehensive literature review of the contributing factors to pedestrian crashes involving turning vehicles at signalized intersections. It examines best practices and safety treatments, evaluating their effectiveness in reducing such crashes. The review also explores innovative technologies and methods designed to eliminate conflicts between pedestrians and turning vehicles.

2.1 Contributing Factors to Pedestrian Crashes with Turning Vehicles at Signalized Intersections

The section presents the findings of the literature review on factors contributing to pedestrian crash frequency, fatalities, and serious injuries involving turning vehicles at signalized intersections.

2.1.1 Contributing Factors to Pedestrian Crash Frequency at Signalized Intersections

Road crashes are rare and random events, affected by many factors that can be generally classified into three groups: human, vehicle, and roadway/environment [6]. Among these three groups, the human factors include age, judgment, driver skill, attention, fatigue, experience, and sobriety; the vehicle factors include design, manufacture, and maintenance; and the roadway/environment factors include geometric alignment, cross slope, grade, pavement friction, weather, visibility, traffic control devices, and signage.

Factors contributing to the frequency of pedestrian crashes at signalized intersections can be classified into four types. These include pedestrian behavior (such as jaywalking or distraction), driver behavior (such as failure to yield or speeding, visibility issues like poor lighting or obstructed views), road factors (such as a lack of crosswalks or inadequate signage), and overall traffic volume. The potential contributing factors for pedestrian crashes with vehicles turning at signalized intersections include:

- When right-turning vehicles and pedestrians on the same approach receive concurrent green and WALK indications, drivers either do not yield to pedestrians or do not see pedestrians due to a blockage of their view [7, 8].
- When right-turn-on-red (RTOR) is permitted, right-turning drivers look to their left side to find a gap to make right turns and never see the pedestrians or bicyclists on their right side [9].
- When RTOR is permitted, a significant percentage of drivers do not come to a full stop before turning right on red, which is a traffic violation and causes a potential safety hazard for pedestrians and bicyclists [10].
- When drivers make permitted left turns with their focus on finding gaps to turn, they either do not see pedestrians crossing streets or cannot react in time to prevent striking pedestrians [11].

- Drivers hit pedestrians at night, dusk, and dawn due to visibility, impairment, and or speeding [12].
- Drivers and/or pedestrians do not comply with traffic laws at signalized intersections [13].
- Drivers’ speeding causes fatalities and serious injuries to pedestrians [14].
- Pedestrians do not press a pedestrian push button to activate a pedestrian call [12].
- Pedestrian volume on the approach leg, pedestrian volume on the receiving leg, vehicle volume on the approach leg, vehicle volume on the receiving leg, corner radius, and shoulder width [15, 16].
- Median channelization, access management, and signal coordination have great effects on pedestrian safety at signalized intersections [17].
- Degraded pavement friction and macrotexture and their variations, as well as pavement roughness and pavement conditions, were confirmed to have significant effects on intersection-related crashes [18].

Due to the increasing trend and complexity of pedestrian and turning-vehicle crashes, it is crucial to implement a more effective combination of engineering, education, and enforcement measures to decrease the occurrence of pedestrian crashes at signalized intersections.

2.1.2 Contributing Factors to Pedestrian Fatalities and Serious Injuries at Signalized Intersections Involving Turning Vehicles

Several factors contribute to pedestrian fatalities and serious injuries during their interactions with turning vehicles at signalized intersections. According to the Centers for Disease Control and Prevention (CDC) report, speed, location, vehicle size, and alcohol are major risk factors for pedestrian fatal injuries [19]. Other studies supporting that statement are as follows:

- Higher vehicle speeds increase both the likelihood of pedestrian crash frequency and injury severity [20, 21].
- Most pedestrian deaths (60% in 2020) occur on high-capacity urban roads that typically have posted speed limits of 45-55 mph [22].
- SUVs can cause more harm to pedestrians than regular cars during a collision [23].
- Alcohol is determined to be a factor in nearly half (49%) of fatal pedestrian crashes [24].

It is stated in the “Guide for Pedestrian and Bicyclist Safety at Alternative and Other Intersections and Interchanges” [25] that the risk of death for pedestrians in a crash significantly increases with higher vehicle speeds. High operating speed implies a long distance to fully stop to avoid a collision with an object. As speed increases, more kinetic energy is transferred during a collision; consequently, the likelihood of severe injuries, even fatalities, tends to increase exponentially, especially for vulnerable road users. The risk of crash severity may be proactively estimated across both the state and local road networks using relationships between the operating speeds and roadway characteristics and features [14, 18].

An American Automobile Association (AAA) study [26] indicates that the average risk of severe injury for a pedestrian struck by a vehicle reaches 10% at an impact speed of 16 mph, 25% at 23 mph, 50% at 31 mph, 75% at 39 mph, and 90% at 46 mph. The average risk of death for a pedestrian reaches 10% at an impact speed of 23 mph, 25% at 32 mph, 50% at 42 mph, 75% at 50 mph, and 90% at 58 mph. Additionally, speeding is more of a factor in the conflicts between pedestrians and left-turning vehicles than right-turning vehicles. Vehicles that turn left typically travel at a higher speed than those turning right due to their greater turning radii.

The following summarizes other contributing factors to pedestrian fatalities and serious injuries at signalized intersections involving turning vehicles.

Right-Turn Lane Design and Right-Turn on Red Signs

Conflicts between pedestrians and right-turning vehicles are linked to different factors that are discussed in this sub-section. For instance, a study [27] indicated that the inadequate design of a channelized right-turn lane increases pedestrian risks at signalized intersections. Thus, adequate design of channelized right turns could reduce traffic delays and the number of conflicts between vehicles and pedestrians at signalized intersections.

Similarly, Right Turn on Red (RTOR), when permitted, can also lead to conflicts between pedestrians and turning vehicles. Zador et al. [28] found that pedestrian crashes increased by 57%, especially in urban areas, and by 79% after the permission of RTOR. However, Compton et al. [29] found the total number of fatalities and injuries caused by RTOR was relatively small.

Pedestrian Exposure, Driver Visibility, Driver Workload, Traffic Signal, and Roadway Width

Several factors can lead to conflicts between pedestrians and left-turning vehicles. Some of those factors are the following:

- **High pedestrian exposure**: Crosswalks with high pedestrian exposure can lead to greater conflicts between pedestrians and left-turn vehicular traffic. The exposure is usually high in urban areas. Between 2014 and 2016 in the United States, nearly 90% of pedestrian fatalities caused by motorists making left turns occurred in urban areas. Additionally, 3% of pedestrian fatalities were due to motorists turning left across parallel paths (see Figure 2-1) [30].

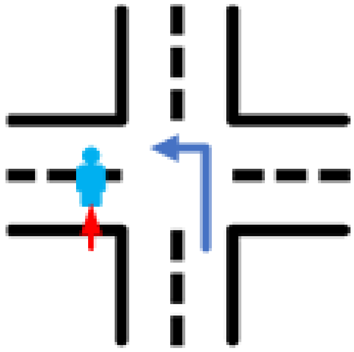


Figure 2-1. Motorists turning left across parallel paths

- **Driver's obscured visibility**: The "A-pillar" of many cars (see Figure 2-2) can obstruct the driver's view of the crosswalk when making a left turn. This issue is further exacerbated at night and poses a safety concern for pedestrians crossing the street.

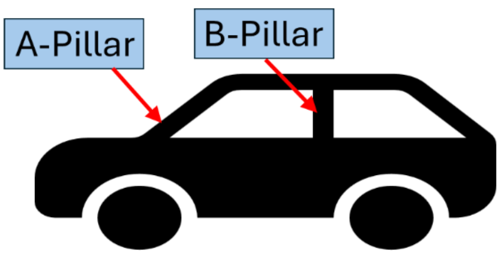


Figure 2-2. Pedestrians obscured by vehicle's "A-pillar" during vehicle's left-turning

- **Driver's workload**: At signalized intersections with permissive left-turn phasing, drivers must look for a gap in the oncoming traffic to make their turns. This coincides with pedestrians also having the right of way to cross. The heavy demands of making permissive left turns can cause drivers to overlook certain tasks and make them unable to complete other tasks, such as scanning the roadway for potential pedestrians [11]. Back pressure that occurs when there is a build-up of vehicles waiting to make a left turn behind a vehicle can push drivers to take more risks.
- **Traffic signal**: Pedestrians cannot differentiate between a fully protected, all-pedestrian phase, and a phase that coincides with turning cars.
- **Roadway width**: According to the NYC DOT's Left Turn Study Action Plan [31], it was discovered that the width of the receiving street is a significant contributing factor. Approximately 69% of left-turn vehicle and pedestrian injury crashes occurred on receiving streets that were 60 feet or wider, likely due to the higher speeds allowed by wider angles. It was also discovered that these crashes usually took place at intersections, specifically at the intersection of a two-way main street and a one-way side street (see Figure 2-3).

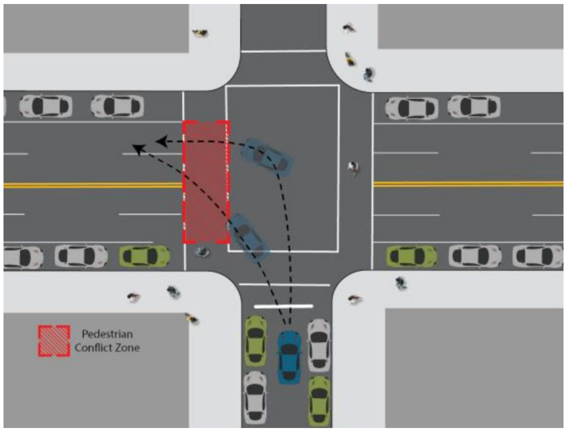


Figure 2-3. The greatest concentration of left-turn injuries in NYC

Source: New York City [31]

Pavement Friction

Pavement friction is a factor that affects the interaction between a vehicle and a pavement surface. Maintaining appropriate levels of pavement friction is essential for reducing traffic crashes, as it enables a vehicle to safely remain in its lane when changing direction and shorten the stopping distance. This is especially important on wet pavement surfaces, where the absence of friction can lead to skidding or hydroplaning. Sharafeldin et al. [32], for example, discovered that increasing the friction number from 25 to 45 can significantly decrease the chances of severe injuries and fatalities at intersections in the State of Wyoming. In 2004, the City of Bellevue in Washington State reported that the installation of a high friction surface treatment on a downhill approach at an intersection resulted in a 78% reduction in intersection crashes [33]. A recent research study conducted by the CUTR project team between 2023 and 2024 also confirmed that pavement friction could statistically reduce crash severity using continuous friction data [14, 18].

Other Contributing Factors from Statistical Estimation

Haleem et al. [34] employed mixed logit models to identify and compare the significant factors that affect the severity of pedestrian injuries at signalized intersections in Florida. They found that the following factors were also associated with a higher risk of severe pedestrian injuries:

- Higher average annual daily traffic (AADT)
- Percentage of trucks
- At-fault pedestrians
- Dark lighting conditions
- Senior pedestrians
- Rainy weather

Stipancic et al. [35] validated the positive correlation between vehicle volumes and pedestrian injuries. The total number of lanes and commercial entrances also increased pedestrian injuries. However, curb extensions, raised medians, and exclusive left turn lanes were all found to decrease pedestrian injuries.

2.2 Best Practices and Safety Treatments to Reduce Pedestrian Crashes Involving Turning Vehicles at Signalized Intersections

This section reviewed best practices and safety treatments (engineering, enforcement, and education) and their effectiveness in reducing the crash risk between turning vehicles and pedestrians at signalized intersections, drawing on academic papers, technical reports, and databases (e.g., CMF Clearinghouse).

2.2.1 Best Engineering Practices and Safety Treatments

Specific guidance should be provided at signalized intersections with complex design features or heavy traffic to accommodate all road users and promote best engineering practices and measures to improve safety. According to the "Guide for Pedestrian and Bicyclist Safety at Alternative and other Intersections and Interchanges" document [25], road users have a wide range of physical, cognitive, and sensory abilities; roadway design should serve the variety of pedestrians that might be present and the different characteristics of those pedestrians. The design principles for pedestrian facilities should include as many positive pedestrian features as possible in the given context and constraints, as follows:

- Minimize pedestrian exposure to high-speed and/or high-volume traffic movements;
- Maximize visibility between pedestrians and motorists by providing pedestrian crossings as perpendicular to conflicting motorists as possible;
- Reduce motor vehicle speeds at conflict areas with uncontrolled or concurrent motor vehicles by minimizing corner radii to slow turning speeds;
- Minimize the severity of conflicts where they cannot be eliminated by separating movements in time using traffic controls; and
- Provide adequate signal timing for pedestrians to clear crossings before permitting conflicting movements to proceed (i.e., by providing pedestrian lead, lag, or exclusive phases when appropriate).

To meet the requirements of federal surface transportation legislation, every state has developed a Strategic Highway Safety Plan (SHSP) to identify current safety conditions and recommend a set of engineering, enforcement, and education countermeasures to improve pedestrian safety [36]. To achieve equity in Vision Zero planning, the Vision Zero Network provides a set of actionable steps and examples to help roadway safety champions make meaningful advancements toward safe, healthy, and equitable mobility for all people [37]. Based on the NCHRP Report 500, the FHWA has offered proven safety measures and underutilized innovations from Every Day Counts in the second edition of intersection safety strategies for various types of crashes [38].

Because intersection safety has been identified as one of the top emphasis areas in Florida's Strategic Highway Safety Plan (SHSP), FDOT developed an Intersection Control Evaluation (ICE) manual that assesses multiple intersection control scenarios using quantitative measures and then prioritizes these scenarios according to their operational effectiveness and safety performance [39, 40]. As one of 11 states, Florida has worked with FHWA to develop Intersection Safety Implementation Plans [41]. In addition, the PSEE (Project Suite Enterprise Edition) Countermeasures Module tracks the implementation of and prioritizes the inclusion of safety countermeasures [42]. The Gold Star countermeasures, identified in the PSEE, are measures and design features proven to effectively reduce or eliminate crash patterns.

The following sub-sections summarize the identified proven engineering practices and safety measures in the literature. These practices and measures help practitioners enhance safety in many ways.

2.2.1.1 Traffic Control and Operational Improvements

Install Traffic Signal Pedestrian Actuation Signs and Signal Timing (R10-1 through R10-4)

Pedestrian signals create gaps in traffic flow, allowing pedestrians to cross the street. In most situations, manual actuation of a traffic signal is required for pedestrians to call a signal phase to cross the roadway. Traffic signal signs applicable to pedestrian actuation are mounted immediately above or incorporated into the push button detector units (Figure 2-4).

The educational signs (R10-3b, R10-3c, R10-3d) improve pedestrian understanding of signal indications at signalized intersections, surpassing the effectiveness of the R10-3 sign [9]. Additionally, the R10-3e educational sign is suitable for locations with countdown pedestrian signals. The R10-3f through R10-3i signs include the name of the street to be crossed, offering additional clarity.

The public is often confused by the impact of pushing buttons and the timing of pedestrian signals. Implementing effective solutions is crucial to addressing this challenge at signalized intersections, including [43]:

- Optimizing the cycle length of WALK and flashing DON'T WALK;
- Making cycle length accommodate slower pedestrians;
- Creating a balance between the pedestrian phase and vehicle right turns and left turns;
- Providing fairness of laws that permit drivers to enter an intersection on a yellow light, while prohibiting pedestrians from doing so during a flashing DON'T WALK signal;
- Balancing the delay of motor traffic with the delay of pedestrians at actuated pedestrian crossings;

- Incorporating pedestrian recall and actuation in a manner that is easily understood by pedestrians; and
- Optimizing coordinated signal timing to create an uninterrupted flow for a pedestrian-friendly downtown [44].

Figure 2-4. Pedestrian signs and plaques

Source: MUTCD 11th Edition [9]

According to CMF (Crash Modification Factor) ID: 8480 [45], installing pedestrian signals at a signalized intersection was found to be effective in reducing the number and severity of crashes. It can reduce total pedestrian crashes by 11.8% and pedestrian-related fatality & injury crashes by 24.5%. However, there was no statistically significant effect on property damage only (PDO) crashes. This is consistent with the fact that pedestrian-vehicle crashes tend to be more severe.

Traffic signals should provide enough time for pedestrians to cross and a sufficient clearance interval, considering a maximum walking speed of 4 feet per second. In areas with a high concentration of the elderly or children, a lower speed of less than 4 feet per second should be used to determine the pedestrian clearance time.

Signals are especially crucial on fast-moving roads, multi-lane roads, and heavily congested intersections. The selection of traffic signal locations is typically based on national guidelines from the Manual on Uniform Traffic Control Devices (MUTCD), which regulates the factors that should be investigated in engineering studies for the installation of a traffic control signal [9].

Install or Implement Pedestrian Countdown Signals

Pedestrian countdown signals (PCS) consist of a standard pedestrian signal head, with an added display showing a countdown of the remaining crossing time (Figure 2-5) [9]. PCS is designed to provide additional information to pedestrians at crossings and help their crossing decisions. The 2023 MUTCD requires the use of countdown pedestrian signals when the pedestrian change interval is greater than seven seconds.

PCSs are now the FDOT standard pedestrian signal on the State Highway System (Policy No. 000-750-010). A countdown pedestrian signal module is used to meet the requirements of the latest ITE LED Pedestrian Signal Specifications and MUTCD [46].

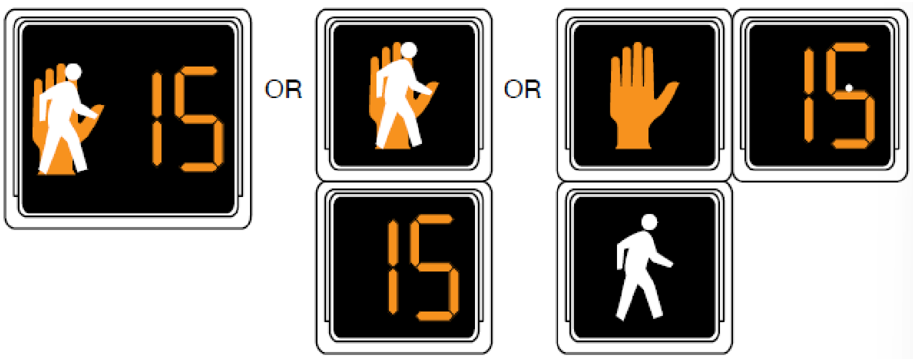


Figure 2-5. Pedestrian countdown timers

Source: MUTCD 11th Edition [9]

The benefits of PCS include: (1) easily understood by all age groups; (2) increases the feeling of safety; (3) reduces the number of pedestrians stranded in the crosswalk when the light changes; (4) are well-suited for wide crossings and areas with large numbers of senior citizens; and (5) are simple to install [47].

According to previous studies and applications, PCSs have been an FHWA proven effective pedestrian safety countermeasure, which was also confirmed by FDOT [48, 49]. However, recent research in Canada indicated that displaying a PCS to drivers increased the approaching speed by 11 kilometers per hour.

Right-Turning Traffic Control Signs

RIGHT TURN ON RED (RTOR) means a right turn is permitted after coming to a full stop at a red light. It was introduced in the 1970s as a fuel-saving measure. The other benefits of the practice are that it [50]:

- Improves travel time by reducing delay at red lights, without compromising safety;
- Reduces congestion by decreasing approach delays; and
- Lowers fuel consumption and emissions from cars idling at signals.

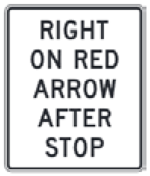
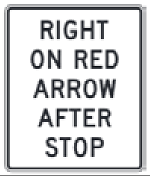
However, it may have adverse effects on pedestrians when motorists do not fully comply with the regulations to come to a full stop and yield to pedestrians before turning right on red [51].

Unlike many North American cities, RTOR is severely restricted in New York City [50], but it is permitted at specific signalized intersections in Staten Island with low traffic and pedestrian volumes. In 2006, a two-tiered review process identified potential RTOR intersections, considering land use, accident history, and roadway features. The second analysis assessed operational and engineering aspects, including accident history, pedestrian volumes, and sight distances. A total of 38 intersections out of 521 were selected for RTOR implementation in a pilot study, with no significant changes in crash rates or pedestrian injuries post-implementation.

Lin et al. [12, 52, 53] at the Center for Urban Transportation Research at the University of South Florida (USF CUTR) conducted a thorough investigation of the safety effects of the various right-turning traffic control signals at signalized intersections in Florida. Due to the complex and unobserved factors that affect pedestrian and turning vehicle crashes, the rate of driver compliance was developed as a surrogate safety measure before and after the treatment.

The project team conducted a before-after study for pilot deployments at identified signalized intersections in Florida. In addition, two combinations of signal control plans were also evaluated: (1) Right Turn on Red after Stop + Turning Vehicles Yield to Peds; (2) No Turn on Red (blank-out signs) + Turning Vehicles Yield to Pedestrians (blank-out signs) + Stop Here on Red. The evaluation results for the pilot implementations are shown in Table 2-1.

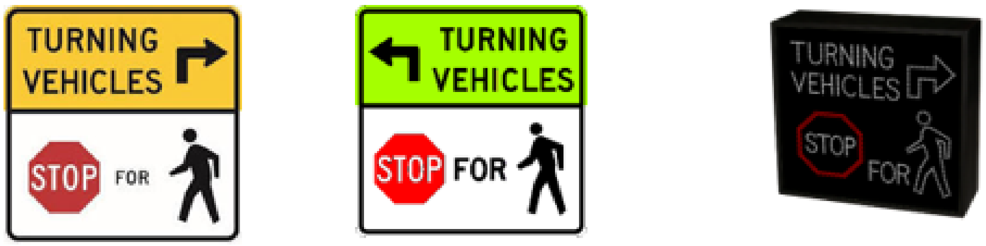
Table 2-1. Safety Evaluation of Right-Turning Traffic Control Signs

Feature Name	Signs	Safety Evaluation
RIGHT TURN ON RED AFTER STOP (R10-17a)		• The rate of driver compliance increased from 10.2% to 25.2%. • Large increases in driver compliance after their implementation. • The statistically significant is at a confidence level of 95% on exclusive right-turn lanes.
RIGHT ON RED ARROW AFTER STOP (R10-17a) + Photo Enforced		• Increased the likelihood of compliant behaviors. • The rate of driver compliance increased from 31.3% to 74.4%.
STOP HERE ON RED (R10-6a)		• Large increases in driver compliance (male and female) after their implementation at a confidence level of 95%.
TURNING VEHICLES YIELD TO PEDESTRIANS (R10-15a)		• Large increases in driver compliance (male and female) after their implementation. • Young drivers had higher compliance than middle-aged and older drivers at a confidence level of 95%.
TURNING VEHICLES YIELD TO PEDESTRIANS (blank-out signs)		• Large increases in driver compliance (male and female) after their implementation at a confidence level of 95%. • The statistical significance is at a confidence level of 95% on exclusive right-turn lanes.
NO TURN ON RED (blank-out signs)		• Increased driver compliance and reduced unnecessary vehicle delay at signalized intersections **as the signs were displayed only when needed**. • 75.2% compliance rate after implementation was lower than the compliance rate of 90.9% from the "No Turn on Red" static signs. • **Consider implementing them based on a time-of-day schedule to coincide with higher pedestrian activity.**
NO TURN ON RED		• 90.9% compliance rate after implementation.
		• Combined pedestrian signage implementation and education outreach can achieve the highest driver compliance.

Source: Lin et al. [12, 52, 53]

Previous studies indicate that right-turning control signs improve driver compliance. Future research could investigate combining various signs and signal controls for enhanced safety, like pairing NO TURN ON RED signs with pedestrian pushbuttons. Screening procedures for sign locations should consider critical factors to ensure treatment effectiveness, especially in school zones and high pedestrian traffic areas. However, there are still challenges in evaluating the treatment's impact based on crash data [53], as it can be difficult to determine which crashes are directly related to the treatment.

TURNING VEHICLES STOP FOR PEDESTRIANS (static or blank-out signs) are also currently available to eliminate the conflicts between turning vehicles and pedestrians (Figure 2-6). It could be used in a jurisdiction where statutes or ordinances specifically require that a driver turning at a signalized intersection must stop for a pedestrian who is legally within a crosswalk. However, the safety effectiveness of TURNING VEHICLES STOP FOR PEDESTRIANS (blank-out sign) needs further evaluation.



a. *MUTCD* [9] b. *FDOT* [54] c. *Signal-Tech Inc* [55]

Figure 2-6. Turning vehicles stop for pedestrians (static or blank-out signs)

Source: Signal-Technologies Inc

Replace Permissive Left Turns with Protected Left Turns

The protected left turn phase (Figure 2-7) provides a GREEN ARROW or a YELLOW ARROW signal indication for left-turning vehicles while stopping both on-coming traffic and parallel pedestrian crossings to eliminate conflicts [9, 56].

Figure 2-7. A protected left turn signal phase

Source: Google

The CMF ID 9892 for protected left turns showed a crash modification factor (CMF) of 0.718 and a crash reduction factor (CRF) of 0.282 or 28.2% concerning vehicle-pedestrian accidents (all severities combined) in New York City [57]. However, vehicle-pedestrian crashes increased in Chicago and Toronto. None of these findings were statistically significant at a 95% confidence level. In addition, vehicle-vehicle injury crashes decreased in all three cities, but only Toronto showed a statistically significant decrease (less than 5 percent). This strategy may be more effective in areas with a larger number of pedestrians and vehicles, especially if there are over 5,500 pedestrians per day. In these busy areas, the evaluation of left-turn phasing showed a potential benefit-cost ratio range of 1:15.6 to 1:38.9.

Using a protected left-turn signal phase successfully enhanced safety for left-turning vehicles [58]. This is one of the countermeasures recommended by the FHWA for signalized intersections to enhance safety, particularly in areas where there is a high occurrence of angle crashes involving left-turning and oncoming through vehicles [38].

Restricted or eliminated turning maneuvers

Restricting or eliminating turning maneuvers is a proven countermeasure at signalized intersections with a high frequency of crashes caused by turning maneuvers [38]. Potential solutions for pedestrian collisions involving practically restricted or eliminated right or left-turn vehicles in certain situations include:

- Prohibiting right turn on red; and
- Using a separate left turn phase (in conjunction with a WALK/DON'T WALK signal).

The prohibition of a turning movement may shift the problem to another location and have a very negative effect on capacity and delay. However, there are situations with heavy pedestrian volumes where left turn prohibition may be justified.

Accessible Pedestrian Signals (APS)

There are two definitions for APS:

- According to MUTCD 2024 [9], APS is a device that communicates information about pedestrian signal timing in a non-visual format, such as audible tones and/or speech messages and vibrating surfaces.
- Accessible Pedestrian Signal — A device that has audible and vibrotactile features indicating the walk interval so that a pedestrian who is blind or has low vision will know when to cross the street. (Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way, CFR Part 1190).

According to the latest definitions, an APS should provide information in both audible and vibrotactile formats (Figure 2-8), which differs from the previous definition that only included audible and/or vibrotactile options.

Figure 2-8. Example of pushbutton-integrated APS from various manufacturers

According to the Accessible Pedestrian Signals: A Guide to Best Practices (2011) [59], previous research has shown that APSs improve crossing performance for blind pedestrians by:

- Providing more accurate judgments of when the WALK interval begins;
- Reducing crossings that start during the DON'T WALK signal;
- Reducing delay;
- Increasing completed crossings before the signal changes; and
- Enabling sighted pedestrians to begin crossing faster.

Van Houten et al. [60] showed that APS with a redundant audible prompt improves safety and accessibility for pedestrians with vision disabilities at signalized crossings. Intelligent Transportation System (ITS) technologies can be used to address various issues faced by APSs, such as increasing motorist awareness, providing feedback to waiting pedestrians via illuminated pushbuttons, in-pavement lighting, detecting pedestrians automatically, and addressing visual impairment concerns.

Add/Modify Signing and Pavement Marking Design

Due to the complexity of driver decisions, especially at large, signalized intersections, well-designed signing and pavement markings can maximize the safety and efficiency of the intersection. At signalized intersections, traffic control devices should include several key functions to enhance vehicle and pedestrian safety, including (Figure 2-9)[17]:

- Advance notice of the intersection.
- Directional route guidance.
- Lane use control, including indications of permissive or prohibited turning movements.

- Regulatory control of channelized right turn movements (e.g., using YIELD signs).
- Delineation and warning of pedestrian crossing locations.

The primary references for use in the design and placement of signs and pavement marking include FHWA's MUTCD [9], ITE's Traffic Engineering Handbook [61], FDOT'S Traffic Engineering Manual [62], and Design Manual [63], and so on.

The FHWA report (FHWA-SA-13-027) provided comprehensive methods for evaluating the safety and operation of signalized intersections to remedy deficiencies [17]. In Florida, these methods can be combined with Gold Star countermeasures in the PSEE (Project Suite Enterprise Edition) Safety Countermeasure Module to develop a sign layout at intersections [42], following the basic thought process for developing a sign layout recommended for engineers in the Signalized Intersections Informational Guide, 2013 [17].

Figure 2-9. Pavement marking at a large signalized intersection

Source: Google Map

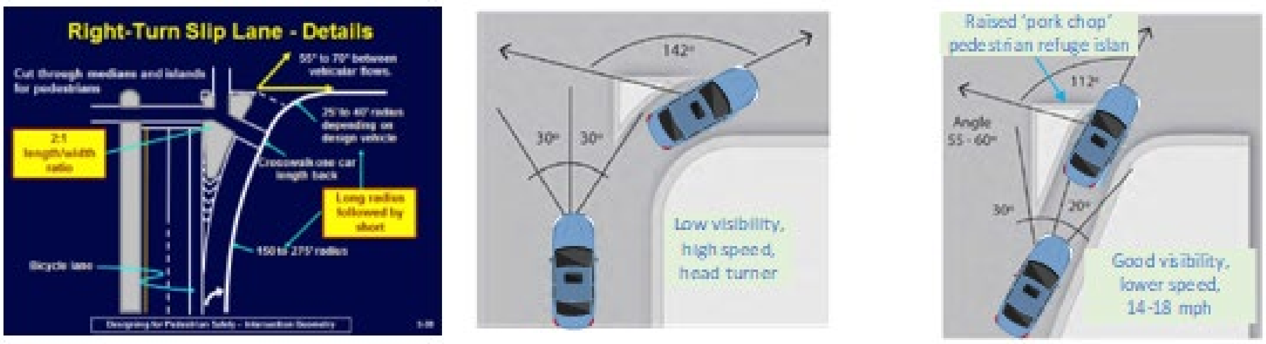
2.2.1.2 Reduce intersection conflicts via geometric improvements

Improved Right-Turn Slip Lanes (with raised pedestrian refuge island)

A well-designed right-turn slip-lane includes several key features [8, 38, 56]:

- The right-turn lane is as narrow as possible while still enabling the design vehicle to make the turn;
- Drivers can easily see pedestrians crossing or about to cross the right-turn lane and have enough space to stop completely when a pedestrian is spotted;

- The crosswalk is located at a 90-degree angle to the right line to optimize sight lines, for example, it should be positioned one car length back from the intersecting roadway to allow drivers to move forward and wait for a gap in oncoming traffic after clearing the crosswalk;
- Using high-visibility crosswalk striping, flashing beacons, and signage to enhance the visibility of the crosswalk to drivers; and
- Pork chop islands are triangular raised islands placed between a right-turn slip lane and through-travel lanes. They channel vehicle traffic and provide a refuge for pedestrians crossing a roadway, where pedestrians can wait for a suitable gap in traffic or the walk phase of a pedestrian signal (Figure 2-10).



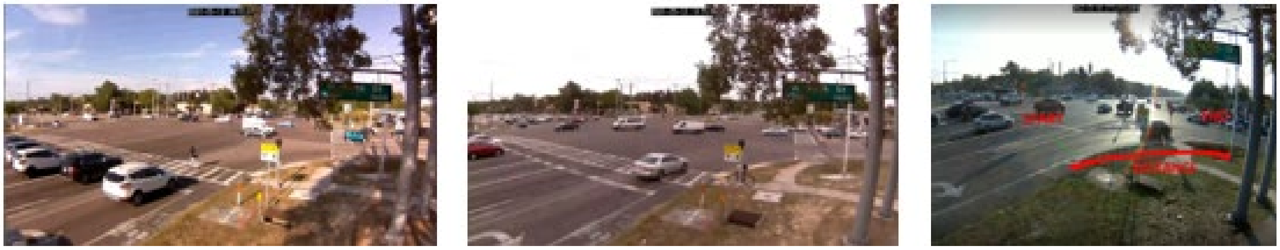
a. Right-turn slip lane | b. Traditional Wide design | c. New Tight design with sharper angles

Figure 2-10. Sharper angles of slip lanes to slow cars and increase visibility

Source: FHWA [8, 56]

Right-turn slip lanes, with suitable radii, slow turning speeds, shorten crosswalks, enhance visibility, sight distance, and reduce driver head-turning angles and right-of-way impacts. They're ideal for signalized intersections with high right-turning traffic volumes or challenging geometries increasing pedestrian crossing distances [56]. It is recommended by FHWA and the Pedestrian Safety Guide and Countermeasure Selection System [38, 56]. The CMF ID: 175 showed its CMF of 0.54 and CRF of 46% at non-signalized intersections. There is no CMF for signalized intersections.

In 2022, USF CUTR evaluated the effectiveness of tight right-turn lanes at signalized intersections in FDOT District 7 [8]. The yielding behavior toward pedestrians and right-turn speeds was reviewed using video data before and after the treatment (see Figure 2-11).



a. Yield to pedestrian b. Not yield to pedestrian c. Right-turn speed

Figure 2-11. Tight right-turn lanes at signalized intersections

Source: USF CUTR [8]

The treatment increased the overall yield to pedestrian rate by 7% for all intersections, irrespective of the time of day and pedestrian right-of-way. The effect is more significant at night (32%). Meanwhile, the tight right-turn lane design significantly reduced the right-turn speed by 20.3%–22.5% (3.9 mph–4.2 mph) at a 99% confidence level.

The literature review has also identified the unsafe design of the treatment mentioned above. As shown in Figure 2-12, corners 1, 2, and 3 (indicated by a red box and located at the front of the crosswalk) may not provide enough space for a vehicle to proceed, which could lead to the vehicle blocking the crosswalk and failing to yield to pedestrians. The layout could be enhanced to increase pedestrian safety.

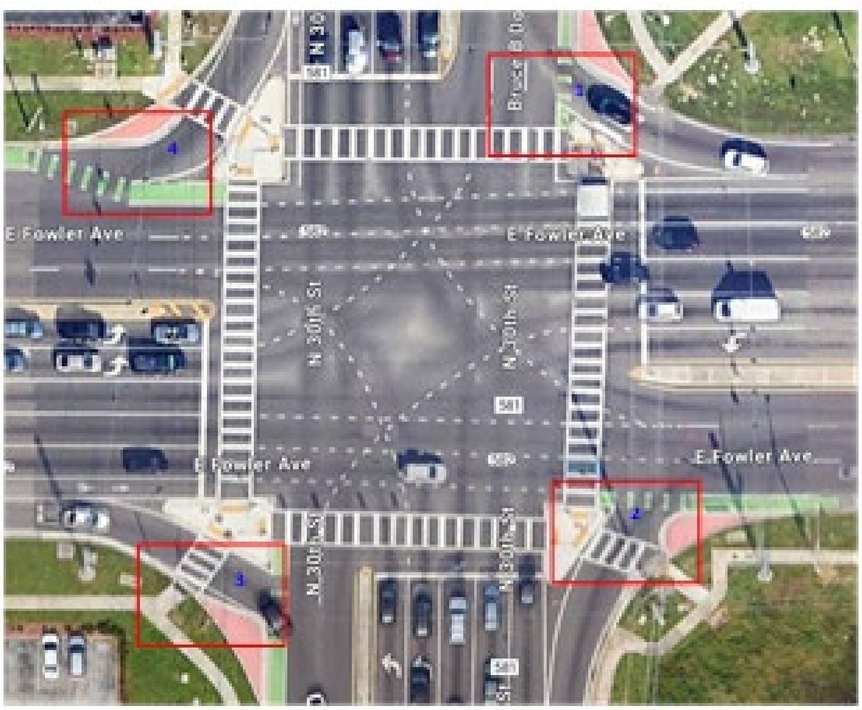
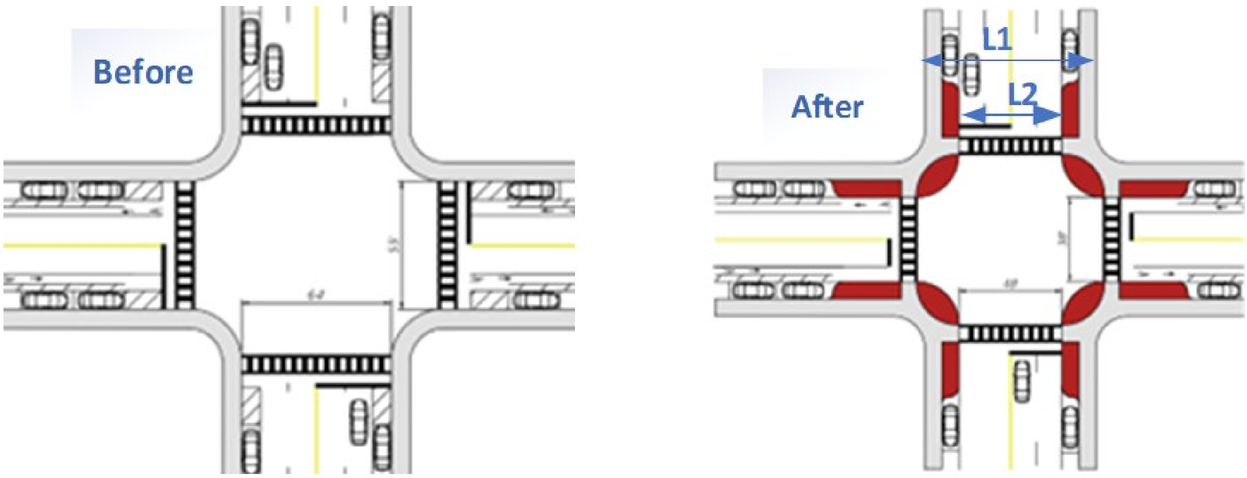


Figure 2-12. Different designs for right-turn slip lanes

Source: Google Map

Curb Extension or Curb Radius Reduction

Traffic calming methods involve the implementation of physical design elements and other measures on existing roadways to reduce vehicle speeds and to improve safety for pedestrians and cyclists [64]. A curb extension is a traffic calming measure in which parts of the curb are extended into the road (Figure 2-13). When designing these extensions at intersections, a CADD (Computer-Aided Design and Drafting) vehicle path should be used to ensure that the design can accommodate designated vehicles [63].



a. Before Extension b. After Extension

Figure 2-13. Curb extensions

Source: FDOT Design Manual [63]

Curb extensions reconstruct the turning radius to a tighter turn. It reduces vehicle turning speeds, shortens the crossing distance for pedestrians, and also improves sight distance between pedestrians and motorists [44, 56, 65].

Offset Left- and Right-Turn Lanes at Intersections

Auxiliary turn lanes, for left or right turns, create a buffer between turning and through traffic at intersections, reducing collisions related to limited sight distance. Offset lanes improve sight distance for approaching vehicles and pedestrians, mitigating conflicts with turning movements. Figure 2-14 shows an Illustration comparing zero offset to positive offset of left- and right-turn lanes,

Based on the CMF Clearinghouse [66], the left-turn lane reduced total crashes by 28%–48% (CMF ID: 260, 268), positive offset left-turn lanes led to 36% less fatal and injury crashes (CMF ID: 6096), and right-turn lanes reduced 14%–26% of total crashes (CMF ID: 285, 2289).

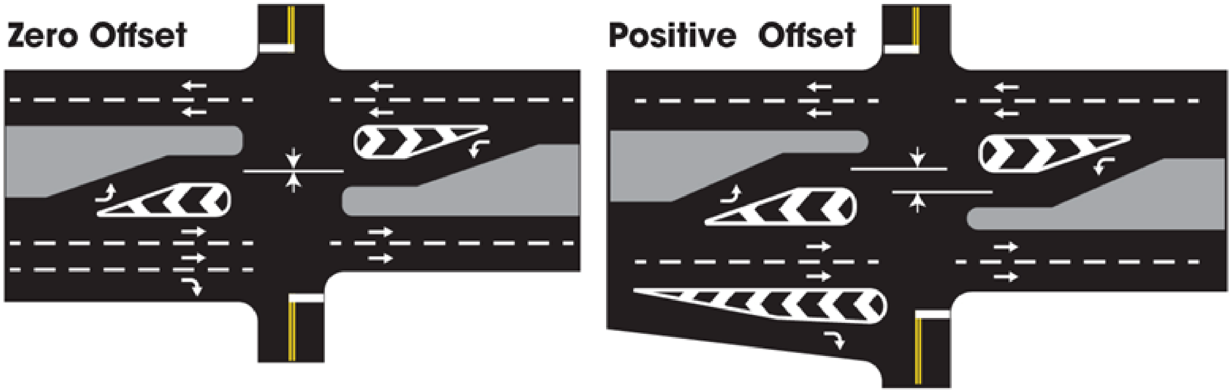


Figure 2-14. Illustration comparing zero offset to positive offset of left- and right-turn lanes

Source: FHWA-SA-21-041 [67]

Left Turn Traffic Calming (LTTC) Treatment

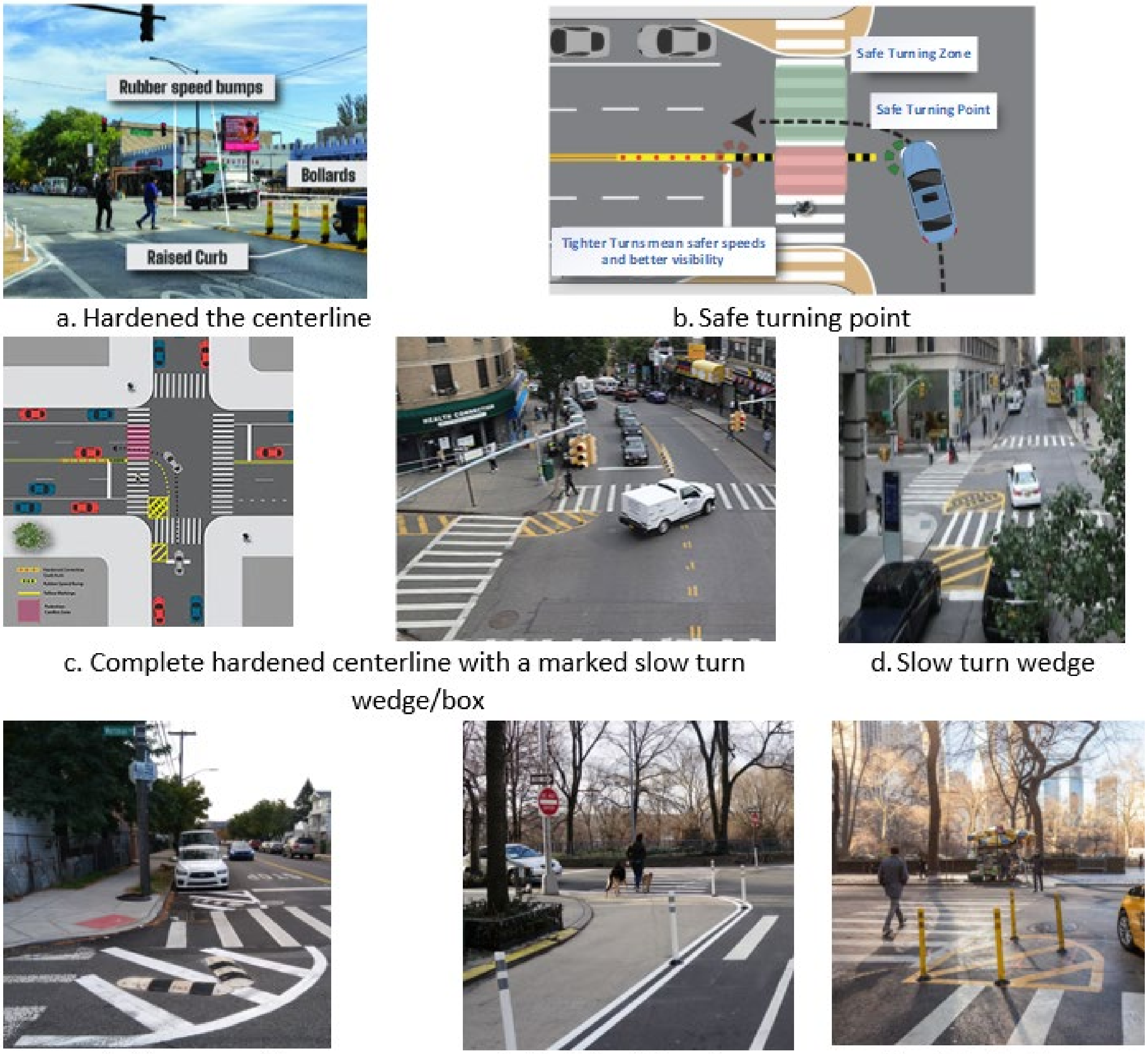
Left-turn traffic calming treatments are simple intersection upgrades to provide a raised/restrictive median or slow-turn wedge to address the turning vehicle and pedestrian crashes caused by left-turning vehicles [68]. The treatments were used to reduce the turning radius to decrease vehicles' turning speed. There are various treatment plans as illustrated in Figure 2-15.

They have improved pedestrian safety and resulted in safer turning behaviors from drivers in New York City and Chicago [31, 68, 69]. In New York City, pedestrian injuries have decreased at a faster rate compared to nearby similar areas. Additionally, LTTCs have resulted in a significant decrease in turning speeds. The crash and speed reductions were as follows:

- Pedestrian injuries and severe injuries have decreased by 18% and 33%, respectively;
- Senior pedestrian injuries and KSI (killed or severely injured) have decreased by 19% and 60%, respectively;
- Median left turn speeds have decreased by 54.3%;
- Average left turn speeds have decreased by 52.6%;
- 85th percentile left turn speeds have decreased by 59.8%; and
- Maximum left turn speeds have decreased by 37.7%.

Chicago DOT has installed LTTC at 18 intersections across the city of Chicago, including its neighborhoods. The safety benefits were as follows:

- The percentage of drivers turning within the safe zone increased from 73% to 97% after the installation;
- The percentage of drivers yielding to pedestrians increased from 73% to 94%; and
- The reduction in left-turn crashes and all crashes on state streets was 24%.



a. Hardened the centerline

b. Safe turning point

c. Complete hardened centerline with a marked slow turn wedge/box

d. Slow turn wedge

e. Rubber speed bumps

f. Flexible delineators

g. Flexible Davidsons

Figure 2-15. Left turn traffic calming in New York City and Chicago

Source: New York City [68] and Chicago DOT [69]

Crossing Islands

Crossing islands, also known as center islands, refuge islands, pedestrian islands, or median slow points, are elevated islands located in the middle of the street at intersections to aid in the safety of pedestrians crossing a multilane road (Figure 2-16). The report from the Pedestrian Safety Guide and Countermeasure Selection System [56] indicated that this measure can decrease pedestrian crashes by 32%.

Figure 2-16. Crossing islands at signalized intersections

Source: Designing for Pedestrian Safety [56]

A crossing island is recommended where pedestrians must cross three lanes of traffic in one direction (on a one-way or a two-way street), but may be implemented at smaller cross-sections where space permits [44].

The implementation should consider the following conditions:

- Install signs and reflectors to illuminate or highlight islands, ensuring that motorists can see them;
- Design islands to accommodate pedestrians in wheelchairs; and
- Crossing islands at intersections or near driveways may affect left-turn access.

Signalized Restricted Crossing U-Turn Intersections (RCUT)

An innovative Restricted Crossing U-Turn (RCUT) intersection is an intersection design that restricts left turns at an intersection but allows the same movement downstream via a U-turn (Figure 2-17).

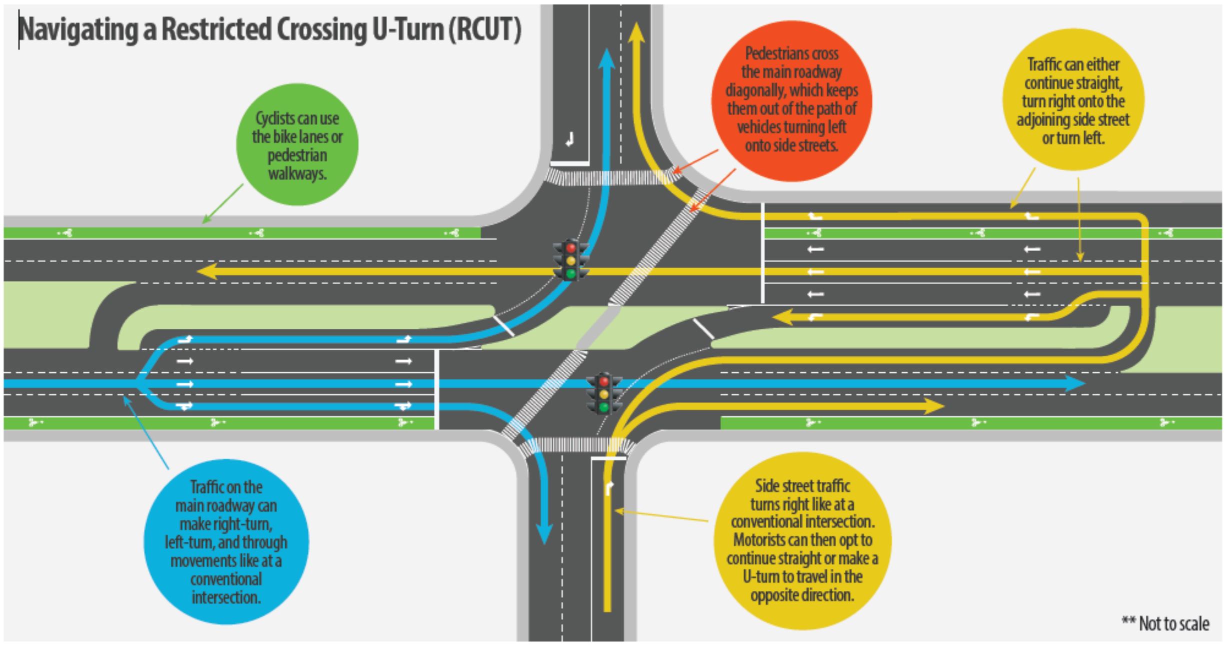


Figure 2-17. FDOT's innovative RCUT

Source: FDOT [70]

It is an innovative, proven solution for improving safety and mobility at signalized intersections [71]. Additionally, it is an effective and efficient way to provide local access to the major highway. Its advantages are:

- Reduce conflict points compared to conventional intersections;
- Simplifies driver decision-making, reduces congestion and delays at intersections, and minimizes the potential for related crashes;
- Provide favorable progression along an urban or suburban corridor; and
- Can easily accommodate pedestrians and adjacent access driveways.

The technical report of FHWA-HRT-09-060 [72] reported RCUT safety effects in 2010:

- There was a 17% decrease in total crashes, a 31% decrease in total crash rate, a 41% decrease in fatal/injury crashes, and a 51% decrease in fatal injury crash rate at the RCUT intersections on the U.S. 23@U.S. 74 corridor in North Carolina; and
- Total crash rates for the US 17 corridor were found to be lower than the 10-year average for 25 signalized conventional intersections in Charlotte, North Carolina, with similar annual average daily traffic.

FHWA published the Restricted Crossing U-turn Informational Guide in 2014 to provide general information, planning techniques, evaluation procedures for assessing safety and operational performance, design guidelines, and principles to be considered for selecting and designing RCUT intersections [73]. It also proposed that RCUTs may not be appropriate at the intersection of two arterials. FDOT has implemented this solution and confirmed another type of RCUT safety effectiveness at signalized intersections to improve pedestrian safety (Figure 2-18) [70].

Figure 2-18. FDOT's innovative RCUT

Source: FDOT [70]

Roundabouts

A modern roundabout, as shown in Figure 2-19, consists of a large, circular, raised island located at the junction of an arterial street and one or more crossing roadways, and it may serve as a replacement for a traffic signal [56, 74]. At roundabouts, vehicles travel in the same direction, eliminating the right-angle and left-turn conflicts commonly found at traditional intersections. Case studies in various states and countries have shown that modern roundabouts offer significantly improved operational and safety features compared to older traffic circles and rotaries [75]. The modern roundabout can:

- Decrease the frequency and severity of pedestrian crashes;
- Decrease the required size of sight triangles for users to have visibility of each other;
- Allow pedestrians to cross one direction of traffic at a time on each section of the roundabout;
- Provide pedestrian refuge; and
- Pedestrians consider only one direction of conflicting traffic at a time.

One of its disadvantages is that pedestrians with vision impairments may have trouble finding crosswalks and determining when/if vehicles have yielded at crosswalks.

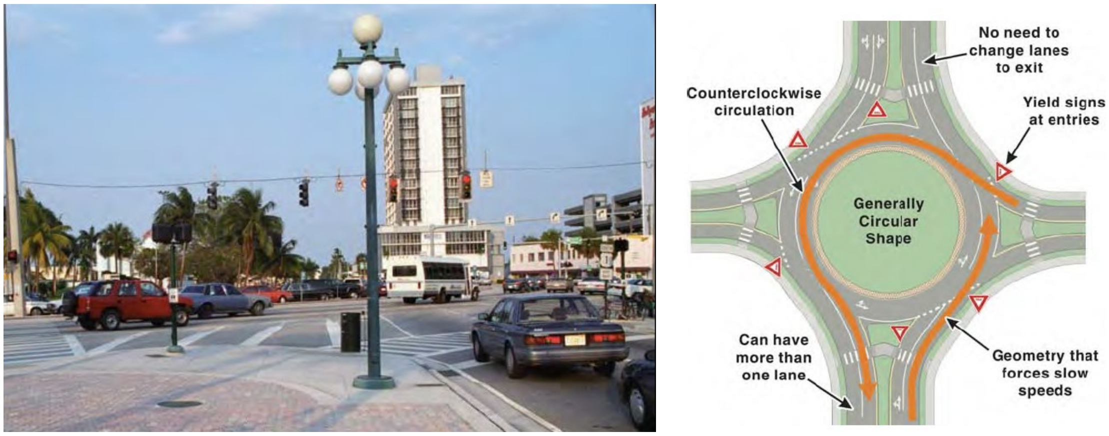


Figure 2-19. An example of a modern roundabout

Source: Roundabouts: An informational guide [75]

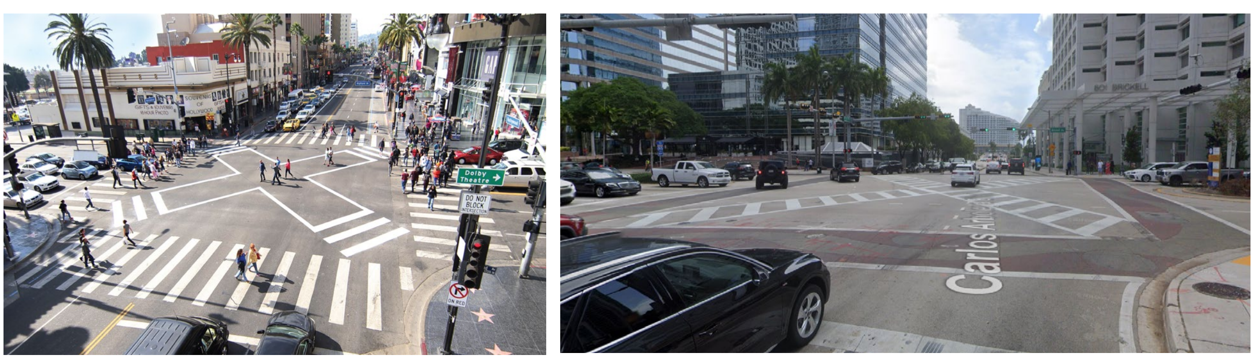
Pedestrian Barriers

Pedestrian barriers, whether permanent or temporary, are intended to direct and safeguard the movements of pedestrians. In areas where crossing the street poses a significant risk of being hit by a car, it may be necessary to limit certain pedestrian crossings. Signs that say "DO NOT CROSS HERE" are often insufficient, so barriers should be utilized to redirect pedestrians away from hazardous crossings [63, 74]. The suitable sites where barriers may be justified at signalized intersections include:

- Locations with high volumes of right-turning vehicles at high speeds, particularly where vulnerable pedestrians such as school-aged children and older adults cross regularly.
- Locations where barriers can direct pedestrians to use an overpass or underpass instead of crossing at street level.

Pedestrian Scramble (or Barnes Dance)

A pedestrian scramble is an exclusive pedestrian phase with no concurring vehicular traffic in any direction, as shown in Figure 2-20 [62].



a. *Source: Los Angeles DOT [76]* b. *Source: FDOT Traffic Engineering Manual [62]*

Figure 2-20. Pedestrian scramble - an exclusive pedestrian phase

Pedestrians are temporarily allowed to cross all intersections in every direction (including diagonally), simultaneously. Walking time is extended for diagonal movement. Ped heads, accessible pedestrian signals, and pavement markings indicate that pedestrians may cross diagonally. Scramble operation:

- Increases pedestrian visibility
- Reduces conflicts between vehicles and pedestrians
- Reduces pedestrian crossing time and exposure
- Reduces the buffer zone between vehicles and pedestrians
- Provides exclusive pedestrian signals

The first implementation was in the City of Los Angeles (LA) in 1956 and was abandoned due to long queues and delays [76]. Pedestrian scrambles have returned to LA and other cities on a larger scale, showing improvements. Post-implementation in November 2015 at Hollywood Blvd and Highland Ave had no pedestrian crashes. Since 1962, New York City installed scrambles, with 635 at T-intersections and 86 at skewed ones. In 2023, the state legislation allowed New York City to implement "scramble" crosswalks outside all of its schools, enabling young children to safely cross the street without the risk of car traffic [77].

The initiative has also been deployed at the SE 8th Street @ Brickell Ave intersection in Miami, Florida. It was found that the implementation increased connectivity and enhanced safety for pedestrians in 2022 [78].

Americans with Disabilities Act (ADA) Design

The newly constructed roadway facilities and most roadway improvements were mandated by the Federal Government to ensure access and mobility for those with physical limitations, based on the *ADA Standards for Accessible Design* [79] and *Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way* [80].

People with physical limitations experienced higher-than-average levels of risk [74]. To meet the mandate by the federal government to ensure access and mobility for those with physical limitations, street designs must accommodate people with disabilities and create a better walking environment for all pedestrians. All new construction or retrofit projects must include [74]:

- Adequate time to cross streets;
- Well-designed curb ramps;
- Limited driveways without steep slopes;
- Sidewalks that are wide and clear of obstructions with minimal cross slope; and
- Eliminating interruptions such as broken or missing sidewalk sections.

Although all streets should be upgraded to be accessible, high-use areas, such as commercial districts, schools, and transit facilities, should be the priorities and should be retrofitted as rapidly as possible. The safety effects of ADA design have been proven by many research studies [74].

Redesign Signalized Intersection

Roadway design has a significant impact on the safety of both driving and pedestrians. Using a safety system approach to analyze signalized intersections is crucial. The Smart Growth website analyzed a real-world example that is from one of the country's most dangerous metro areas to show how our streets are dangerous by design, leading to fatal crashes (Figure 2-21) [81]. The factors causing the safety problems are as follows:

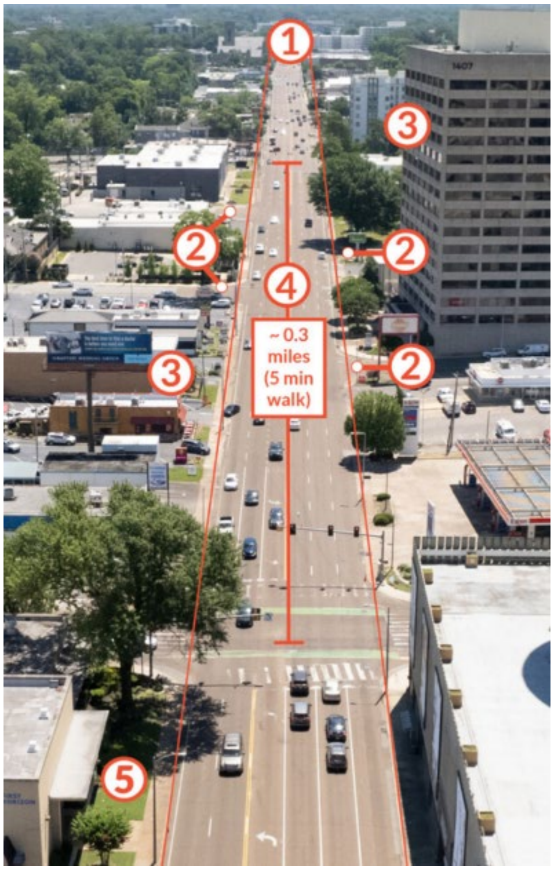


Figure 2-21. Dangerous Union Avenue

Source: Smart Growth America [81]

① Roads are wide and straight with plentiful lanes. Intersections are infrequent or non-signalized. As a result, people feel safe and comfortable driving at higher speeds, even when the posted speed limit is as low as 25-35 mph;

② Other streets regularly intersect Union Ave but lack crosswalks or signals;

③ Numerous destinations cause more people volume;

④ Marked, signalized crosswalks are located too far, at 0.4 miles apart; and

⑤ Sidewalks are narrow with numerous curb cuts for turns and frequent obstructions, no calm design to reduce vehicles' turning speed.

In June 2016, New York State identified the current safety conditions and recommended a distinct set of engineering countermeasures that can be accomplished over the next five years to improve pedestrian safety at signalized intersections in communities outside of New York City. The low-cost improvements and implementation goals are presented in Table 2-2.

Table 2-2. New York State Low-Cost Treatments at Signalized Intersections

Signalized Intersections – Low-Cost Improvements	Implementation Goal
Re-time traffic signals for proper amber and red clearance intervals and proper pedestrian clearance time/intervals.	All urban signalized intersections studied or 50% of urban signalized intersections on state roads.
Re-time traffic signals for better coordination.	Based upon study recommendations.
Install backplates with retroreflective borders.	All urban signalized intersections studied where a structural analysis indicates load capacity is adequate for backplates.
Upgrade existing pedestrian signals to include countdown pedestrian indications at remaining eligible locations.	All urban signalized intersections were studied with a pedestrian signal.
Upgrade existing marked crosswalks to high-visibility: Add high-visibility crosswalks at unmarked signalized intersections.	All urban signalized intersections studied or 50% of urban signalized intersections on state roads. High-visibility crosswalks shall be used at crosswalks traversing the "mainline" and cross streets or commercial driveways of at least three lanes.
Restrict parking at intersections.	Consider restricting parking within 20' of an intersection at locations where it is explicitly allowed.
Evaluate left-turn phasing: Consider protected/permitted left turn phasing and protected only left turn phasing. Consider upgrading permitted phasing from green ball to flashing yellow arrow.	Based upon study recommendations.
APS (Accessible Pedestrian Signal)	Based upon study recommendations. Consider key pedestrian generators such as schools, malls, and transit hubs.
LPI (Leading Pedestrian Interval) + Overhead blank-out "No turn on Red" + Accessible Pedestrian Signal	Based upon study recommendations. Consider locations where there is a history of pedestrians being hit by turning vehicles.

Table 2-2. New York State Low-Cost Treatments at Signalized Intersections (Continued)

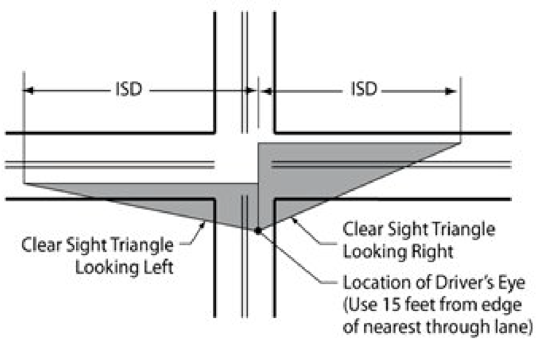
Signalized Intersections – Low-Cost Improvements	Implementation Goal
Install a new pedestrian signal.	Based upon study recommendations. Consider when crossing distances > 40' or > 3 lanes or crossing a state highway. Include countdown, latching pushbuttons, and APS.
Add advanced cross street name signs.	Based upon study recommendations
Add signal ahead signs.	Based on study recommendations.
Use turning vehicle yield to pedestrian signs (R10-15).	Based upon study recommendations.
Add NO TURN ON RED SIGNS (standard or blank-out) with optional plaques (R10-11, R10-30, NYR7-4P, NYR7-5P).	Based upon study recommendations. Evaluate if the existing No Turn On Red is overhead; Install NO TURN ON RED where warranted.
Move regulatory signs overhead.	Regulatory signs are located according to the MUTCD.

Source: New York State [36]

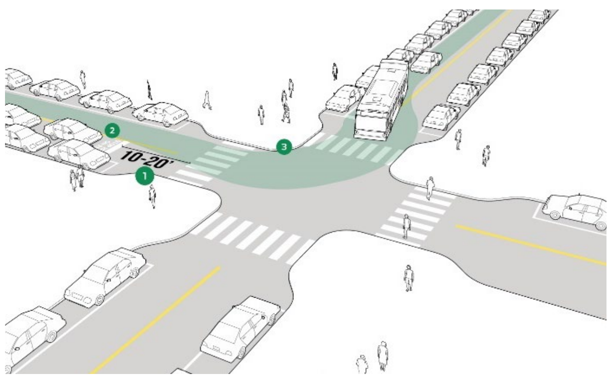
2.2.1.3 Improve sight distance at signalized intersections

Clear Sight Triangles

Based on AASHTO's *A Policy on Geometric Design of Highways and Streets* (2018), intersection sight distance is the distance a motorist can see approaching vehicles before their line of sight is blocked by an obstruction near the intersection (Figure 2-22) [82].



a. Intersection sight triangles
Source: Intersection sight distance [82]



b. Recessed stop line
Source: Transit Street Design Guide [83]

Figure 2-22. Clear sight triangles

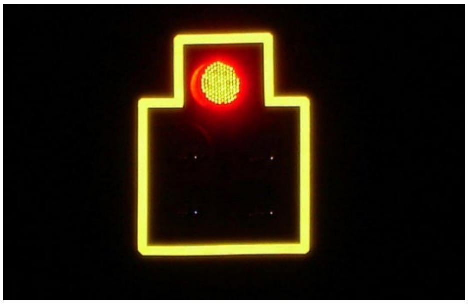
Clear sight triangles must be maintained at signalized intersections with a high occurrence of collisions between vehicles making right turns on red from one street and vehicles traveling straight on the other street, or crashes involving left-turning traffic where landscaped medians or street parking are present.

Signalized intersections with permitted parking on the approaches may present a safety hazard either by blocking sight distance or due to parking maneuvers. Maintaining the landscaped medians at a suitable height and removing/restricting street parking are proven practices [84]. Recessed Yield/Stop lines allow pedestrians and drivers to have a clear view of each other and more time to react. The effectiveness of this measure depends on whether motorists obey the stop line [83].

2.2.1.4 Improve driver awareness of intersections and signal control

Installing signal backplates/retroreflective backplates can improve driver awareness of intersections and signal control. A signal backplate/retroreflective backplate is a yellow retroreflective strip with a minimum width of one inch and a maximum width of three inches that may be placed along the perimeter of the face of a signal backplate to project a rectangular appearance at night [38]. Adding backplates to a traffic signal head could enhance the visibility of the illuminated face of the signal by introducing a background with controlled contrast (Figure 2-23).

Source: FDOT[85]



Source: FHWA [86]

Figure 2-23. Retroreflective borders

The advantages of retroreflective borders are:

- A low cost per unit and contributes to big safety benefits;
- Make the signal heads more visible and noticeable in both daytime and nighttime conditions;
- Enhance traffic signal visibility, conspicuity, and orientation for both older and color vision-deficient drivers; and
- Provide a visible cue for motorists to stop at the intersection ahead during periods of power outages.

According to the Crash Modification Factors Clearinghouse (CMF ID: 1410), the CMF is 0.85 and the CRF is 15% at urban signalized intersections [87]. As of 2014, over half of the state highway agencies in the United States have a policy, specification, or standard for using backplates with retroreflective borders. The Federal Highway Administration (FHWA) has recommended implementing retroreflective backplates as a standard practice for signalized intersections throughout a jurisdiction, based on the safety performance observed in numerous case studies

[88]. This will ensure that the treatment is consistently included in all new construction and modernization projects.

According to the FDOT Design Manual (2024), retroreflective backplate borders are required to be installed on traffic signals for all approaches [63]. There are two methods to meet this requirement for both new and existing signal structures:

- Provide rigid retroreflective backplates for all new signal structures; and
- Flexible retroreflective backplates may be used on existing signal structures following the FDOT Traffic Engineering Manual [62].

2.2.1.5 Improve safety via other infrastructure treatments

The intersection should accommodate the needs of road users with age-related diminished capacities. Elderly pedestrians are the most vulnerable road users. In a proactive response to the pending surge in aging road users, the intersection design should incorporate research findings and treatments to improve the safety of the transportation system for the aging population [84].

Poor crosswalk visibility contributes to pedestrian crashes, which may be caused by poor lighting conditions, obstructions such as parked cars, and horizontal or vertical roadway curvature [89]. On the other hand, strategically placed and well-designed marked crosswalks can enhance pedestrian safety [63]. The FHWA has recommended three main enhancements to increase crosswalk visibility and prevent pedestrian crashes. These enhancements consist of the following:

- High-visibility crosswalks,
- Improved lighting [74], and
- Enhanced signing and reflective pavement markings.

They can be implemented individually or in combination at specific locations as needed.

Marked Crosswalks and Enhancements

Marked crosswalks are desirable at high pedestrian-volume locations to guide pedestrians along a preferred walking path. It is also useful to supplement crosswalk markings with warning signs. In some locations, signs can get "lost" in visual clutter, so care must be taken in placement.

Pedestrians are sensitive to out-of-the-way travel, and reasonable accommodations should be made to make crossings both convenient and at safe locations with adequate visibility. The most effective approach is to combine engineering treatments with enforcement and education.

a. Enhanced by crosswalk materials

It is important to ensure that crosswalks are visible to motorists, particularly at night. Crosswalks should not be slippery or create trip hazards. Even though brick, granite, or cobblestones are aesthetically appealing materials, they are generally not appropriate for crosswalks. The best material today for marking crosswalks is inlay tape, which is installed on new or repaved streets. It is highly reflective, long-lasting, slip-resistant, and does not require maintenance [74]. Although initially more costly, inlay tape is more cost-effective than paint or thermoplastic in the long run. Thermoplastic is also superior to paint, being longer lasting and more visible.

b. Recessed Yield/Stop Lines [74]

At signalized intersections, the vehicle stop line can be moved further back from the pedestrian crosswalk for an improved factor of safety and improved visibility of pedestrians. At some places, the stop line has been moved back by 5 m to 10 m (10 feet to 15 feet) relative to the marked crosswalk with considerable safety benefits for pedestrians (Figure 2-24).

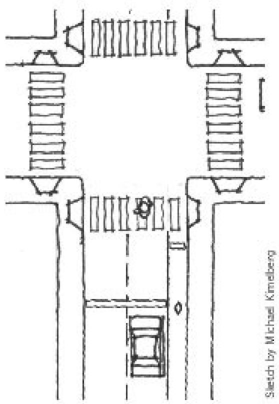


Figure 2-24. Recessed stop line

Source: FHWA [74]

Recessed stop lines improve visibility between pedestrians and drivers, but their effectiveness varies based on motorists' compliance. They are useful for non-signalized crosswalks on multi-lane roads. NYC experiments suggest other signal-related measures are more effective than high-visibility crosswalks in reducing crashes. These measures include increasing the total cycle length, implementing the Barnes Dance, using split phase timing, and installing signals [90]. Increasing cycle length and the Barnes Dance reduce pedestrian crashes, but the Barnes Dance may potentially increase multiple-vehicle crashes. Split phase timing and signal installation reduce pedestrian and vehicle crashes. It is important to balance the benefits of these countermeasures for all types of road users.

Signal Head Visibility

Traffic signal heads are placed overhead, using one signal head per lane. Its benefits are as follows [84]:

- Enhancing the visibility of traffic signals at intersections and clarifying the information they convey, especially for individuals with visual and cognitive impairments associated with aging;

- Physically separating the designated signal from other distractions in the roadside environment;
- The use of overhead signals, particularly with a backplate, offers a notable advantage for older drivers with reduced ability to focus on specific stimuli; and
- Reduction in response time for approaching lanes near intersections.

The total number of crashes has been reduced in locations where overhead signals are positioned above each lane on the approach. This practice is promising and has been regularly implemented in Iowa, Minnesota, Virginia, and the cities of Las Vegas, Nevada, and Grand Rapids, Michigan, among others [84].

Intersection Lighting Improvements

According to the FHWA Lighting Handbook (2023) [91], 25% of vehicle miles traveled (VMT) occur at night, and the number of fatal crashes occurring in daylight is about the same as those occurring in darkness. As a result, the nighttime fatality rate (per VMT) is three times the daytime rate. Based on the Signal Four Analytics [92], there were 344 intersection-related pedestrian fatalities at night and 143 during the daytime in Florida in the past three years (2021-2023), as shown in Figure 2-25. Using the VMT data from the FHWA Light Handbook, this means that the nighttime intersection-related pedestrian fatality rate (per VMT) was 7.22 times the daytime rate.

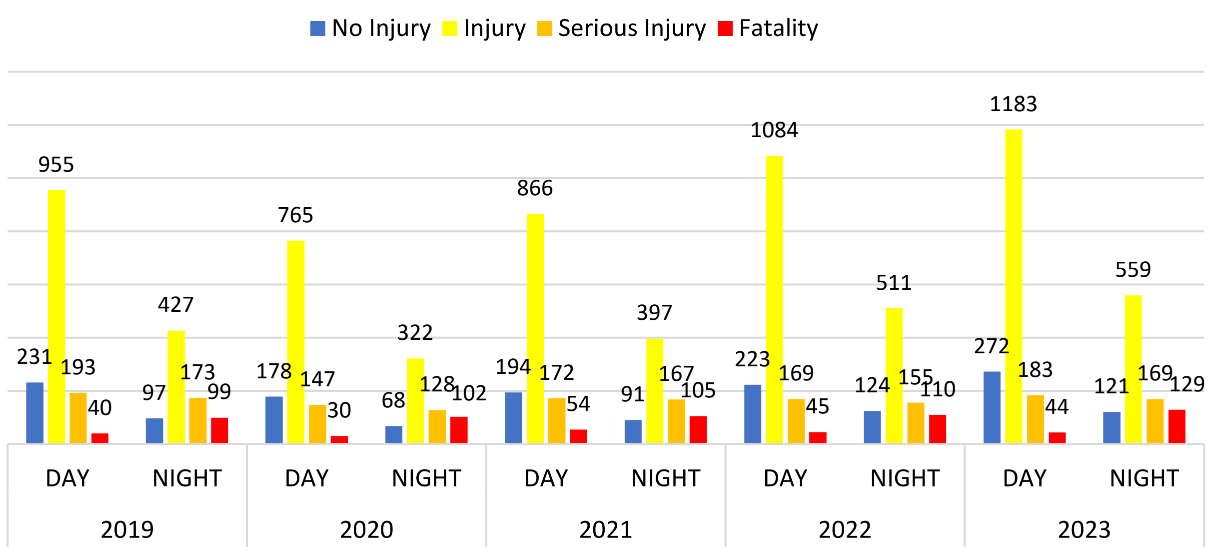


Figure 2-25. Historical intersection-related pedestrian crash severity in Florida (day and night)

In 2024, the Florida Department of Highway Safety and Motor Vehicles reported that the risk of pedestrian crashes increases when Daylight Saving Time ends and it gets darker earlier [93]. The majority of hit-and-run fatalities occur at night or during low-light hours.

Lighting improvement is one of the significant FHWA-proven safety countermeasures [94]. Proper lighting and placement can improve the environment and also promote comfort and safety. Pedestrians often mistakenly believe that drivers can see them at night, as they are deceived by their ability to see the approaching headlights. However, without adequate overhead lighting at nighttime, vehicles traveling at higher speeds may not be able to stop when a hazard or change in the road ahead becomes visible by the headlights.

It is important to increase visibility at intersections and pedestrian crossings at nighttime, as different modes of travel intersect at these locations, given the high pedestrian crash rates at night. Agencies should consider providing lighting at intersections, considering factors such as a history of nighttime crashes, traffic volume, the number of non-motorized users, the presence of crosswalks and raised medians, and the presence of transit stops and boarding volumes. The safety benefits are as follows:

Lighting can reduce crashes up to:

- 42% for night-injury pedestrian crashes at intersections (CMF ID: 436, 433, 192) [95]; and
- 33-38% for nighttime crashes at rural and urban intersections (CMF ID: 2376) [96].

The CUTR team has developed an Advanced Lighting Measurement System (ALMS) [97] and data analysis tool (http://its.cutr.usf.edu/lita/v5.html). The ALMS provides a low-cost and time-effective solution to collect high-resolution lighting data for a large-scale roadway network. A computer tool developed on the ArcGIS web-GIS platform provides core functions for lighting pattern diagnosis, nighttime crash risk prediction, and data visualization.

Modern lighting technology has also shown more potential to address the problems (Figure 2-26) [94]:

- Modern lighting technology has enabled more precise control of lighting intensity, improving both energy efficiency and user experience, which provides minimal excessive light affecting the nighttime sky or spilling over to adjacent properties.
- Most new lighting installations provide breakaway features, which make the light poles break in a consistent, predictable fashion, regardless of the vehicle's angle of impact, thus saving lives and reducing property damage.
- The new lighting installations are fully shielded to reduce the adverse effects on the environment.
- The lighting system is placed far enough from the roadway to reduce the probability and/or severity of fixed-object crashes.

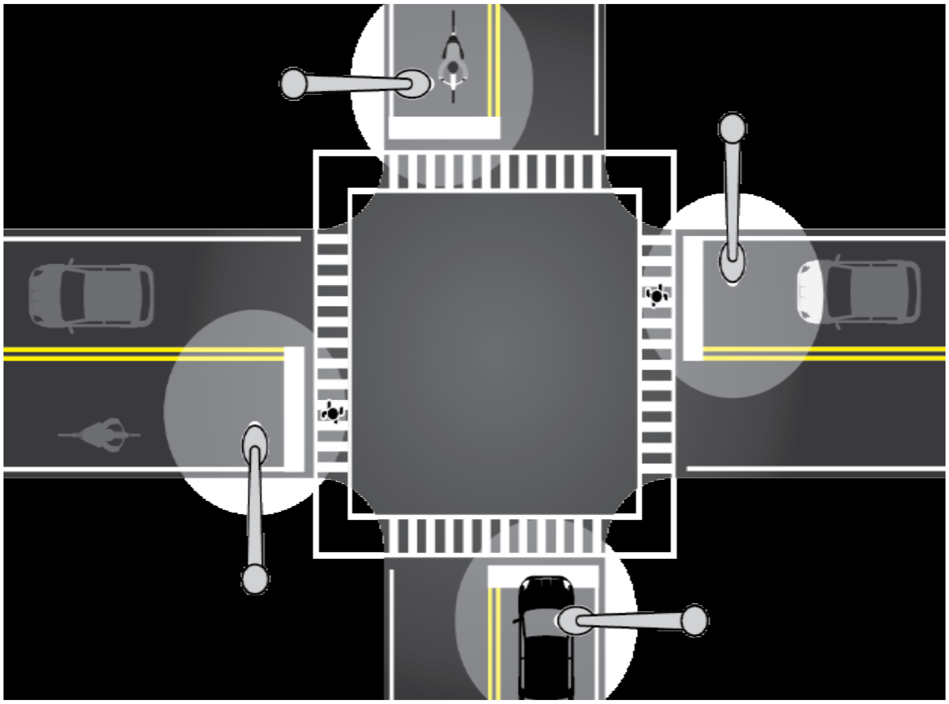


Figure 2-26. Modern lighting technology

Source: FHWA [94]

School Zone Improvements

Various roadway improvements that can be utilized to improve the safety and mobility of children in school zones are as follows [74]:

- Well-trained adult crossing guards help children safely cross streets;
- Provide sidewalks or separated walkways and paths for a safe trip from home to school on foot;
- Develop adult crossing guard training and supervision programs, and provide them with a bright orange safety vest and a STOP paddle;
- Police enforcement in school zones may be necessary where drivers are speeding or not yielding to children in crosswalks;
- Parking prohibitions near intersections and crosswalks near schools;
- Increase child supervision;
- Use signs and markings, such as the school warning sign and SPEED LIMIT 25 MPH WHEN FLASHING;
- Schools should develop "safe route to school" plans and work with local agencies to identify and correct problem areas; and
- Marked crosswalks can help guide children to the best route to school.

Children lack the skills, physical ability, and experience for safe street crossings. By ages seven to nine, most can cross safely but remain easily distracted. School crossing guards play a vital role in ensuring safe crossings, serving as role models, and assisting children in developing street skills and behavior. Basic standards and guidance for supervision of school crossings by adult crossing guards are provided in the MUTCD 11th Edition [9].

At signalized intersections, crossing guards choose appropriate traffic gaps. Jurisdictions should establish policies for crossing guard qualifications, selection, and training. Florida has developed the Florida School Crossing Guard Training Guideline [98] in 1992 and updated it in 2023. It provides information on trainer training, specific guidelines for training, certifying and supervising crossing guards, a training curriculum, and information resources.

Connected Vehicles

Connected vehicle technology enables cars, buses, trucks, trains, roads, and roadside infrastructure, as well as other devices such as cellular telephones, to communicate with one another [9]. The MUTCD 2023 classifies Connected Vehicle Technology into two types as follows:

- Vehicle-to-vehicle (V2V): Connected vehicle technology enabling vehicles to communicate with each other; and
- Vehicle-to-infrastructure (V2I): Connected vehicle technology enabling vehicles to communicate with infrastructure.

Connected vehicle technology allows equipped vehicles on the road to be aware of the location and status of other nearby equipped vehicles or devices. Road users can receive notifications and alerts of dangerous situations, such as a vehicle about to have a conflict with a pedestrian at an intersection (Figure 2-27).

Figure 2-27. Connect vehicles and pedestrians at signalized intersection

Source: U.S. DOT [99]

Since 2015, USDOT has implemented the Connected Vehicle Pilot Deployment Program (CVPDP) to integrate connected vehicle and mobile device technologies in innovative and cost-effective ways. The program selected three pilot sites, including the Wyoming Pilot (WYDOT), New York City Pilot (NYCDOT), and Tampa Pilot (THEA, Tampa-Hillsboro Expressway Authority). It was found the CVPDP improved pedestrian safety. Two of the three sites with specific safety evaluations for pedestrian and intersection deployment are listed in Table 2-3.

Table 2-3. CVPDP Evaluation

Safety Application	Description and Safety Evaluation	Agency
Pedestrian Collision Warning (V2I) [100]	• Warns drivers of the presence of pedestrians in a crosswalk. • Issued a total of 12 alerts (March 2019 - June 2020). • Difficult to determine the crash avoidance effectiveness or changes in driver performance, due to limited samples.	THEA
Pedestrian in Crosswalk Warning (V2I) [101, 102]	• Helps drivers avoid pedestrian crashes at intersections. • Issued a total of 29 alerts during the yearlong deployment. • Conflicts between vehicles and pedestrians cannot be obtained because of their function. **Proposals:** • Can be more useful when the driver's sight is blocked, or in places with complicated intersection geometries or poor visibility conditions.	NYCDOT
Mobile Accessible Pedestrian Signal System (I2P)[1] [101, 102]	• Provides audible crosswalk signal information to visually-impaired drivers. • All the participants agreed that the information provided by the application is helpful, with 67% strongly agreeing and 33% somewhat agreeing. • 50% of the participants felt much safer when using the application in comparison to not using it, 33% felt slightly safer, and the remaining 17% of the participants retained the same level of perceived safety. **Further expectations:** • Suggested testing at more complex geometry intersections and locations with LPI signals. • Integrate it with existing accessible or navigation application.	NYCDOT

Note: 1 Infrastructure for pedestrians

2.2.1.6 Improve access management near signalized intersections

Access management is the coordinated planning, regulation, and design of access between roadways and land development [103, 104]. Previous studies have indicated that managing access on the roadway can positively impact traffic flow and safety [17], which is supported by recent research conducted by the CUTR team in 2024 for FDOT [18].

Treatments to improve access management near intersections (within 250 ft upstream or downstream) include changes in infrastructure, geometry, or signing to close or combine driveways, provide turn lanes, or restrict or relocate turn movements [17]. The objects of access management are accomplished by applying the following principles:

- Restrict direct access to main roads;
- Encourage a hierarchy of intersections;
- Place traffic signals to prioritize through movements;
- Preserve the functional space of intersections;
- Limit the number of conflict points;
- Separate conflict areas;
- Remove turning vehicles from through-traffic lanes;
- Use non-traversable medians to control left-turn movements; and
- Provide a supporting street and circulation system.

There are several references available for more information on access management, including AASHTO's A Policy on Geometric Design of Highways and Streets [82]; NCHRP 420: Impacts of Access Management Techniques [105]; ITE's Transportation and Land Development [106]; TRB's Access Management Manual [103], and FDOT's Multimodal Access Management Guidebook [104]. The issues related to access management are summarized in Table 2-4.

Table 2-4. Issues Related to Providing Access Management

Characteristic	Potential Benefits	Potential Liabilities
Safety	Few access points generally reduce crashes along a corridor.	The horizontal and vertical features for turning restriction may contribute to an increase in fixed object crashes.
Operations	Few access points generally increase the level of service and capacity.	The overall capacity of the signalized intersection may be reduced due to an increased number of U-turns. The weaving may increase due to turning left.
Multimodal	Fewer access points reduce the number of potential conflicts for pedestrians.	The operating speed along the arterial may increase, which increases pedestrian crash frequency and severity.

Source: FHWA-SA-13-027 [17]

2.2.1.7 Increase Pavement Friction

Maintaining adequate pavement friction is crucial for reducing crashes and injuries. Higher friction decreases stopping distance, allowing motorists to stop before collisions. Even if crashes occur, reduced speed from higher friction can mitigate injury severity. In high-speed, low-visibility, or poor road conditions, friction is vital for preventing intersection crashes and protecting vulnerable road users.

High friction surface treatment (HFST) is an innovative pavement material that dramatically enhances the road surface's frictional characteristics with a long-lasting service life (10 years). FDOT District 7 is extending the application of HFST at intersections along high-traffic corridors to reduce intersection crashes, especially for pedestrians (Figure 2-28). The project team has evaluated the safety effectiveness of HFST at signalized intersections in Florida urban areas [107]. Vehicles' stopping behaviors with and without HFST were compared in before-after studies (Figure 2-29). It was found that HFST reduced improper stopping rates and crosswalk-intrusion behaviors for all scenarios (daytime, nighttime, dry surface, and rainy weather).

Figure 2-28. HFST construction and field photo at Hillsborough Ave @ N Central Ave, Tampa, Florida

Source: USF CUTR [107]

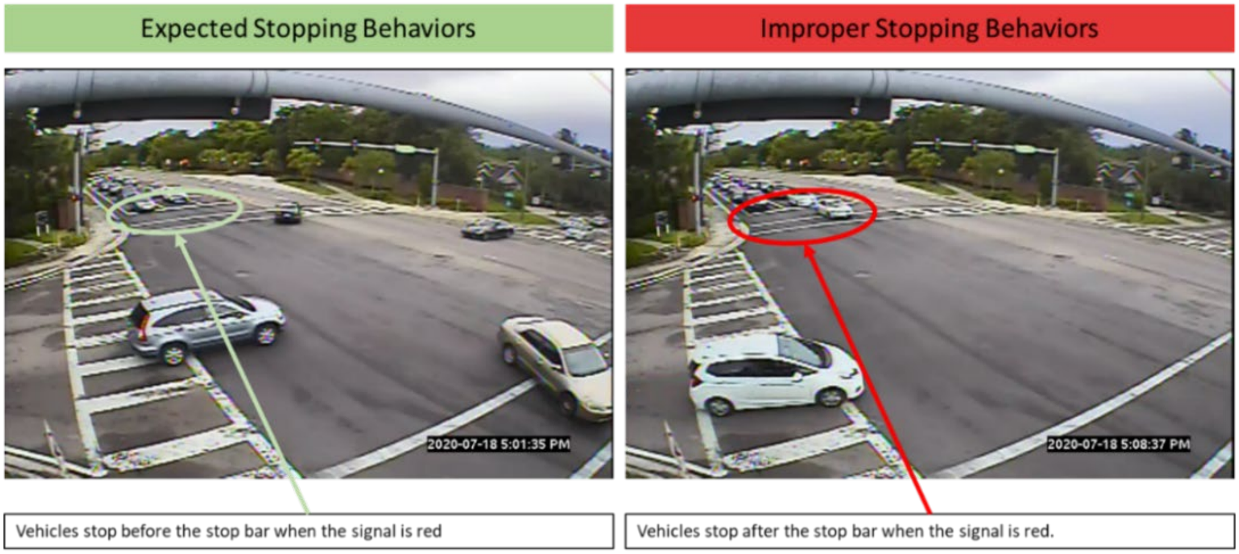


Figure 2-29. Stopping behaviors at signalized intersections

Source: CUTR [107]

2.2.2 Best Law Enforcement Practices and Effectiveness

Developing and implementing selective enforcement is crucial in reducing the frequency and severity of pedestrian and turning vehicle crashes at signalized intersections. Without traffic law enforcement, there will be an increase in crash frequency and severity, and fewer people will choose to walk [74]. A summary of several factors that effective law enforcement should take into consideration according to NHTSA's (National Highway Safety Administration) "*Pedestrian Safety Enforcement Operations: A How-To-Guide"* [108] is discussed next.

2.2.2.1 Law Enforcement Candidate Locations

Law Enforcement implementation faces numerous challenges because police departments are constantly pressured to prioritize "more serious" crimes. Enforcing pedestrian laws may not be a top priority for many departments. Therefore, FHWA recommended that the most appropriate pedestrian pilot projects should prioritize areas with school children, senior citizens, and strong community support [74]. Speeding enforcement initiatives should be at candidate locations where speeding motorists occasionally hit pedestrians and where residents are asking for better enforcement. The key is to develop enforcement activities as public demand and support grows.

Law enforcement should focus on signalized intersections with a high frequency of crashes related to drivers either being unaware of (or refusing to obey) traffic laws and regulations that impact traffic safety [38]. The Seattle Enforcement Program targeted key intersections based on reported crashes, citizen complaints, and police observations. In addition, it is beneficial to conduct periodic site evaluations before and after enforcement to assess how the program affects driver behavior in yielding to pedestrians.

2.2.2.2 Automated enforcement for speeding and red light running

According to global roadway safety experts and engineering practices, speed control is considered one of the most crucial methods for decreasing fatalities and severe injuries [109]. Roadway agencies should set safe, consistent speed limits at signalized intersections, a proven FHWA safety measure for safer streets [109]. Cities like New York, Washington, Seattle, and Minneapolis have reduced local speed limits to curb fatalities and injuries, often requiring state legislature approval. FHWA promotes Expert Systems tools and the Safe System Approach for non-statutory limits, based on MUTCD engineering studies.

Speeding and red light running significantly contribute to fatal crashes at intersections [110]. For the enforcement program, cameras are placed at intersections identified as having a high incidence of speeding or red light running, and/or associated crashes (Figure 2-30).

Figure 2-30. Enforcement cameras to identify red-light runners

Source: Brian Chandler [17]

According to the assessment of more than 350 jurisdictions that have implemented or previously implemented automated enforcement programs, NCHRP Report 729 offers the most effective strategies and lessons learned for the successful implementation and operation of current and future programs [110]. Key elements include:

- Having a solid engineering basis;
- Using a multidisciplinary method;
- Regularly monitoring and evaluating the program; and
- Ensuring transparency to the public and media throughout the entire program.

The FHWA-SA-13-027 report stated that the enforcement reduced right-turning vehicle/pedestrian crashes [17]. The NCHRP Report 729 also confirmed the safety performance as follows:

- In Portland, Oregon, enforcement resulted in a reduction of 69%–93% in red-light running violations.
- In Virginia Beach, Virginia, it reduced red light violations by more than 69% since the activation of red-light cameras over 13 months.
- In San Diego, California, it revealed an 8% decrease in crashes caused by red-light running and a 16% decrease in crashes related to red-light running at intersections with cameras.
- The overall impact on violations and crashes related to a red-light enforcement program needs further study.
- In Washington, DC, the increased police enforcement increased pedestrian safety. Additionally, DC has seen a significant drop in the number of annual fatalities, both for vehicle occupants and pedestrians over the last decade, indicating that crash severity has

been reduced through both enforcement and engineering measures. However, because many other factors can be involved, it's difficult to definitively tie those statistics to enforcement operations only.

2.2.3 Best Education Practices and Effectiveness

Education can make a difference. States and cities that have active pedestrian programs incorporating strong educational components have reported declines in fatality rates [74]. The following are various education programs that have been proven to improve roadway safety.

- The FHWA's Intersection Safety Strategies recommend providing public information and education about signalized intersections where there is a high frequency of crashes caused by drivers who are either unaware of or refuse to obey traffic laws and regulations that affect traffic safety, particularly red-light running, speeding, and failure to yield to pedestrians[38].
- Regarding pedestrian safety, FHWA has developed a comprehensive education program [74]. The pedestrian safety education program is outlined as follows:
    - ✓ Implementing an education program that targets both pedestrians and motorists is one of the most cost-effective measures to improve safety and promote walking in the community. The education program should reach all ages and types of pedestrians and collaborate with community efforts. It should reach out to adults, teens, and special audiences. Training and other educational activities should also focus on the specific needs of individuals with disabilities and seniors.
    - ✓ The education program should be ongoing education to ensure that the education has continuity and depth. It means the traffic education program has a full range of curricula. Consider implementing a comprehensive traffic education program that covers grades K through 6, or even better, grades K through 10 or 12. At a minimum, provide three years of pedestrian education.
    - ✓ The education program for drivers could use materials created by NHTSA, FHWA, and the American Association of Retired Persons. These materials provide essential information for drivers, including seniors, to prevent crashes with pedestrians at signalized intersections. Furthermore, there are courses and materials available specifically for professional truck drivers, buses, school buses, and delivery vans.
    - ✓ Educate motorists via materials developed by NHTSA, FHWA, and the American Association of Retired Persons, which include information a driver needs to know to avoid a crash with a pedestrian at signalized intersections. In addition, the material includes courses and materials designed for professional truck drivers, buses, school buses, and delivery vans.

- ✓ Reaching professionals - educating teachers, designers, and enforcement personnel.
- ✓ Cooperate with all agencies, individuals, and organizations.
- ✓ Making time for education in schools.
- ✓ Using a variety of media is one technique.
- ✓ Providing people with active, skill-based learning via first-hand experience.
- ✓ Education with other E's of engineering, enforcement, and encouragement.

2.3 Innovative Technologies and Methods to Eliminate Conflicts between Pedestrians and Turning Vehicles

This section identified innovative technologies and methods to reduce or eliminate conflicts between pedestrians and turning vehicles, including Leading Pedestrian Interval (LPI), automated pedestrian detection, application of "No Turn on Red" blank-out signs, and advanced traffic signal control operations to allow omission of permitted left turns during protected and permitted left-turn operations.

2.3.1 Leading Pedestrian Interval (LPI)

Leading Pedestrian Intervals (LPI) are pedestrian traffic signals that display a WALK sign three to seven seconds before vehicles are allowed to turn right or left [89]. Longer WALK intervals generally improve pedestrian service and encourage better compliance with signals. It is one of the most efficient and low-cost measures to decrease the number of pedestrian deaths and severe injuries in traffic accidents [89, 111]. LPIs enhance safety by:

- Improving the visibility of pedestrians to drivers making turns across the crosswalk
- Reducing conflicts between pedestrians and vehicles
- Increasing the likelihood of drivers yielding to pedestrians
- Enhanced safety for pedestrians who may be slower to start into the intersection

LPIs are critical at intersections where there is heavy right or left-turning traffic, as this creates consistent conflicts and safety concerns between vehicles and pedestrians. This advanced phase approach has been used successfully in several places. In the 1980s, LPIs were being used in New York City. The New York DOT analyzed crash rates at 26 locations with LPIs, by comparing the available ten-year crash data (five-year "before" and five-year "after") in the research. The results indicated that LPIs had a positive effect on pedestrian safety, which was similar to the Florida study findings [112]. Fayish et al. [113] also surveyed and proved the safety effect of the implementation of the LPI at ten signalized intersections in Pennsylvania, which showed to reduce pedestrian-vehicle collisions by as much as 60% at treated intersections.

The developed CMF (CMF ID: 9918) suggested that LPIs reduced 13 pedestrian-vehicle crashes with a potential B/C ratio range of 1:207-1:517 at intersections, according to the crash data from 2009 to 2015 before and after LPI treatment at 105 sites in Chicago, Illinois; New York City, New York; Charlotte, North Carolina; and Toronto, Ontario [57]. In June 2016, LPI + overhead blank-out “No turn on Red” + Accessible Pedestrian Signal were listed as a low-cost improvement for signalized intersections in the State of New York in their next five-year plan [36].

The Urban Street Design Guide [44] describes various strategies to accommodate pedestrians on high-risk crosswalks at major intersections (Figure 2-31). The listed strategies (including the LPI) are as follows:

- Use LPI to give pedestrians a head start entering the crosswalk.
- Add pedestrian safety islands where possible.
- Eliminate channelized right turn lanes to slow turning speeds.
- Create self-enforcing yielding to pedestrians.
- Installing a curb extension and tight corner radii at intersections to improve the visibility of pedestrians and reduce pedestrians' exposure time.

Figure 2-31. LPI application at a major signalized intersection

Source: Urban Street Design Guide [44]

Van Houten et al. [112] conducted the field evaluation of an LPI signal phase at three urban signalized intersections in downtown St. Petersburg, Florida. The research indicated that the introduction of the LPI virtually eliminated conflicts for pedestrians departing during the start of the WALK interval.

USF CUTR developed Florida statewide guidelines for implementing LPIs in 2017, based on previous research, surveys, interviews, telephone conferences, and pilot deployment initiatives

[114][114]. The deployment initiatives showed that LPIs effectively reduced vehicle-pedestrian conflicts at signalized intersections. The NO TURN ON RED signs (static or blank-out) or TURNING VEHICLES YIELD TO PEDESTRIANS signs, along with an LPI implementation, were recommended due to mixed results of drivers' yielding behaviors in this pilot LPI implementation. The 2019 FDOT Transportation Symposium: Traffic Engineering Manual Update reported that LPIs led to a 60% reduction in pedestrian-vehicle crashes at intersections [115].

2.3.2 No Turn on Red Sign (Blank-out Sign)

Upon detecting a crossing pedestrian, either by push button or by automated pedestrian detection, the advanced technology would activate a "No Turn on Red" Blank-out sign to eliminate the conflict of a stopped right-turning vehicle from crossing the crosswalk. It is displayed for the period for one or more portion(s) of a particular cycle of the traffic control signal during which the prohibition is applicable [9], shown in Figure 2-32. Traditionally, there has been a low level of compliance with static "No Right Turn on Red" signs.

Figure 2-32. Site with "No Turn on Red" blank-out sign

Source: FDOT BDV25-977-43 [12]

In 1986, a report recommended the addition of the red ball "No Turn on Red" sign to the Manual on Uniform Traffic Control Devices, as it was found to be more effective than the standard black and white "No Turn on Red" sign [116].

The USF CUTR team conducted a thorough qualitative and quantitative analysis of the interaction between drivers and pedestrian features in Florida in 2019 [12]. The pilot implementation of "No Turn on Red" blank-out signs demonstrated their effectiveness in improving safety by increasing driver compliance and reducing unnecessary vehicle delays at signalized intersections. The signs were only displayed, when necessary, with a black display at all other times. Their performances were as follows:

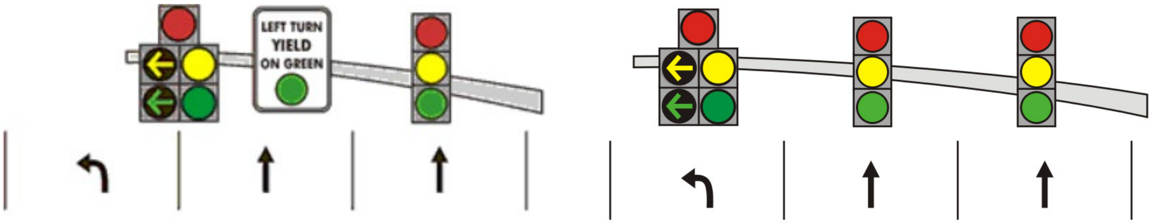
- After implementing the "No Turn on Red" blank-out signs, the driver compliance rate was 77.5%, lower than the 90.9% compliance rate with static signs. While blank-out signs don't achieve as high a compliance, they offer the advantage of activating only when pedestrians press buttons, reducing unnecessary vehicle delays.
- Based on the analysis of driver behaviors and compliance before and after the implementation, it is recommended that the signs be implemented on a schedule based on the time of day to coincide with higher pedestrian activity.
- The research team suggests that regular law enforcement at these locations is likely to improve driver compliance rates. The analysis also showed that a combination of implementing pedestrian signage and conducting education outreach can achieve the highest driver compliance.

In 2005, the Alabama DOT stated that Blank-out signs may vary depending on the viewing angle. This can be problematic if the head sways due to wind or is not properly aligned, causing it to appear to "blank out" when the viewing angle is too large [117].

Meanwhile, a research project (2022-2024) by the Institute for Transportation at Iowa State University aimed to better understand the compliance rates of static and dynamic “No Turn on Red” signs, their maintenance requirements, and to develop recommendations for their placement [118].

2.3.3 Omission of Permitted Left Turns During Protected and Permissive Left-turn Operations

A combination of protected and permissive left-turn phases is referred to as protected-permissive (PPLT) or permissive-protected left-turn operation [17]. Figure 2-33 shows a typical five-section signal head and associated signage arrangement that implements this type of phasing. Other configurations can be found in the MUTCD.



a. Using a five-section head located directly above the lane line that separates the exclusive through and exclusive left-turn lane, along with an accompanying sign

b. Using a five-section signal head located directly above the exclusive left-turn lane

Figure 2-33. Possible signal head and signing arrangement for protected and permissive phasing

Source: FHWA [17]

However, this type of 5-section signal may create a potential “Yellow Trap”, as shown in Figure 2-34.

This “Yellow Trap” happens when a driver enters an intersection on a green circular signal and waits for a gap in oncoming traffic before making a left turn. This is a legal and common practice in many places. While waiting, the driver's signal turns yellow. To exit the intersection before the signal turns red, the driver assumes that oncoming traffic also has a yellow signal and will slow down and stop. However, the driver is then hit by an oncoming vehicle because the oncoming traffic still had a green signal [119].

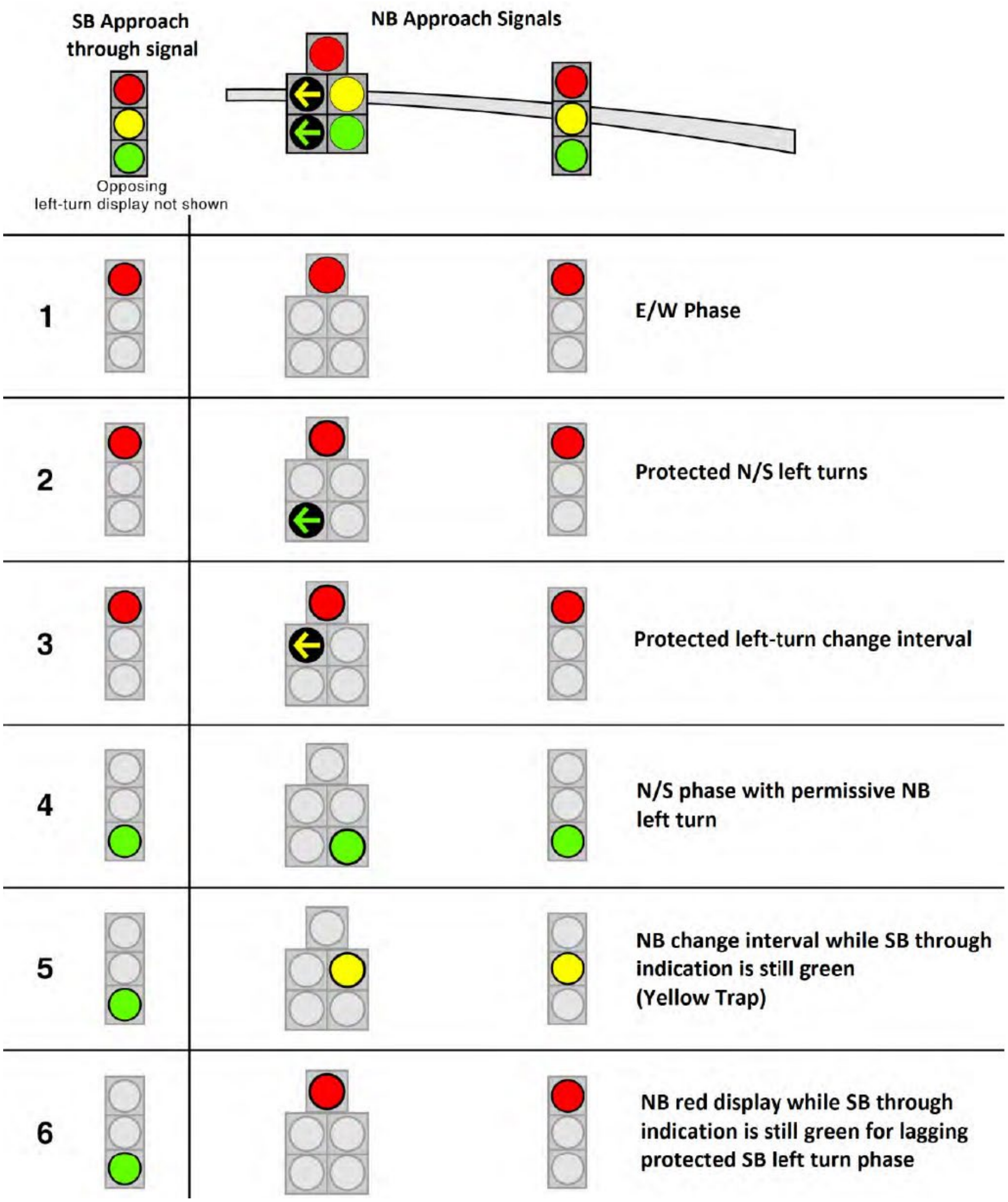
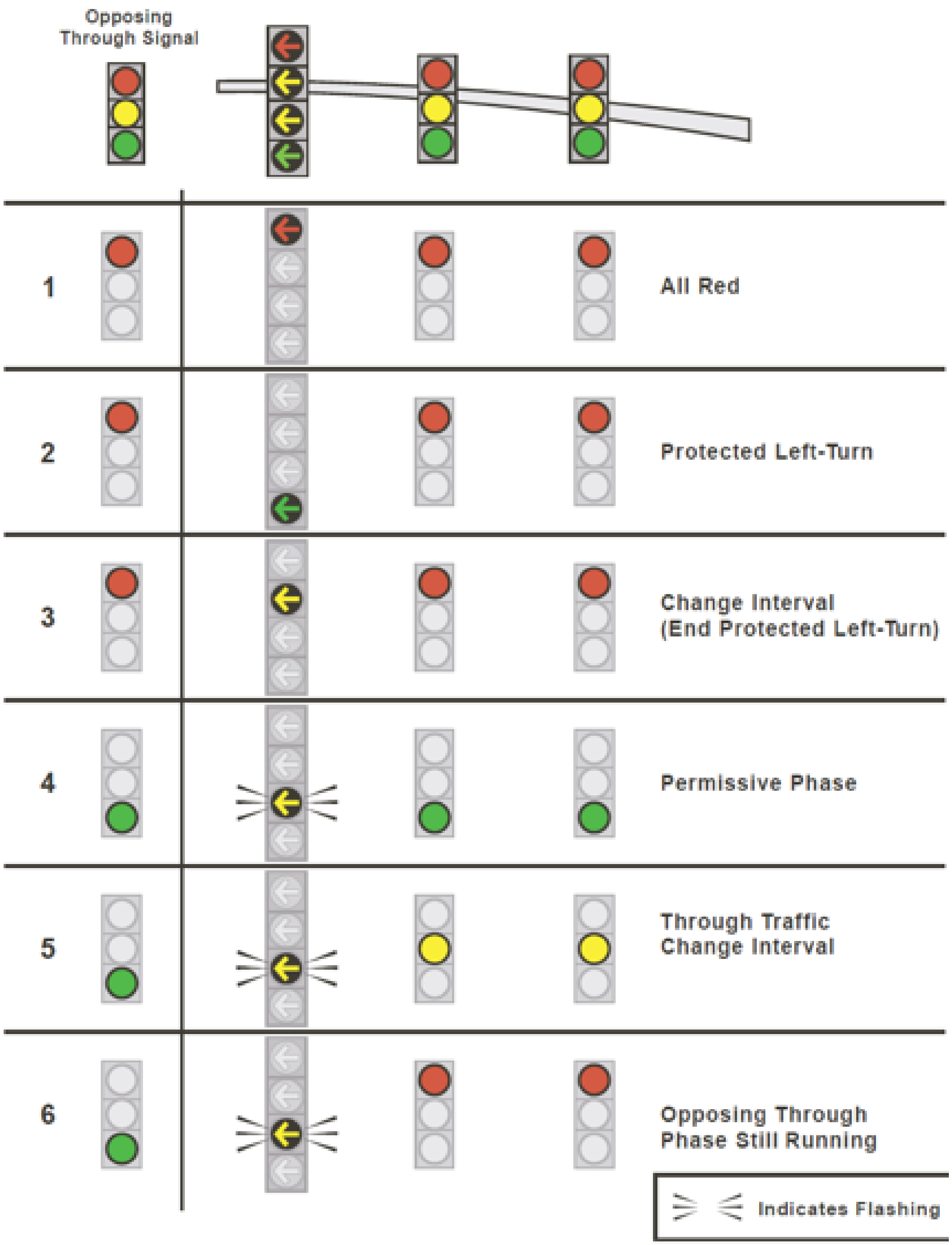


Figure 2-34. Illustration of the yellow trap

Source: FHWA Signalized Intersection Guide [17]

According to previous research and field tests, the 2019 MUTCD has approved the use of FLASHING YELLOW ARROW (FYA) for the permissive left-turn movement to eliminate the "Yellow Trap" situation. Figure 2-35 shows the FLASHING YELLOW ARROW logical link to eliminate the "Yellow Trap"[127].



s

Figure 2-35. Flashing yellow arrow logical link eliminate the "Yellow Trap"

Source: NCHRP report, No. 493 [127]

The FYA is a feature in traffic signal control that provides a flashing yellow arrow to indicate that drivers can turn left after yielding to oncoming traffic and pedestrians. An animation of this traffic control is available at https://www.youtube.com/watch?v=KPKjcPI5Sko [120]. The signal timing sequence may allow the permissive left-turn phase (FYA) to continue until the opposing traffic's through phase ends, even if the adjacent through phase has already ended. However, there are many applications of typical five-section signal heads and associated signage arrangements in Florida (Figure 2-34).

During the permissive left-turn movement in Phase 5 in Figure 2-35, the left-turn vehicles must look for a gap in the oncoming traffic to make their turn, where pedestrians also have the right of way to cross. The heavy demands of making permissive left turns can cause drivers to overlook certain tasks and be unable to complete other tasks, such as scanning the roadway for potential pedestrians [11]. This may result in pedestrian and left-turning vehicle crashes, which also occur in the flashing left-turn YELLOW ARROW phase (Phases 4, 5, and 6) in Figure 2-36.

According to the 2024 FDOT Traffic Engineering Manual [62], at locations where a history of drivers failing to yield to pedestrians during permissive left-turn phases has been documented, the following countermeasures may be implemented:

- Omit the FYA when the pedestrian phase is activated; and
- Implement leading LPI following Traffic Engineering Manual 3.11.

When a pedestrian call is detected during a phase with FYA, there are two possible outcomes [129]. If time remains in the through phase, the FYA will terminate early, or the pedestrian phase will be served in the next cycle without FYA. This approach ensures that pedestrians are prioritized when present, while still allowing efficient traffic flow when no pedestrians are waiting.

The implementation of omitting FYA is the following [121]:

- FYA can be programmed with a negative pedestrian condition or a "not pedestrian" condition for traffic control.
- If FYA is on and a pedestrian call is received, the pedestrian will have to wait. If there is still time in the through phase, the FYA will terminate early or the pedestrian phase will be served in the next cycle without FYA.

Omitting FYA during pedestrian phases can enhance safety by guaranteeing that pedestrians are given priority. However, it is essential to maintain a balance with the overall efficiency of traffic flow at signalized intersections. The developed CMFs for North Carolina-specific intersections where protected-only left turn signals were converted to PPLT operation show that overall, safety decreased slightly at the intersections deploying FYA for PPLT. Therefore, an Excel-based simulation tool was developed to recommend protected-only left turn phasing based on "conflict-point SPFs" and conflicting traffic volumes. Alaska DOT allowed permissive phasing during off-peak times when the protected-only criteria were not met [122].

2.3.4 Automated Pedestrian Detection (APD) Technology

Automated pedestrian detection refers to a system or technology's ability to detect and identify pedestrians in real-time or automatically. According to the FHWA Traffic Control Handbook [123], inductive loops, radar, infrared, ultrasonic, and video processing are some of the most used technologies to detect vehicles and/pr pedestrians. The functionality of those technologies is constantly improving as technology advances. Those advanced technologies can help improve road safety by providing extra pedestrian protection.

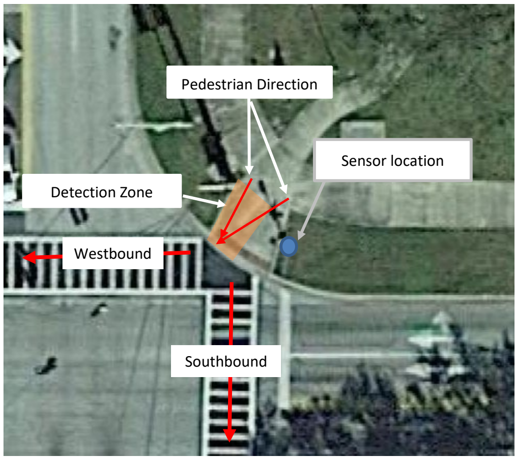
According to previous studies, each sensor and detection technology used for pedestrian detection has its strengths and weaknesses in terms of accuracy, cost, installation and maintenance requirements, liability, and accessibility. In the UK, pedestrians are requested to press a button to call the WALK signal and then use the on-crossing pedestrian detector to provide an extension to the pedestrian clearance period while pedestrians are still on the crossing. In the United States (U.S.), APD devices are used to detect when a pedestrian is waiting at a crosswalk and sends a signal to the traffic controller to switch to a "WALK" phase [56]. Some APD field applications and performance at signalized intersections are presented in Table 2-5 and Figure 2-36.

a. Temple and San Pedro (Los Angeles, CA) *b.* Crittenden and Lattimore (Rochester, NY)

Source: FHWA-RD-00-097 [124]

Figure 2-36. APD applications at signalized intersections

c. Central and Earll (Phoenix, AZ)
Source: FHWA-RD-00-097 [117]



d. USF Tampa campus
Source: USF, CUTR [125]

Figure 2-36. APD applications at signalized intersections (Continued)

Table 2-5. APD Applications at Signalized Intersections

Time	Country	Highlights
2001 [117]	Phoenix, AZ	• Microwave detector **Functionality:** • Detected pedestrians who arrived in the queuing area at the curb. **Advantages:** • An overall 24% increase in the number of pedestrians who began to cross during the Walk signal; and an 81% decrease overall in the number of pedestrians beginning to cross during the DON'T WALK signal. • Pedestrian performance can vary widely across sites. • Decreased the conflict number experienced by pedestrians while crossing. **Disadvantages:** • Occasionally falsely detected slow-moving, right-turning vehicles next to the pedestrian detection zone. • The heavy rain caused the sensor to malfunction. • Cannot detect pedestrians outside of the detection zone.

Table 2-5. APD Applications at Signalized Intersections (Continued)

Time	Country	Highlights
	Los Angeles, CA	• A microwave and an infrared detector installed respectively at each location **Functionality:** • Detect and monitor pedestrians who were crossing in the crosswalk. • Extended the clearance interval. **Advantages:** • Significant reduction in pedestrians beginning to cross during the Don't Walk signal. • The extension capability for pedestrians who finished crossing during the steady Don't Walk signal has increased from 47 percent to 53 percent. • Infrared and microwave detectors similarly significantly reduced vehicle-pedestrian conflicts. **Disadvantages:** • The false call rate was 3.5 percent in rainy weather. • Through traffic in the curb lane and right-turning vehicles triggered the false calls and the missed call rate was 1.5 percent. • Pedestrians who crossed very close to the sensor pole accounted for the missed calls.
	Rochester, NY	• Microwave detector **Functionality:** • Detected pedestrians who arrived in the **queuing** area at the curb. **Advantages:** • The microwave detector with the push button significantly reduced the number of pedestrians beginning to cross during the Don't Walk signal. **Disadvantages:** • A significant change was not achieved due to Failure to use the push button.
	Portland, OR	• Infrared and/or microwave **Functionality:** • Detected pedestrians who **arrived** in the queuing area at the curb. **Advantages:** • A decrease in the likelihood that pedestrians will begin crossing during the steady Don't Walk signal. • A decrease in the number of conflicts experienced by pedestrians while crossing. **Evaluation:** • Microwave detectors performed better than infrared detectors in terms of fewer false calls (1 percent vs. 4 percent). • Microwave detectors were more likely to miss calls (7 percent vs. 1.5 percent for infrared). • The detection zone was larger for the microwave [15 m (49 ft) in length and up to 6 m (20 ft) in width] than it was for the infrared [14 m (45 ft) in length and up to 1 m (3 ft) in width].

Table2-5. APD Applications at Signalized Intersections (Continued)

Time	Country	Highlights
2007 and 2011	United Kingdom (UK) [126, 127]	• PUFFIN - requires pressing the button to call the WALK signal • Two types of sensors: a pressure-sensitive mat and an infrared detector **Functionality:** • On-crossing pedestrian detector (infrared) to provide an extension to the pedestrian clearance period while pedestrians are still on the crossing. • Pedestrian curbside detector (pressure-sensitive mat) to cancel the pedestrian demand if there are no pedestrians in the waiting area. **Advantages:** • Reduce both driver and pedestrian delay. • Significantly reduce crash severity (serious and fatal crashes). • The number of injury accidents decreased by 26% for all crashes and by 39% for pedestrian crashes. However, the results were not statistically significant. • The number of injury accidents decreased by 24% for all crashes and by 38% for pedestrian crashes. Meanwhile, the results were statistically significant at 5%. • The cancel facilities were functional but were purposely disabled to avoid perceived problems. **Disadvantages:** • Infrared detection is degraded if the object remains still. • Cannot discriminate the direction of pedestrian movement. • Cannot determine the number of detected objects.
2009 and 2012	San Francisco, CA [48, 128]	• Video detection technology • 9% decrease in the number of incidents where a pedestrian was trapped on the roadway (2009). • Had a relatively small impact on improving safety at its particular location in 2021.
2019	USF, CUTR [118]	• Thermal machine vision technology, microwave radar **Functionality:** • Automatic actuation of pedestrian “Walk” signal indications. • Remove the call when the pedestrian walks out of the detection zone prematurely before the call is served. **Advantages:** • Thermal machine vision technology had the highest detection accuracy (90%) for pedestrians approaching crosswalks, and the lowest detection rate (5%) for pedestrians walking away from crosswalks. • Thermal machine vision technology detected pedestrians 94% of the time and placed a pedestrian service call 90% of the time at a signalized intersection. • Thermal machine vision technology detected the disappearance of pedestrians 98% of the time and removed the pedestrian call 97% of the time when they left the detection zone early.

Table 2-5. APD Applications at Signalized Intersections (Continued)

Time	Country	Highlights
2023	Irving and Arlington, TX [129]	• LiDAR sensors **Functionality:** • Analyzing the pedestrian waiting time before crossing, generalized perception-reaction time to the WALK sign, and crossing speed. **Advantages:** • The developed software (or solution) could reliably collect pedestrian behaviors and collected thousands of pedestrian behavioral samples at each intersection over many months. **Disadvantages:** • LiDAR uses active sensors that supply their own illumination source.

Note: 1 PUFFIN is Pedestrian User-Friendly Intelligent

Based on previous research, the project team has identified that the thermal machine vision system was the most accurate in 2019 [118]. Thermal technology is a combination of passive infrared and automated image processing technologies. Its measurement is not affected by variations in ambient light. The commercially available products (FLIR TrafiOne Smart City Sensor) in the U.S. have the following advantages:

- Control traffic signals by detecting pedestrians and bicycles that are approaching or waiting at curbside or walking on the crosswalk;
- Use thermal detection in complete darkness, through shadows, and under sun glare;
- Provide real-time detection and monitoring 24/7; and
- Connect to the traffic signal controller via dry contact outputs or TCP/IP communication to enable dynamic signal control based on vehicle presence, traffic volume, or flow data.

According to the FHWA Pedestrian Safety to Congress report, the APD could also be used at signalized intersections to improve pedestrian safety as follows [130]:

- Use in combination with LED signs or traffic signal control procedures that prohibit turns across crosswalks when pedestrians are present;
- Activate lighting to enhance pedestrian visibility at night; and
- Limit the pedestrian phase to the time when pedestrians are in the crosswalk.

With the advancement of technologies, pedestrian call extension and cancellation functions can be integrated into APD to further improve pedestrian safety and also reduce vehicle delay at signalized crossings. If a pedestrian is seen in the crosswalk at the end of the planned walk time, pedestrian call extensions lengthen the phase time for a pedestrian crossing. If a pedestrian presses a pedestrian push button, leaves the curb detection zone, and does not re-enter any detection zone for the same crossing within a predetermined amount of time, the signal controller would be able to terminate the pedestrian call, known as call cancellation.

3 In-Depth Interviews to Obtain Expert Experience, Suggestions, and Recommendations

This chapter presents the outcomes of interviews conducted with experts across various sectors, including agencies, consultants, researchers, and technology vendors to gather insights, suggestions, and recommendations on countermeasures used to improve pedestrian safety at signalized intersections. These interviews delved into various technologies and countermeasures designed to enhance pedestrian safety at signalized intersections. Specifically, the discussions focused on combining leading pedestrian intervals (LPIs), automated pedestrian detection, application of “No Turn on Red” blank-out signs, and advanced traffic signal control operations to allow omission of permitted left turns during a protected and permitted left-turn operations to reduce or eliminate conflicts between pedestrians and turning vehicles. This chapter includes the planning, preparation, and execution of the interviews and a synthesis of the results and findings related to key countermeasures.

3.1 Methodology

The research methodology for this project included in-depth interviews with four distinct groups of experts: transportation agencies, consultants, researchers, and technology vendors. Each group was selected to provide unique insights and a thorough understanding of various countermeasures, particularly emphasizing the four key countermeasures examined in the project for improving pedestrian safety at signalized intersections.

- **Agencies**: Interviews with transportation agency representatives provided insights into regulatory frameworks and real-world challenges faced in implementing the pedestrian safety measures considered in the project. These experts contributed knowledge about best practices.
- **Consultants**: Discussions with consultants offered practical applications and solutions based on their experience with various projects. Their expertise helped to highlight effective strategies and the practical aspects of deploying safety measures in diverse environments.
- **Researchers**: Researchers provided a broad perspective on current research findings and approaches. Their input helped to further understand the effectiveness of different countermeasures and technologies.
- **Vendors**: Interviews with technology vendors focused on algorithms, tools, and innovations available for enhancing pedestrian safety. This group contributed insights into the latest technological advancements and on automatic pedestrian detection and how these tools can be applied to mitigate pedestrian-vehicle conflicts.

The decision to use interviews rather than surveys was driven by the need for a more interactive and detailed exploration of the subject matter. Interviews allowed for real-time follow-up questions, enabling a deeper understanding of complex issues and immediate clarification of responses. This approach facilitated a richer collection of qualitative data, capturing nuanced insights and expert opinions that might not be fully captured through a survey format. Overall, this methodology ensured a comprehensive knowledge of the countermeasures and technologies for developing effective strategies and recommendations.

3.1.1 Planning, Preparation, and Execution for In-Depth Interviews

This section offers a thorough overview of the interview process, detailing each stage: planning, preparation, and execution. It describes the strategic approach used to ensure effective interviews, beginning with the careful selection and identification of participants based on specific criteria. The preparation phase is outlined, including the development of interview questions, participant briefings, and the preparation of necessary materials. Finally, the section covers the execution phase, detailing how sessions were scheduled, coordinated, and conducted to facilitate a smooth and productive interview process.

3.1.2 Description of Interviewees

Interviewees were strategically selected from four key categories: transportation agencies, consultants, researchers, and vendors. Specifically, six experts were chosen from five distinct agencies, three from three separate consulting firms, three researchers from three different institutions, and three selected vendors. Each interviewee brought valuable insights and deep expertise to the discussions. Their extensive knowledge and diverse perspectives significantly enriched the interviews, offering a comprehensive and nuanced understanding of the topic.

3.1.3 Design of Interview Questions

A detailed interview questionnaire was developed to align with the study’s objectives. The questionnaire aimed to gather comprehensive information on several key topics: LPIs, automated pedestrian detection systems, the use of "No Turn on Red" blank-out signs, and permitted left turn omission. Specifically, it sought insights on how these technologies and strategies could reduce or eliminate conflicts between pedestrians and turning vehicles.

The questionnaire predominantly featured open-ended questions, allowing for in-depth responses. It was tailored to each group of experts to elicit targeted information relevant to their area of expertise. For instance, the set of questions varied slightly between agencies, consultants, researchers, and vendors to address specific aspects pertinent to their roles and experiences.

Additionally, the questionnaire aimed to evaluate the effectiveness of the highlighted countermeasures and technologies. It included questions about any existing guidance within organizations for implementing these solutions, any before-and-after studies assessing their impact, and lessons learned throughout the process. The objective was to understand whether experts had integrated various countermeasures and technologies and to assess the effectiveness of these combinations.

The questionnaire also sought input on nighttime countermeasures, emerging technologies, and new solutions. Experts were invited to provide suggestions, recommendations, and key takeaways for minimizing conflicts between pedestrians and turning vehicles. For vendors, the focus was on algorithms, products, and calibration factors used to enhance pedestrian safety at intersections.

After drafting the questions, the team thoroughly reviewed and organized them to ensure a logical flow. Each question was refined for clarity, conciseness, and precision. The team aimed to keep questions brief and focused to fit within the one-hour interview timeframe. Clear instructions were provided at the beginning of the survey to inform participants about the study's purpose and scope. Following several revisions, the final version of the questionnaire was completed (see Appendix).

3.1.4 Selection of Interview Candidates

The interview participants were selected to ensure that individuals with the most relevant expertise and experience were chosen to meet the research objectives. This targeted approach was essential for obtaining detailed and specialized information. The research team sought participants with substantial knowledge and practical experience in key areas of the study: LPIs, blank-out signs, advanced traffic signal control systems, and video analytics for automatic pedestrian detection. Initially, a broad list of 10 to 12 potential experts was compiled for each category—agencies, consultants, researchers, and vendors—using a combination of literature reviews, online searches, and the team's professional network. This initial selection was based on documented expertise and significant involvement in relevant projects.

After an evaluation of their past and current work, the team refined the list to four to six experts per category. This narrowing process involved a detailed assessment of each expert's contributions, experience, and relevance to the study's objectives. By concentrating on this smaller, more focused group, the team aimed to enhance the depth and quality of the information collected, ensuring that the interviews would provide a rich, insightful, and well-rounded perspective on the subject matter.

3.1.5 Coordination, Scheduling, and Execution of Interviews

The project team initiated the interview process by sending an introductory email to each of the selected experts—four to six per group—inviting them to participate. This initial email included a brief overview of the project, outlined the objectives of the interview, and inquired about the expert's availability. To ensure responses, follow-up emails were sent at intervals of three days to one week after the initial outreach, with up to four follow-ups sent as necessary. Once an expert confirmed their willingness to participate and provided their availability, the project team coordinated to schedule the interview, considering both the expert's and the team's schedules. If required, the team requested alternative times to accommodate all parties. All experts responded to the initial invitations. Two experts indicated they were not the most suitable subject matter experts but recommended alternative contacts.

The interviews were generally scheduled for one hour, although one was shortened to 30 minutes due to the expert's limited availability. The interviews were conducted via the Teams meeting application. During each interview, experts shared their insights and responded to the prepared questions. All sessions were recorded to facilitate accurate notetaking and to allow the team to review the discussions as needed. These recordings were stored confidentially in a secure folder accessible only to the project team. Additionally, extensive notes were taken during the interviews to capture key points and insights.

3.2 Results and Findings from Interviews on Key Countermeasures

The findings from the interviews are summarized in this section and organized into several key parts: an overview, key countermeasures, combinations of countermeasures, nighttime and other countermeasures, as well as successes, lessons learned, and major findings. Each key countermeasure is detailed and categorized based on the expertise of the contributing professionals, ensuring a clear understanding of their perspectives and contributions.

3.3 Overview of Key Countermeasures and Innovative Technologies

This sub-section summarizes the interview results, highlighting key countermeasures and innovative technologies, their combinations, nighttime countermeasures, emerging or other technologies, and the overall effectiveness of these measures in reducing conflicts between pedestrians and turning vehicles. The interviews focused on four primary countermeasures: LPI, “No Turn on Red” blank-out signs, the omission of permitted phases when pedestrians are present, and automatic pedestrian detection.

Although there are various countermeasures available, these four were selected due to their specific focus on enhancing pedestrian safety. Advanced controllers and innovative technologies, including automatic pedestrian detection, present new opportunities for improving pedestrian safety at signalized intersections. Unlike traditional methods, these technologies offer more dynamic and responsive solutions.

Implementing three or four of the key countermeasures considered in this report at a single intersection can significantly reduce conflicts between pedestrians and turning vehicles at that intersection. This combination, including automatic pedestrian detection systems, can enhance pedestrian safety for more accurate and timely pedestrian calls to the traffic controllers.

The following sub-sections delve into the detailed findings for each countermeasure, including their individual and combined effects, nighttime countermeasures, and emerging technologies or countermeasures. They also highlight the successes achieved and lessons learned from implementing these measures, offering valuable insights into their practical application and effectiveness in reducing pedestrian-vehicle conflicts.

3.3.1 Leading Pedestrian Intervals (LPIs)

This sub-section provides a comprehensive summary of insights related to LPIs. It synthesizes contributions from agency experts, consultants, and researchers to offer an overview of their perspectives and findings. The synthesis includes an analysis of how LPIs are implemented, their effectiveness in improving pedestrian safety, and any associated challenges. Subsequent sub-sections will delve into detailed findings and expert opinions on this subject.

3.3.1.1 Agency Insights

Interviews with agency experts reveal that LPIs are implemented across various locations in the U.S., with durations ranging from 3 to 10 seconds. Agencies using a 3-second LPI have noted that this duration might be insufficient for larger intersections, where a 7 to 10-second LPI could be more effective. Most agencies follow specific guidelines, such as Manual on Uniform Traffic Control Device (MUTCD) standards or internal traffic engineering manuals, when implementing LPIs. Some agencies have deployed LPIs at over 100 intersections, incorporating them into new projects based on evaluations during retiming studies. LPIs are typically avoided at intersections with five-section signals if there is a significant imbalance in opposing left-turn volumes, as this could increase pedestrian risk. In such cases, alternative solutions like four-section signals are considered.

In a few regions, LPIs are part of broader initiatives and are installed across all signals in urban areas. Despite receiving no or a few complaints from drivers, agencies continually adjust LPIs based on feedback and technical assessments to ensure they effectively meet pedestrian needs. For instance, one agency that participated in the interview has adopted LPIs extensively as part of its Vision Zero initiative, moving beyond initial selection criteria to implement them wherever technically feasible. This agency modernizes outdated controllers to support LPIs and includes them in annual traffic network optimizations. Although it is challenging to isolate the impact of LPIs from other countermeasures, safety data shows improvements in pedestrian-related crashes, leading the agency to expand LPIs to all feasible locations.

Conversely, another agency has not implemented LPIs at its intersections. Previous trials indicated no significant benefits, primarily due to conflicts with right-turning vehicles. This agency is reconsidering the use of LPIs, acknowledging that while they can be useful and cost-effective, they are not a one-size-fits-all solution. Traffic engineers are required to evaluate LPIs during future retiming studies, weighing their impact on driver behavior and overall corridor coordination. For that agency, the debate continues regarding their effectiveness in different contexts.

3.3.1.2 Consultant Insights

LPIs are increasingly popular among agencies for improving pedestrian safety. It is now a standard consideration during signal retiming projects. Agencies in Florida have implemented LPI at hundreds of intersections, some LPIs with a duration of 3 seconds. When conducting Traffic Engineering and Management (TEM), LPIs are incorporated into intersections after assessment.

Mobility specialists recommend installing Accessible Pedestrian Signals (APS) at intersections with LPI, as these signals help blind pedestrians by allowing them to listen for traffic cues. If APS cannot be installed, it is suggested to provide extended walk times to ensure blind pedestrians have adequate time to cross safely. Although LPIs are considered an established technology, their proven effectiveness has led to their growing popularity and widespread adoption for improving pedestrian safety.

3.3.1.3 Researcher Insights

Researchers conducted interviews with pedestrians crossing streets to assess their satisfaction with LPIs. The findings revealed that compliance with traffic signal indications was notably higher at crosswalks equipped with LPI. This improvement in compliance suggests that LPIs enhance pedestrian safety and signal adherence.

Interestingly, some pedestrians were not aware of the additional leading time provided by the LPI. This indicates that while LPIs are effective in increasing compliance, their benefits might not be fully recognized by all users. Despite this, the overall positive impact on pedestrian behavior highlights the effectiveness of LPIs in improving traffic signal adherence and safety. Further education and awareness efforts might be beneficial to ensure that all pedestrians understand and appreciate the advantages of LPIs.

3.3.2 Blank-out Signs

This sub-section provides a synthesis of insights on “No Turn on Red” blank-out signs, incorporating perspectives from agency experts, consultants, and researchers. It offers a comprehensive overview of the topic based on their contributions. Subsequent sub-sections will detail the key findings and perspectives.

3.3.2.1 Agency Insights

"No Turn on Red" blank-out signs are typically activated during the pedestrian walk phase to eliminate or reduce potential conflict between right-turning vehicles on red and pedestrians to improve safety. Another blank-out sign of "Turning Vehicles Yield to Pedestrians" displayed during the vehicle green phase is also frequently installed at signalized intersections to ask drivers to yield to pedestrians. Recently a trend was observed to shift the blank-out sign from "Turning Vehicles Yield to Pedestrians" to "Turning Vehicles Stop for Pedestrians" signage to further improve pedestrian safety. Blank-out signs with dual modes are becoming more popular. These blank-out signs are appreciated for their clear, enforceable messages and are especially effective in high-conflict areas, as they capture drivers' attention and ensure compliance. An additional advantage of "No Turn on Red" blank-out signs over static signs is to allow right-turning vehicles to turn right on red when the traffic on the cross street is light and no pedestrian is present. However, this transition must account for structural factors, such as the capacity of overhead structures to support the new signs and withstand wind loads.

The District Department of Transportation (DDOT) in Washington D.C., deemed blank-out signs unnecessary because most of their intersections are pre-timed, with only a small fraction in suburban areas having actuated signals. For this agency, static "No Turn on Red" signs are preferred due to their effectiveness in managing traffic and their compatibility with pre-timed intersections, where pedestrian signals are automatically displayed in every traffic signal cycle. This setup simplifies pedestrian signal access, reduces delays, and is particularly beneficial for elderly pedestrians.

3.3.2.2 Consultant Insights

In Florida, blank-out signs are employed at various locations to enhance pedestrian safety, particularly at intersections with public concerns. These signs are effective in safeguarding pedestrians and can be easily integrated into traffic signal controllers using logical statements that adapt to specific conditions. Their display can also be adjusted according to the time of day.

When a pedestrian activates the crossing signal, the “No Turn on Red” message is shown and remains visible until the end of the red signal indication. It has been noted that using a simple “No Turn on Red” symbol sign is often more effective than displaying detailed written instructions.

3.3.2.3 Researcher Insights

Blank-out signs are commonly implemented across numerous jurisdictions, reflecting their widespread adoption in managing traffic and enhancing safety. These signs, particularly "No Turn on Red" blank-out signs, are highly favored by many transportation agencies for their effectiveness in improving pedestrian safety. By clearly prohibiting right turns on red, they help reduce conflicts between turning vehicles and pedestrians, making crossings safer. Agencies are increasingly interested in these methods because they contribute significantly to pedestrian-friendly traffic management, demonstrating a growing commitment to prioritizing pedestrian safety at signalized intersections.

3.3.3 Omission of Permitted Left Turn

This sub-section offers a thorough summary of insights related to permitted left turn omission. It synthesizes input from agency experts, consultants, and researchers. The synthesis includes an analysis of the implementation of permitted left turn omissions, their impact on pedestrian safety, and any associated challenges.

3.3.3.1 Agency Insights

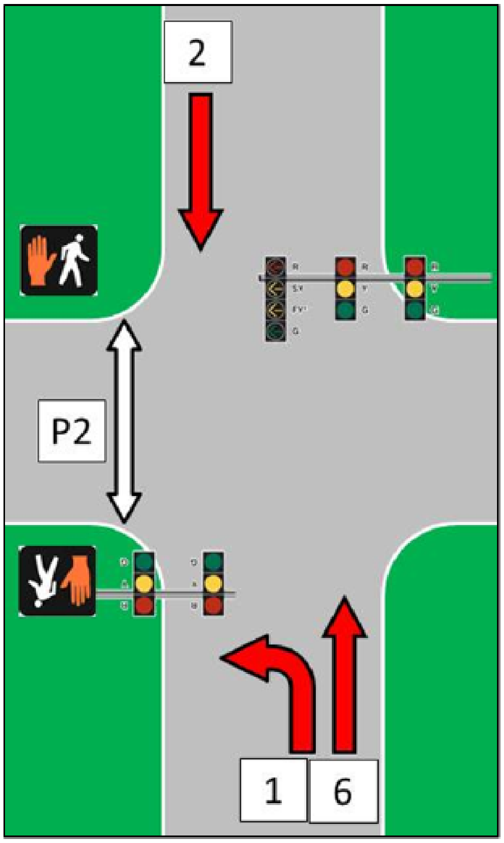
An agency omits permitted left turns when four-section head signals are installed for protected plus permitted left turns, especially if there is a frequent conflict with pedestrian calls. This approach completely avoids conflicts between pedestrians and left-turning vehicles, providing the safest treatment for pedestrian crossings. However, in some cases, the omission has been reversed due to delays. Currently, controllers can be programmed to omit permitted left turns when pedestrians activate the signal, ensuring that left turns are only allowed when pedestrian calls are not present. This programming helps in maintaining safety and minimizing conflicts at intersections with high pedestrian volumes.

The implementation of left turn omission for flashing yellow arrows was first applied at an intersection on Alt 19 and Tampa Rd. This measure was introduced after feedback from school crossing guards and observations of frequent pedestrian and bicycle conflicts. The system has been programmed so that when a pedestrian activates the signal, the left turn operates only in a protected mode. While this practice is recommended for high pedestrian demand areas, such as downtown cores and urban areas, it will not be applied universally.

In summary, when the protected and permitted signal operation is used, the omission of permitted left turn when a pedestrian call is activated has been identified as a best practice to eliminate the conflicts between pedestrians and left-turning vehicles. If there is no need to use protected and permitted signal operation to increase left-turn capacity at a signalized intersection, a protected left-turn signal operation is recommended.

3.3.3.2 Consultant Insights

The practice of prohibiting permitted left turns during pedestrian calls is widely adopted and can be effectively managed using modern traffic controllers. An example setup is illustrated in Figure 3-1. This approach is often customized based on the time of day and applied on a case-by-case basis, depending on specific conditions and timing.



WITH PEDESTRIAN DEMAND

		P2	2	1	6
1	Red Clearance	DW	R	< R	R
2	Protected Left	DW	R	< G	G
3	Change Interval	DW	R	< Y	G
4	Red Clearance	DW	R	< R	G
5	Pedestrian WALK	W	G	< R	G
6	Pedestrian Change	FDW	G	< R	G
7	Change Interval	DW	Y	< R	Y
8	Red Clearance	DW	R	< R	R

WITHOUT PEDESTRIAN DEMAND

		P2	2	1	6
1	Red Clearance	DW	R	< R	R
2	Protected Left	DW	R	< G	G
3	Change Interval	DW	R	< Y	G
4	Red Clearance	DW	R	< R	G
5	Permissive Left	DW	G	< FY	G
6	Change Interval	DW	Y	< Y	Y
7	Red Clearance	DW	R	< R	R

Figure 3-1. Permitted left turn omission during pedestrian demand

Source: Albeck Gerken, Inc.

Modern traffic control systems are equipped with programmable logic to handle such scenarios efficiently. For instance, these systems can be configured to prevent phase overlaps when a pedestrian call is active. On the other hand, pre-timed signals are typically unsuitable for locations that require accurate pedestrian detection, as they do not adapt to real-time conditions.

3.3.3.3 Researcher Insights

Evaluating the omission of permissive left turns can be challenging due to several factors. The complexity arises from the interplay between traffic flow, pedestrian safety, and driver behavior. Assessing the impact of removing permissive left turns involves analyzing how this change affects overall traffic patterns and crash frequency, which can differ significantly from one intersection to another. Furthermore, the effectiveness of this change must be evaluated against various safety and operational metrics, including reductions in collision rates and alterations in traffic congestion. Given these complexities, a comprehensive and detailed approach is essential for accurately understanding the implications of eliminating permissive left turns. Although the overall impact of omission of permissive left turns is complex, this left-turn signal operation treatment offers elimination or reduction of the conflicts between pedestrians and left-turning vehicles.

3.3.4 Passive Pedestrian Detection

This sub-section presents a comprehensive summary of insights on automated pedestrian detection based on contributions from agency experts, consultants, researchers, and technology vendors. It includes a detailed analysis of the implementation of automated detection systems, their effects on pedestrian safety, and the challenges encountered.

3.3.4.1 Agency Insights

Agencies are actively evaluating various automated pedestrian detection systems, including AI-based video detection units and thermal cameras, to enhance pedestrian safety and traffic management. In Florida, a multi-phase FDOT pilot project is underway to advance these technologies. Phase 1 of the project focused on integrating connected vehicle technology to improve communication between vehicles and traffic management systems. LIDAR-based detection was used to accurately determine object locations, and various aspects, such as message sharing and delay times between intersections and back offices, were explored. A significant finding from this phase was the necessity of edge-based detection to enable timely message sharing. The main challenge identified was predicting pedestrian intent before they entered a travel way, as even with immediate messaging, preventing collisions was often too late.

Phase 2 involved testing computer vision technology, which faced difficulties in accurately determining object locations and inferring intentions. Different products and vendors were assessed for their effectiveness in accuracy and object detection. Although one vendor performed well in providing accurate location information, their system struggled with predicting movement trajectories likely due to a joint pedestrian waiting area instead of two separate waiting areas. The system could indicate the direction a pedestrian might move, but was not reliable in forecasting whether they would enter a travel path. However, the software offered useful features such as heat maps and time-to-collision metrics, which provided surrogate safety measures for assessing and mitigating crash risks.

Phase 3 aims to enhance intersection efficiency with pose detection technology to estimate the probability of pedestrians entering intersections. This phase also focuses on improving the accuracy of speed measurements, thereby extending pedestrian crossing times. Additionally, the project is exploring the possibility of holding traffic signals until pedestrian intent is confirmed, with the goal of optimizing intersection functionality and potentially shortening cycle lengths, which could lead to better pedestrian compliance.

Research into improving pedestrian compliance has led to the introduction of a blue light on pedestrian buttons, which confirms signal reception. This modification has resulted in increased compliance rates, and further tests are being conducted to evaluate the impact of the blue light on pedestrian behavior. Additionally, experiments are underway with audible pedestrian buttons, and the agency is collaborating with researchers to develop effective messages that could enhance compliance rates.

In another Florida initiative, the City of Sarasota in FDOT District One is testing Connected Vehicle (CV) technologies with AI-powered video detection systems, including DERQ's platform implemented at 16 signalized intersections. In this CV application project, this technology is designed to monitor and reduce conflicts and near-miss incidents at or near a signalized intersection by alerting drivers with Onboard Units (OBUs) equipped in their vehicles to the presence of pedestrians and bicyclists from distances up to 75 feet. The system will trigger flashing alerts to drivers with the OBUs in their vehicles when a pedestrian or bicycle is detected by intersection cameras, allowing vehicles time to react and slow down. Additionally, the pedestrian detection system using DERQ's AI platform can extend the pedestrian crossing time for elderly individuals, people with disabilities, and children with slower walking speeds, providing extra time to clear the roadway when needed.

Other agencies are also deploying automated pedestrian detection systems, with systems fully deployed and in the proof-of-concept stage. FLIR cameras are used at certain locations to detect pedestrians, addressing issues of low compliance and accidents. Despite their promise, these technologies also face challenges such as occasional false detections and occlusion problems that can impede their effectiveness.

There have been notable successes for pilot testing and the start of field implementation of passive pedestrian detection systems. Lessons learned from these initiatives highlight some challenges, particularly with the systems meeting Americans with Disabilities Act (ADA) requirements and still relying on physical pedestrian push buttons. Testing of APS systems, which provide tactile feedback, is ongoing. At some intersections, APS units vibrate to notify pedestrians of their location, but issues remain with the timing of the vibration response. Current APS models include Polara and Campbell.

Additionally, research is needed to address issues with a joint pedestrian waiting area at a corner of a signalized intersection to cross two different crosswalks. Unlike separate waiting areas that have highly accurate pedestrian detection rates, a joint waiting area makes it difficult for pedestrian detection AI algorithms to accurately determine pedestrian intention and place a pedestrian call to the traffic signal controller. Occlusion problems, such as street light poles obstructing camera views, have led to missed detections, underscoring the need for proper integration of pedestrian detection systems and existing infrastructure configurations. Testing has shown that some sensors have limited effectiveness, with detection accuracy around 85%, and thermal cameras have not consistently met performance specifications for all agencies.

3.3.4.2 Consultant Insights

Automated pedestrian detection systems (see example display in Figure 3-2) provide substantial benefits, particularly by accommodating pedestrians who may not use traditional push buttons.

Over the past decade, there has been a significant shift in pedestrian signal management towards automatic recall systems. Many local agencies are increasingly adopting these automatic pedestrian detection systems, which activate without requiring a button press, though they often retain the push buttons as a backup.

Figure 3-2. Sample display of an automated pedestrian detection system

Source: Iteris

This shift is driven by its advantages, including enhanced accessibility and reduced dependence on costly and maintenance-intensive push-button installations. Automated pedestrian detection systems are especially beneficial in high-traffic urban and suburban areas, tourist destinations, and communities with specific accessibility needs. By eliminating the need for manual interaction, these systems ensure that pedestrian signals are activated for all pedestrians, including those who might not otherwise use the buttons. For example, a microwave detection system has been successfully implemented at an intersection in Florida near a temple to automatically detect pedestrians, particularly during the Sabbath, thereby removing the need for manual activation.

Some challenges remain, particularly among state agencies, regarding the technologies and the potential need for setting new precedents for guidelines. Issues such as false triggers and the need for precise placement to avoid inaccuracies also contribute to this hesitancy. Additionally, the relatively high cost and maintenance requirements of automated pedestrian detection systems limit their use, making them suitable primarily for locations with pedestrian safety concerns or where push-button activation is infrequent. In such cases, the benefits of passive pedestrian detection systems must outweigh their investment and maintenance costs to justify their implementation

3.3.4.3 Researcher Insights

Researchers explored the use of infrared cameras for automatic pedestrian detection but encountered challenges due to occlusions and limited camera coverage. The cameras struggled to capture both pedestrians and turning vehicles effectively, especially if the camera was not positioned at every corner of an intersection. This resulted in inaccurate detection and highlighted the difficulty of setting effective detection zones with current technology. It is also sometimes hard to set detection zones for automated pedestrian detection.

Another group of researchers explored long-term, real-time solutions for detecting and preventing conflicts between pedestrians and vehicles. The team aimed to leverage video technology to monitor and address these conflicts more frequently and in real-time. They utilized both video and LIDAR systems to capture detailed data from intersections and incorporated signal timing information to identify problematic phases, particularly those where right-turning vehicles intersect with pedestrian phases. Additionally, they recognized the importance of considering different times of day, as visibility issues during dawn, dusk, and inclement weather can affect pedestrian safety.

To tackle the challenges of near-miss detection, the researchers refined their approach to define and analyze severe events. Originally relying on time-to-collision metrics, they shifted to a more nuanced understanding of near misses by examining vehicle trajectories, braking behaviors, and significant reductions in speed. This refinement aimed to capture a more accurate representation of dangerous interactions and improve safety assessments. They collected and analyzed days of video footage to identify severe events and assess the effectiveness of countermeasures.

Their video technology provided insights into both performance and safety metrics. By tracking the number of pedestrians and vehicles passing through intersections, they could evaluate how different traffic phases impacted safety. The technology allowed them to rank intersections based on the severity of issues and categorize problems into pedestrian and vehicle-related concerns. This comprehensive analysis supported the development of targeted countermeasures and performance improvements.

The system categorized vehicles into several types, including motorcycles, cars, trucks, and vans, and pedestrians into groups such as walkers, bicyclists, and skateboarders. However, distinguishing between some sub-categories proved challenging, which occasionally reduced the accuracy of the technology. Despite these limitations, advancements in camera and LIDAR technology continued to enhance detection accuracy over time.

Directional cameras, which observe traffic from specific angles, were limited in their ability to capture complete intersection activity, particularly pedestrian movements. To address this, the researchers used fisheye cameras and LIDAR systems positioned above the intersection for comprehensive coverage. The choice of camera and its placement depended on the size and complexity of the intersection. Large intersections with multiple lanes often required multiple fisheye cameras to ensure full coverage, though image quality could vary.

The technology's accuracy in tracking both pedestrians and vehicles could reach up to 90-95% when images were of high quality. Proper camera setup was crucial for capturing a complete view of the intersection. To maintain privacy, videos were not stored for extended periods, and occasional fine-tuning was necessary to achieve optimal accuracy. This involved setting up and calibrating equipment, analyzing initial data, and adjusting as needed.

In addition to assessing intersections, the researchers used their technology to evaluate traffic during special events, such as football games. They analyzed traffic patterns before, during, and after these events to predict changes and improve event planning. They also studied the impact of signage on driver behavior, aiming to develop effective safety measures based on data from multiple intersections.

The overall goal was to use the data to understand human behavior at various intersections. The algorithms provided detailed metrics on throughput, deceleration, acceleration, and average velocity for different directions. While the technology was still evolving, it offered valuable insights into traffic dynamics and safety, with a user interface allowing for easy access to the collected information.

3.3.4.4 Technology Vendor Insights

The interview discussed technologies for passive pedestrian detection, focusing on the advantages and considerations of various systems. One vendor specializes in both thermal and optical detection solutions. Optical systems, which utilize camera technology, are often preferred for widespread implementation due to their simpler hardware requirements and additional functionalities, such as automated detection of vehicles, bikes, and pedestrians. These systems are commonly used at mid-block locations with Rectangular Rapid Flashing Beacons (RRFBs) or Pedestrian Hybrid Beacons (PHBs).

Thermal sensors, while more specific, require multiple units per intersection—typically between four to eight sensors. These sensors are valuable but can be more complex to deploy and maintain compared to optical systems. Key factors in deploying these technologies include proper mounting height, angle, and field of view. As AI technology evolves, training models to accurately interpret pedestrian data becomes increasingly important.

Modern traffic controllers generally support various detector inputs and can handle dynamic pedestrian movements such as call cancellations and phase extensions. Controllers manufactured within the last few decades should be compatible with these systems. Some controllers have built-in features to automatically cancel pedestrian phases under certain conditions, streamlining the process.

When implementing pedestrian detection systems, selecting regions of interest where pedestrian activity is anticipated is vital. This often involves utilizing existing infrastructure and evaluating the feasibility of sensor mounting. Tools like Google Maps help determine appropriate locations for sensor installation. Additionally, understanding the local climate and pedestrian behavior—such as the tendency to seek shelter from the elements—can impact system performance and requires careful configuration.

Optical systems integrated with AI technology offer advanced capabilities, including learning pedestrian behavior and predicting intentions. These systems also incorporate data from mechanical push buttons to enhance their functionality. This AI-driven approach helps in adapting to various scenarios and improving detection accuracy.

Another vendor provides automated detection as part of their controller solutions, integrating pedestrian detection directly into the controller software. This system uses cameras to classify users and extend pedestrian crossing times if necessary, ensuring safety and accommodating unexpected pedestrian movements. The vendor's services include customizing solutions for specific client needs, such as those used by agencies in Santa Clara County, Connecticut DOT, and NYC DOT.

Some vendors focus on training AI models based on project-specific needs, ensuring that pedestrian safety models are highly efficient and tailored to the requirements of each location. These models can detect near misses between vehicles and vulnerable road users, as well as illegal crossings. Agencies can review video footage to analyze conflicts and determine appropriate countermeasures, enhancing overall safety and operational effectiveness.

3.4 Combination of Countermeasures and Technologies

Agency experts, consultants, and researchers provided valuable insights into the integration of multiple key countermeasures for this project. This summary, organized by the type of organization, details the various combinations implemented and evaluates their effectiveness.

3.4.1 Agency Insights

The agency expert interview revealed insights into the application and effectiveness of combining the key countermeasures evaluated in the project, particularly regarding combining LPI, blank-out signs, omission of permissive left turns during pedestrian presence, and automatic pedestrian detection. For one agency, some intersections use LPIs alongside “No Turn on Red” blank-out signs, though this is not yet a standard practice. It was noted that driver compliance with LPIs tends to be low when there is no accompanying blank-out sign. Drivers often disregard

LPIs, especially in areas with aggressive driving behavior, where they are more focused on making turns and may exhibit frustration towards pedestrians.

Another effective strategy highlighted by another agency involves the use of LPIs in conjunction with the omission of permissive left turns using flashing yellow arrows at intersections to reduce pedestrian crashes. Additionally, combining dual messages such as “No Turn on Red” and “Turning Vehicles Yield to Pedestrians” with passive pedestrian detection systems was identified as one of the most effective methods for improving compliance. This approach helps ensure that drivers are more aware of pedestrian crossing rules and prompts them to yield when necessary. The interview also touched on the effectiveness of dual-message blank-out signs combined with automated pedestrian detection. This combination helps reinforce pedestrian safety by making sure that drivers are aware of both the prohibition on turning and the need to yield to pedestrians when the LPI is active.

3.4.2 Consultant Insights

Across the U.S., many locations use a combination of "No Turn on Red" blank-out signs and LPI to enhance pedestrian safety. This strategy helps manage traffic flow and reduce conflicts between vehicles and pedestrians. However, in intersections with multiple turning lanes, violations of "No Turn on Red" rules are common, as drivers frequently disregard the restriction and turn right. Therefore, the effective installation of LPIs and blank-out signs requires a tailored approach, considering the specific context and challenges of each intersection.

Protective left turn phases combined with lagging LPIs have also been successful in improving pedestrian safety. Nonetheless, the effectiveness of these measures is currently under scrutiny, especially with the increasing discussion about implementing Flashing Yellow Arrows (FYA) for right turns. Resident feedback from a corridor study has raised concerns, as some individuals felt less safe crossing streets with flashing yellow arrows. In response to these concerns, there have been requests for the installation of buttons that can change the flashing yellow arrows to red lights, enhancing pedestrian safety.

The integration of LPI with the omission of permitted left turns during pedestrian calls is an effective practice. For example, Figure 3-3 outlines a recommended method for implementing these measures. It is advised to transition from five-section to four-section head signals when applying this combination. These practices are well-established. The use of automatic or automated pedestrian detection systems is still under-explored, highlighting a need for further research and evaluation in this area to significantly enhance pedestrian safety at signalized intersections.

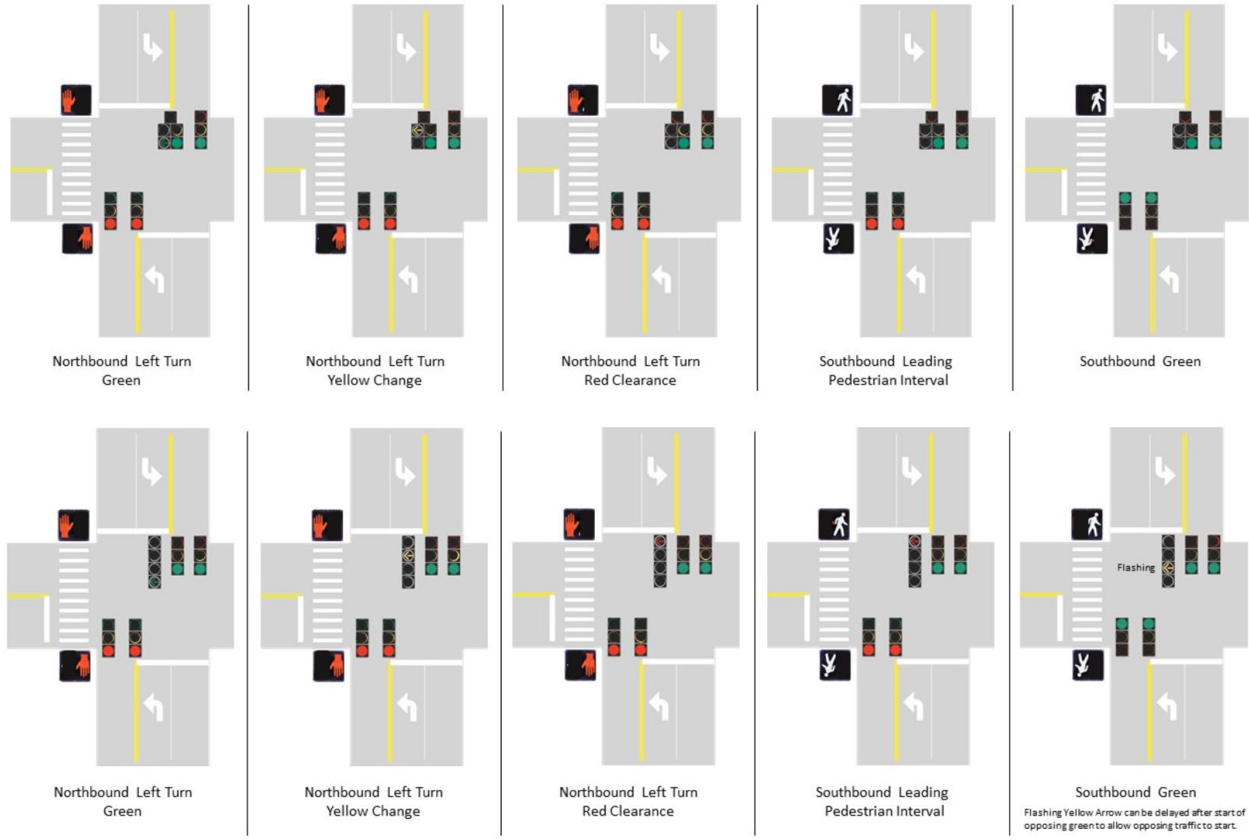


Figure 3-3. Approaches to combine LPI with omission of permissive left turn

Source: Iteris, Inc.

3.4.3 Researcher Insights

The combination of LPIs and "No Turn on Red" blank-out signs is a prevalent practice across the United States. Many locations implement these measures to enhance pedestrian safety, reflecting a strong interest from agencies in promoting pedestrian-friendly solutions. Both LPIs and "No Turn on Red" signs are favored for their effectiveness in managing pedestrian traffic and reducing potential conflicts between pedestrians and turning vehicles. Their widespread use underscores their importance in improving intersection safety and pedestrian compliance.

3.5 Nighttime Pedestrian Safety Countermeasures

For this project, interviewees provided insights into nighttime countermeasures aimed at reducing conflicts between pedestrians and turning vehicles. The summarized responses are outlined in this section. Experts from all four types of interviewees emphasized lighting as a crucial element in enhancing nighttime safety. Detailed findings and further insights are presented next.

Street lighting plays a critical role in enhancing pedestrian safety at night. Pedestrian visibility at night is crucial for safe crossings, and effective lighting is key to ensuring pedestrians are seen both when waiting and while crossing. Notably, locations with a high frequency of nighttime crashes often suffer from inadequate lighting, underscoring the importance of improved street lighting for nighttime safety. Agencies often follow specific street lighting guidelines to address these concerns.

One effective approach is to operate streetlights at 70% of their maximum luminosity under normal conditions and increase the brightness to 100% when a pedestrian is detected at an intersection. This adjustment helps improve the visibility and awareness of pedestrians, particularly at busy intersections. For example, in Park Blvd, Pinellas Park, Florida, increased lighting brightness is employed when pedestrians push the crosswalk button, focusing on the crossing area to address nighttime safety issues.

An agency in Florida has experimented with crosswalk lighting by installing a downlight under the mast arm aimed directly at the crosswalk. This setup, tested at a mid-block crossing, has shown potential for improving intersection safety by highlighting pedestrians on the crosswalk. The type of lighting, its application, and the illumination levels are all vital factors for ensuring pedestrian safety at night. The Federal Highway Administration is leading a study to use an inexpensive light meter as an initial measure of lighting levels. Although this tool is not intended to replace comprehensive lighting studies, it can provide useful spot measurements to gauge whether lighting is adequate for pedestrian visibility.

Quantifying optimal lighting levels remains a challenge. Excessive brightness can negatively impact pedestrian safety and potentially contribute to crashes. There has been considerable discussion on pedestrian-activated lighting systems, where lights are triggered by push buttons or automated detection systems. Research is ongoing to assess the effectiveness of these systems and determine whether continuous lighting is necessary or if activation based on need is sufficient. Given the high cost of lighting, it is essential to balance effectiveness with expense. Incorporating smart street lighting systems could improve pedestrian safety at night, although no current solution fully addresses all challenges associated with night conditions.

Thermal sensors are advantageous for nighttime pedestrian detection as they do not rely on lighting and can function both day and night. Meanwhile, optical systems are advancing in low-light conditions and have the potential to integrate additional sensor data, such as radar or LIDAR, to enhance detection capabilities.

Additionally, public outreach and distribution of reflective materials can further improve pedestrian visibility and safety. Pedestrians should be encouraged to wear visible clothing, such as light-colored attire, to enhance their visibility. Other solutions, such as speed management, can enhance pedestrian safety at night. For example, implementing left-turn hardening and calming measures can help slow down turning movements and enhance safety throughout the day and night.

In summary, achieving optimal nighttime safety requires ongoing advancements in lighting technology and detection systems, as well as continuous public education. The current tools and strategies, including thermal sensors and advanced optical systems, offer promising solutions but also highlight the need for further research and development to address the unique challenges of nighttime visibility and safety.

3.6 Other Countermeasures and Technologies

The interviews covered a range of technologies, including emerging innovations, designed to mitigate conflicts between pedestrians and turning vehicles. This section summarizes insights from all experts on both technological and non-technological countermeasures. Further details and findings are presented subsequently.

Emerging technologies for pedestrian safety are rapidly evolving, incorporating advanced systems to better manage and protect pedestrians at intersections. One such innovation is the use of a pedestrian detection system equipped with AI covering crosswalks to predict pedestrian movement and adjust crossing times dynamically. This allows the system to truncate the crossing phase if pedestrians clear the intersection earlier than anticipated, optimizing traffic flow and safety. For safety concerns, truncating a crossing phase should not be implemented without 100% confirmation. Additionally, new technologies such as AI video analytics and radar conflict analytics are being explored to enhance traffic control systems. However, upgrading traffic controllers to incorporate these advancements may take several years.

Connected vehicle technologies represent another significant advancement. These systems enable communication between vehicles, bicycles, and pedestrians, enhancing safety by alerting pedestrians to potential dangers in their vicinity. Geofencing further refines this approach by sending warnings only to pedestrians within a specific zone, minimizing unnecessary alerts for others. For example, the integration of connected vehicle technologies in the City of Sarasota involves a detailed process: controllers provide signal phase and timing (SPaT) data and video analytics to the DERQ processor, which tracks the speed and trajectory of objects. This data is converted into PSM (Personal Safety Messages) and broadcast via a roadside unit (RSU) mounted above traffic signals. The goal is to develop apps that communicate with these systems to alert pedestrians about signal phases and potential conflicts.

Pedestrian touchless technology is also emerging, enhancing safety by allowing interactions with traffic signals without physical contact. Protected intersections are another effective treatment, which can slow vehicle speeds, increase pedestrian visibility, and provide safer crossing conditions. Key features of protected intersections include reducing crossing distances, minimizing turn radii to encourage slower vehicle speeds, and repositioning stop bars to give pedestrians more space and time to cross safely.

The "Leading Through Interval" (LTI) is a technique that allows traffic to proceed through an intersection while holding back right and left turning traffic. This strategy gives pedestrians more time to cross safely. Although not widely adopted, it offers potential benefits, especially in situations where roadways are narrower. For roads with three to four lanes, LPIs are often more effective in improving safety compared to LTIs. To address pedestrian-vehicle conflicts, methods like left-turn hardening can also be employed. This technique involves design modifications to reduce the likelihood of conflicts between turning vehicles and pedestrians. Future applications might include four-section flashing yellow arrows combined with pedestrian signals, as tested by FDOT District 5 in Florida. This approach uses synchronized signals to alert drivers to pedestrian conflicts at right turns.

3.7 Successes and Lessons Learned

During the interviews, successes and lessons learned were explored, focusing on various critical factors such as technology, education, contextual considerations, speed, and effective signage. Insights into these elements, along with the impact of different countermeasures, were discussed. The following paragraphs offer a detailed examination of these topics and their implications.

The agency’s exploration of ultra-wideband (UWB) short-range wireless communication technology underscores the potential for enhancing pedestrian safety. UWB offers unparalleled precision compared to traditional GPS, with accuracy within half an inch versus GPS’s ±3 to ±12 feet. This high level of precision is crucial for distinguishing between pedestrians on the sidewalk and those in the street, which could lead to more effective real-time alerts and safety measures.

Integrating UWB with existing wireless communication protocols like Wi-Fi and Bluetooth aims to leverage smartphone data for connected vehicle systems, particularly at intersections. Early tests show UWB's accuracy to within 1.5 to 2 inches, making it a promising tool for pedestrian localization and warning systems. This technology could significantly improve pedestrian safety by providing timely and accurate alerts, thus reducing accidents and saving lives.

The experience of introducing new technologies, such as the flashing yellow arrow, highlights the importance of public outreach and education. Initial resistance and confusion were overcome through effective communication, leading to wider acceptance and demand. Similarly, real-time feedback mechanisms like blank-out signs can enhance road safety by keeping users informed of current conditions.

The effectiveness of countermeasures is highly dependent on the context of their implementation. An agency’s ability to respond to diverse needs is enhanced by having a wide array of countermeasures, including curb extensions, protected intersections, and median refuges. Prioritizing multimodal safety and adapting countermeasures to regional needs are essential for effective pedestrian safety improvements.

Automated pedestrian detection systems need to demonstrate high accuracy before they can be reliably used for traffic signal decisions. The accuracy of such systems must meet a certain threshold to be deemed effective. Additionally, caution is advised when testing new technologies to ensure they meet the necessary requirements and can deliver on their promises.

The impact of turning vehicle speeds on pedestrian safety is significant, especially at larger intersections with higher speeds. Wider intersections with faster turning movements pose greater risks to pedestrians and cyclists. Understanding these dynamics is crucial for designing safer intersections and mitigating risks associated with high-speed turns.

Various countermeasures, such as raised crossings, speed-reducing technologies, automated speed enforcement cameras, and centerline islands, are employed to reduce pedestrian-vehicle conflicts. Protected intersections and curb extensions are effective in creating safer environments by slowing down vehicles and improving visibility for pedestrians.

Effective signage at intersections is fundamental for safety. Technologies that use AI algorithms predict pedestrian intent to cross streets and activate blank-out signs in advance allow turning vehicles to respond appropriately. When properly implemented, these systems can provide adequate response time and improve overall safety at intersections.

3.8 Interviews Summary and Findings

As previously mentioned, we conducted interviews with 15 experts from diverse fields, including agency managers and specialists, consultants, researchers, and technology vendors and providers. Although there was some overlap in their insights, each expert offered distinct and valuable perspectives on the topic. This section summarizes the key findings from these discussions. The main findings are outlined as follows:

- LPIs are increasingly implemented across the U.S., with durations ranging from 3 to 10 seconds. Agencies have found longer LPIs (7-10 seconds) more effective at larger intersections, while shorter durations may be insufficient. Implementation often follows MUTCD standards or internal guidelines.
- Deployment of LPIs varies, with some agencies using them at over 100 intersections and incorporating them into new projects based on retiming studies. However, LPIs are typically avoided at intersections with five-section signals where left-turn volume imbalances could increase pedestrian risk.
- Mobility specialists recommend pairing LPIs with Accessible Pedestrian Signals (APS) or extended walk times for blind pedestrians. Increased education on LPIs' benefits is also suggested.
- Blank-out signs are highly valued for their clear, enforceable messages and effectiveness in high-conflict areas, capturing drivers' attention and ensuring compliance. Installation must account for structural factors, such as the capacity of overhead structures to support the signs.
- While some agencies find blank-out signs beneficial for pedestrian safety, others prefer static "No Turn on Red" signs, especially in areas with pre-timed signals, such as urban core, where these signs are sufficient and more compatible with recalled pedestrian signals in every traffic signal cycle.

- Omission of left turns to eliminate conflicts between pedestrians and vehicles is easier with four-section head signals. This approach is effective, but it may be reversed in some cases due to delays. For protected and permitted left-turn traffic signal operations, prohibiting or the omission of permitted left turns during pedestrian calls is widely adopted and can be managed with modern traffic controllers. For pre-timed signals, this treatment is less suitable.
- Automated pedestrian detection systems are particularly beneficial at locations with high pedestrian traffic, pedestrian safety concerns, infrequent use of pedestrian push buttons, and accessibility focus, reducing the need for manual activation. However, issues like false triggers, high costs, and maintenance requirements make agencies cautious. Continuous improvement and advancement using AI-powered technologies could lead to more deployment of automated pedestrian detection systems in the future.
- The primary challenge in automated pedestrian detection is predicting pedestrian intent before they enter a crosswalk. While real-time messaging can be helpful, it often comes too late to prevent collisions. To address this, efforts are underway to hold traffic signals until pedestrian intent is confirmed, aiming to enhance safety and potentially reduce cycle lengths, which could improve intersection functionality and pedestrian compliance. This issue is particularly pronounced at the junction of two crosswalks at intersection corners. When each crosswalk has its own waiting area, pedestrian intent is clearer, significantly easing the challenge. Consequently, automated pedestrian detection systems are most effective at signalized intersections where each crosswalk has a distinct waiting area.
- Passive pedestrian detection systems often struggle with ADA compliance and rely on physical buttons, which may not always provide timely feedback. Ongoing testing aims to address issues like vibration timing in APS and the effectiveness of combined ramps versus separate ramps for pedestrian standing areas.
- Fisheye cameras and LIDAR systems are used for comprehensive intersection coverage, with optical systems often preferred for their simplicity and added functionalities. Thermal sensors, while effective, require multiple units and careful deployment to be fully operational. Proper camera setup and calibration are crucial for accurate pedestrian and vehicle tracking.
- AI-enhanced optical systems offer advanced capabilities by learning pedestrian behavior and predicting intentions. Integration with AI helps improve detection accuracy and system adaptability. Training AI models based on specific project needs ensures high efficiency and effectiveness in monitoring pedestrian and vehicle interactions.
- AI video analytics and radar conflict analytics are being explored to enhance traffic control systems. However, upgrading traffic controllers to incorporate these advancements may take several years for some transportation agencies.

- Agencies are also testing advanced systems such as cameras and AI video detection to monitor conflicts and extend pedestrian countdowns. Despite their promise, these systems face challenges like false detections and occlusion issues.
- The agency's exploration of ultra-wideband (UWB) short-range wireless communication technology underscores the potential for enhancing pedestrian safety.
- Technologies like blue lights on pedestrian buttons and audible signals have improved compliance rates.
- Some agencies use LPIs alongside "No Turn on Red" blank-out signs to enhance pedestrian safety, though this is not yet a universal practice. Compliance with LPIs alone tends to be low, especially in areas with aggressive driving behaviors, where drivers may disregard pedestrian signals in favor of making quick turns. Additionally, violations are common at intersections with multiple turning lanes, where drivers frequently ignore the turn restrictions.
- LPIs are popular for enhancing pedestrian safety. Trials have shown high rates of right-turning drivers yielding or stopping for pedestrians when combining LPI with "No Turn On Red" static or blank-out signs.
- Combining LPIs with permitted left turn omission and blank-out signs with dual messages like "No Turn on Red" and "Turning Vehicles Yield to Pedestrians" has proven effective in improving driver compliance. This approach is anticipated to increase driver awareness and ensure adherence to pedestrian crossing rules.
- Integrating LPIs with the omission of permitted left turns during pedestrian calls is a common practice that improves safety. Transitioning from five-section to four-section head signals is recommended for this combination. However, this transition must account for structural factors, such as the capacity of overhead structures to support the new signs and withstand wind loads.
- Experts anticipated that dual-message blank-out signs, including "No Turn on Red" and "Turning Vehicles Yield to Pedestrians," combined with automated pedestrian detection, can effectively enhance pedestrian safety.
- Experts agreed that proper street lighting is crucial for nighttime pedestrian safety. A recommended approach is to operate streetlights at 70% brightness under normal conditions and increase them to 100% when pedestrians are detected at intersections. This can be complemented by public outreach and distributing reflective materials to boost pedestrian visibility.
- While increased lighting improves safety, excessive brightness can have negative effects and potentially contribute to crashes. Pedestrian-activated lighting systems, whether triggered by push buttons or automated detection, are under research to determine if continuous lighting or activation based on need is more cost-effective.

- Thermal sensors offer an advantage for nighttime detection as they operate independently of ambient light. Optical systems are improving in low-light conditions and can be enhanced with additional data from radar or LIDAR to improve detection capabilities.
- Public education on wearing visible clothing and implementing speed management measures, such as left turn hardening, can enhance pedestrian safety at night.
- Turning vehicle speeds significantly affect pedestrian safety, with wider intersections and faster turns presenting higher risks for pedestrians and cyclists.
- Measures to slow down turning movements help improve safety during both day and night. Protected intersections can reduce vehicle speeds, increase pedestrian visibility, and provide safer crossing conditions. Techniques like the LPI, left-turn hardening, and four-section flashing yellow arrows to alert drivers to pedestrian conflicts at right turns can all help reduce pedestrian-vehicle conflicts.
- Technologies that predict pedestrian intent and activate blank-out signs in advance help turning vehicles respond more effectively, thereby improving overall safety.

4 Pilot Deployment and Evaluation of Recommended Countermeasures

This chapter presents the results of the pilot deployment and evaluation of proposed countermeasures to mitigate conflicts between pedestrians and turning vehicles. The proposed countermeasures include the integration of leading pedestrian intervals (LPI), "No Turn on Red" blank-out signs, advanced traffic signal control operations that omit permitted left turns during pedestrian phases in the protected and permitted left-turn operations, and automated pedestrian detection. The pilot deployment included six signalized intersections in the Tampa Bay area and one in the City of Sarasota to implement individual or combined countermeasures where significant conflicts have been identified. To assess the effectiveness of omitting left turns during the pedestrian phase, historical crash data were analyzed in a before-and-after study to evaluate the impact. Additionally, field data were collected and analyzed through a cross-sectional approach at sites featuring at least two of the proposed countermeasures.

4.1 Research Methodology

This section describes the research approach applied in the pilot study. The approach includes field data collection, video processing, human review, and statistical analysis.

4.1.1 Field Data Collection

The research team installed cameras at the selected sites in the Tampa Bay area to record traffic operations, including turning vehicles, pedestrians, cyclists, and micromobility users. The treatment operations (LPI, blank-out sign, and O-FYA) and associated traffic signal status were also recorded. The videos were recorded at FHD (1920 × 1080) in good weather conditions. Figure 4-1 shows the installation and views of installed cameras.

The research team utilized two cameras to support data collection as described below:

- **Top Camera**—One camera was installed on a high tripod at a height of 24 feet. The top camera covered the entire intersection and recorded pedestrian/vehicle behaviors.
- **Signal Camera**—Two cameras were installed to monitor traffic signal status on two target approaches. The signal cameras also recorded pedestrian push button behaviors.

At the Sarasota intersections, students with training observed pedestrian behaviors before and after implementing APD devices.

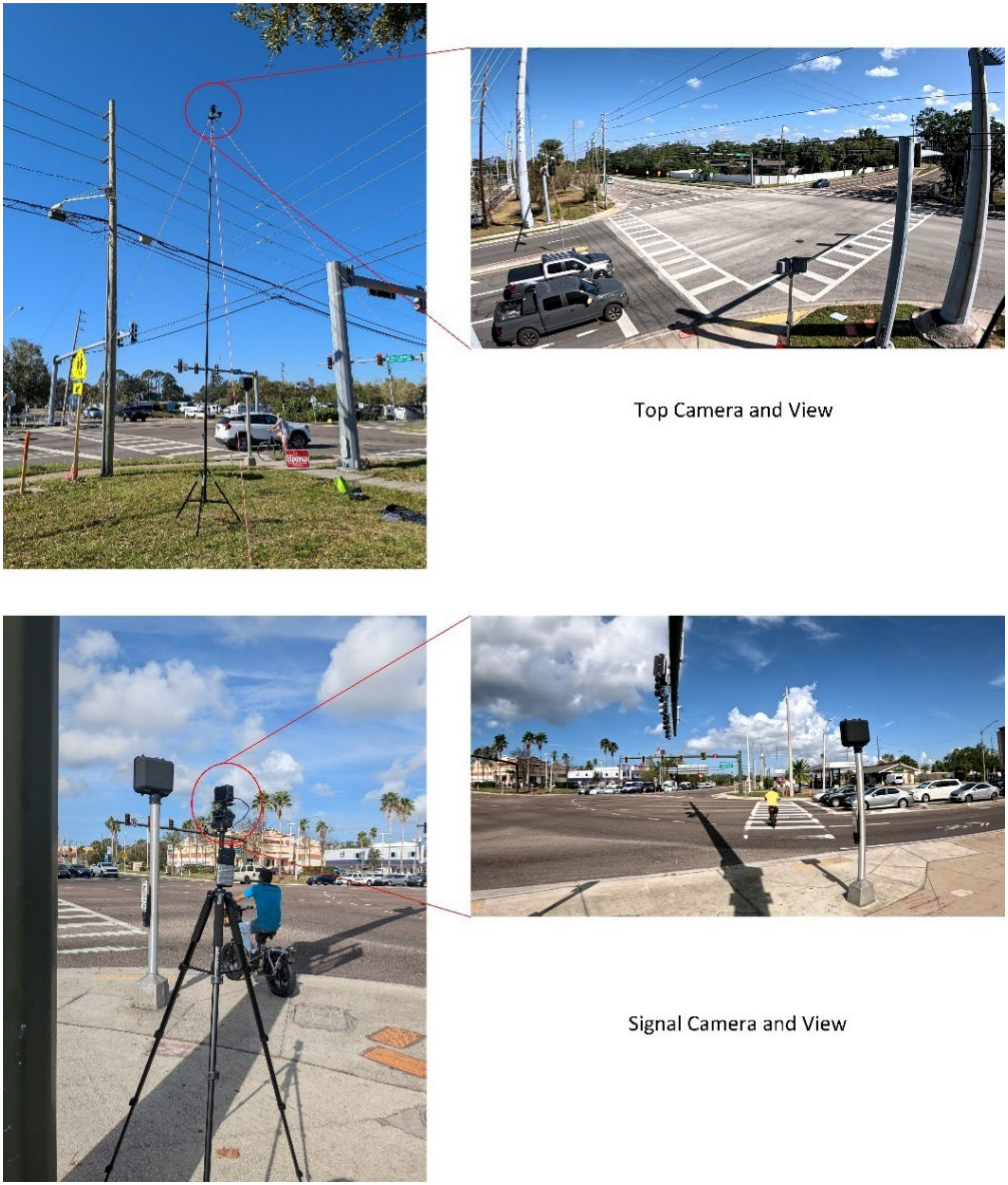


Figure 4-1. Camera installation and views in field data collection

4.1.2 Video Processing

Figure 4-2 shows the procedure of video processing. The key steps include (1) identifying pedestrian scenes, (2) synchronizing signal scenes, and (3) human review.

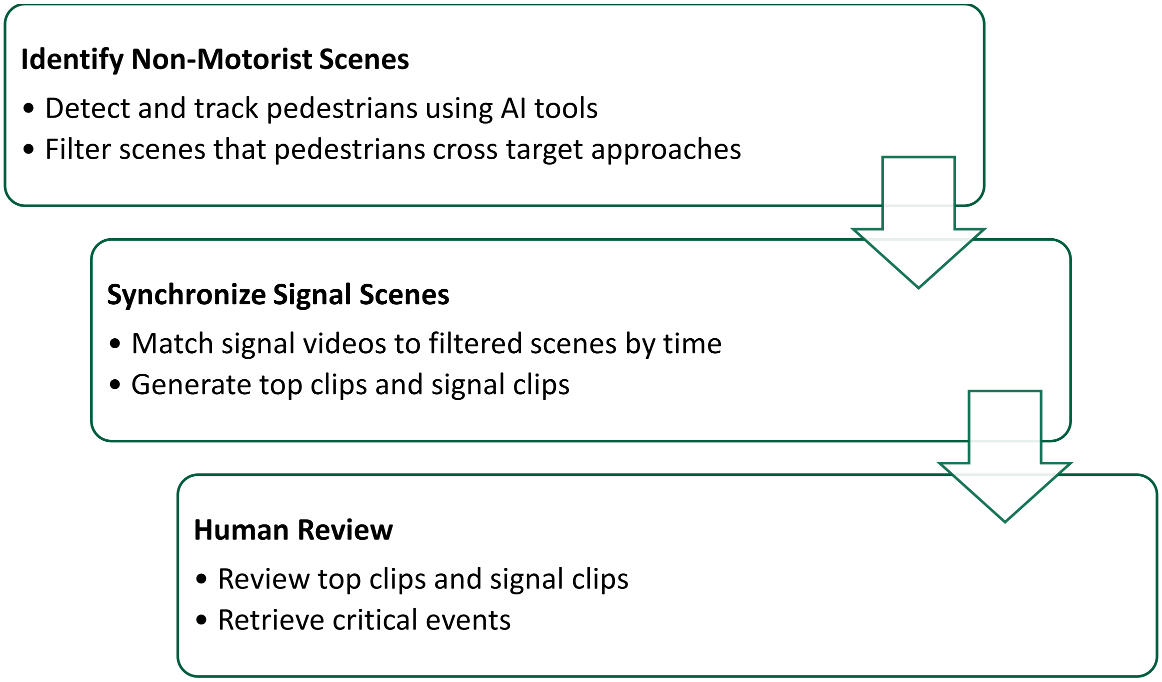


Figure 4-2. Video processing procedure

4.1.2.1 Identification of Non-motorist Scenes

The research team used CUTR's AI tools, as shown in Figure 4-3, to detect and track pedestrians (including pedestrians, bicyclists, and micromobility users) from the top-camera videos. The pedestrian trajectories were produced from the AI analysis.

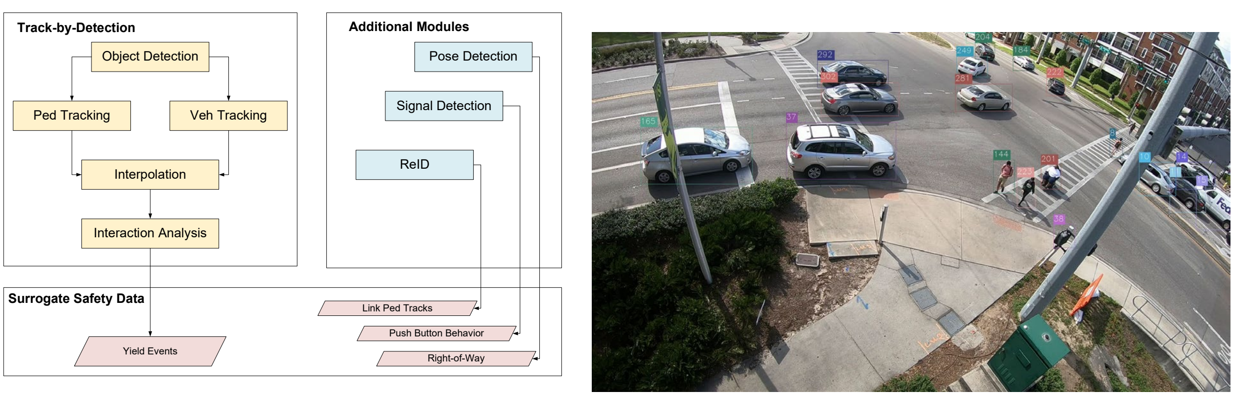


Figure 4-3. CUTR's AI tools for video data analysis

The research team filtered the trajectories to identify pedestrian video scenes by the following criteria:

- Pedestrians crossing on target approaches, and
- Potential conflicting turning vehicles (left or right) presenting.

The target approach indicates the approach on which the treatment impacts. For example (Figure 4-4), a blank-out sign is installed to control eastbound (EB) right turns onto southbound (SB). The research team filtered pedestrian scenes that cross northbound (NB) (the target approach from south to north) since they potentially conflict with the right-turn vehicle onto eastbound (EB).

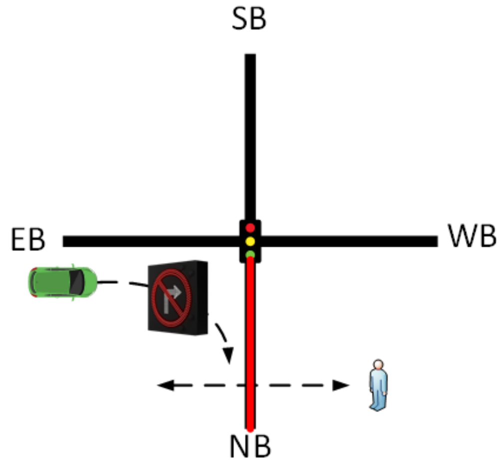


Figure 4-4. Example of target approach in non-motorist scene identification

The pedestrian scenes were extracted from raw videos and output as short footage showing the whole procedure of a roadway user crossing the approach.

4.1.2.2 Synchronization of Signal Scenes

For each identified pedestrian scenario, the research team needs to know the traffic signal status and treatment operations when a pedestrian crosses the street. The research team matched the top-camera videos and signal videos based on the video recording timeline. The research team extracted short clips that are matched to the pedestrian scenes. Figure 4-5 shows an example of matched top camera and signal camera scenes (matched at 11/10/2024 13:16:30).

Top Camera Scene Signal Camera Scene

Matched at 11/10/2024 13:16:30

Figure 4-5. Matched top camera scene and signal camera scene

4.1.2.3 Human Review

The research team reviewed the pedestrian scenes and matched signal clips to produce behavior safety data. Table 4-1 summarizes the data generated from the video review. Multistage reviews were conducted to ensure the review quality.

Table 4-1. Safety Data from Video Review

Category	Data	Description
Pedestrian	Mode	Pedestrian, bicycle, micromobility, or mixed
	Crossing Time	Date/Hour/Minutes
	Crossing Route	Side, direction, use of crosswalk
	Crossing Behavior	Right-of-Way, push button
Turning Vehicle	Traffic Signal	Traffic signal status for turning vehicles
	Yield	Turning vehicle yield to non-motorist
	Unsafe event	Conflict between turning vehicles and pedestrians, too close to pedestrians, or other risk situations
Treatment Operation	Omission of FYA	FYA is omitted during a protected plus permissive left-turn operation when pedestrians cross the street
	Blank-out Sign	A blank-out sign displays "No Turn on Red" when pedestrians cross the street with the right of way
	LPI	LPI is activated when pedestrians cross the street
	Automated Pedestrian Detection	Directly observed in field, trigger pedestrian phase or not

4.1.3 Statistical Analysis

This research primarily utilizes qualitative and quantitative methods for data collection and analysis, employing both before-and-after and cross-sectional approaches to evaluate the effectiveness of various countermeasures. The evaluation process is divided into three methods:

- **Cross-Sectional Analysis**: The safety measures obtained from field data collection were compared between treatment sites (blank-out sign + LPI or O-FYA + LPI) and control sites (no treatment) to evaluate the impacts of the two treatment combinations in reducing the conflicts between pedestrians and turning vehicles.
- **Before-and-After Left Turn Crash Analysis**: Historical crash data (left turn-pedestrian crashes) were compared before and after the implementation of FYA omission.
- **Before-and-After Analysis**: The data observed at the Sarasota sites were compared before and after the implementation of automatic pedestrian detection (APD) to examine the safety impacts of APD treatment. Due to the limited resources in the City of Sarasota after a hurricane, the APD treatment was evaluated individually.

In the evaluation, descriptive statistics and hypothesis tests were applied to examine the significance of the treatment effectiveness.

4.2 Blank-out Sign and Leading Pedestrian Intervals

This section describes the evaluation of the implementation of combined blank-out sign and leading pedestrian intervals (LPI) countermeasures for pedestrian safety. The content includes treatment description, study sites, field data collection, and evaluation results.

4.2.1 Treatment Description

A blank-out sign is an electronic traffic sign that can be activated or deactivated based on traffic conditions or time of day. These signs are typically used to regulate right-turn movements by displaying a "No Right Turn" message (R3-1) when the turn is prohibited and going blank when the turn is allowed.

Figure 4-6 shows the operation of the blank-out sign during pedestrian phases:

- As shown in Figure 4-6A, if pedestrians do not push the pedestrian signal button, the signal head for right-turn vehicles displays green and the blank-out sign display is blank. Vehicles can make the right turn but need to yield to crossing pedestrians.
- As shown in Figure 4-6B, if pedestrians push the pedestrian signal button (set a pedestrian call to the traffic controller), the blank-out sign displays a “No Right Turn” message. Right-turning vehicles must stop before the stop bar and wait for the next green signal. The conflicts between right-turn vehicles and crossing pedestrians are eliminated or reduced.

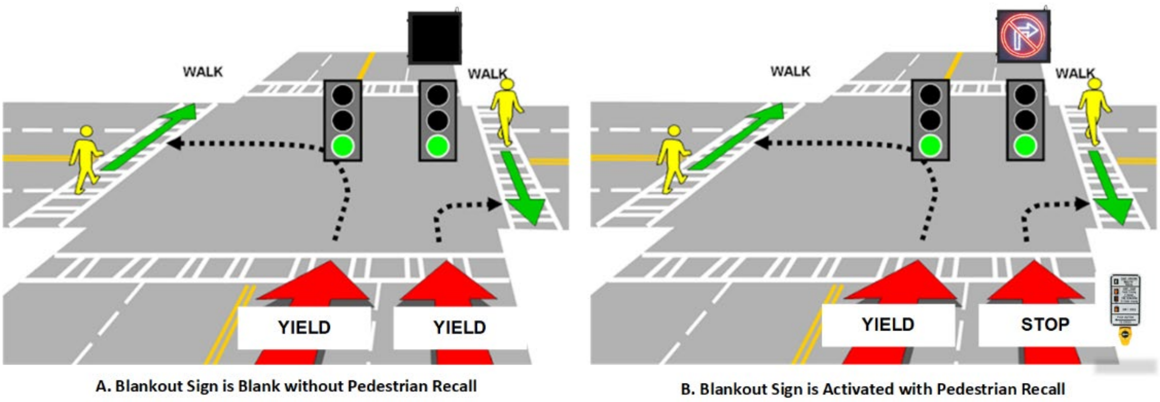


Figure 4-6. Concept of blank-out sign for right-turn movement

A leading pedestrian interval (LPI) displays the WALK signal for 3-7 seconds for right-turn vehicles before the green signal for vehicles in the parallel direction. The concept of LPIs is given in Figure 4-7. This study evaluated the joint safety effects of the blank-out sign plus LPIs in preventing right-turn and pedestrian conflicts and improving pedestrian safety at signalized intersections. Because implementation of the combined two treatments could not be found during the study timeline, the study adopts the cross-sectional method rather than a before-after approach.

4.2.2 Study Sites

4.2.2.1 Site Characteristics

Pinellas County has implemented blank-out signs plus LPIs at their signalized intersections. The research team identified two signalized intersections based on the following considerations:

- Equipped with blank-out signs plus LPIs
- Significant pedestrian volumes
- Significant right-turn vehicles

Figure 4-7 shows the layouts of the two signalized intersections: (1) Bayshore Blvd @ Curlew Rd/Causeway Blvd, Dunedin, Florida, and (2) East Bay Dr @ Missouri Ave/Seminole Blvd, Largo, Florida. At Bayshore Blvd @ Curlew Rd, blank-out sign plus LPI is available for right turns from EB to NB, and blank-out sign without LPI is available for pedestrians on NB. At East Bay Dr @ Missouri Ave, the treatment is available for all approaches.

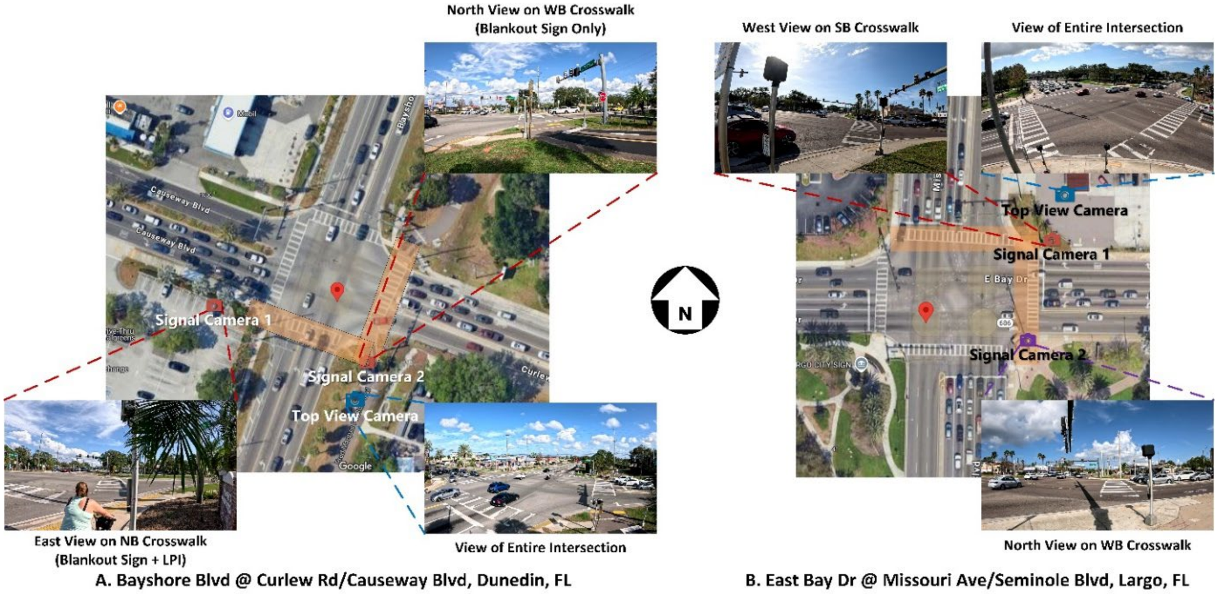


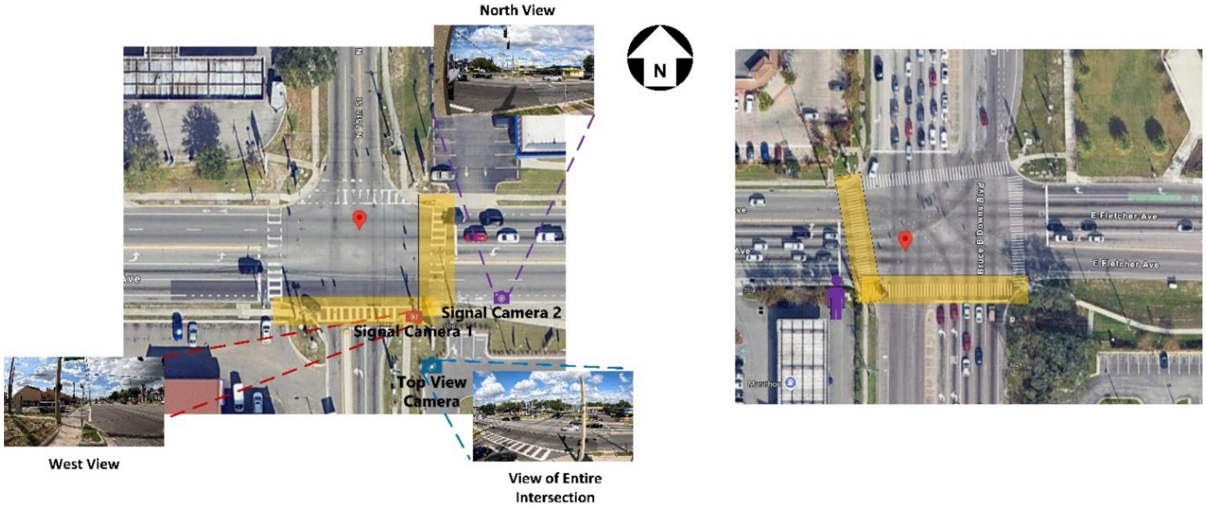
Figure 4-7. Study sites for blank-out sign plus LPIs

The research team also identified two control intersections, (1) Fletcher Ave @ 15th St and (2) Fletcher Ave @ Bruce B Downs Blvd, Tampa, Florida, based on the following considerations:

- Geometry, speed limit, and traffic patterns are similar to treated sites
- Allow Right-Turn-On-Red
- No blank-out sign and LPIs
- Significant pedestrian volumes

- Significant right turn volumes

The layout of control sites is shown in Figure 4-8. The characteristics of treated and control intersections are summarized in Table 4-2.



A. Fletcher Ave @ 15th St, Tampa, FL B. Fletcher Ave @ Bruce B Downs Blvd, Tampa, FL

Figure 4-8. Control sites for blank-out sign plus LPIs

Table 4-2. Summary of Study Sites for Blank-out Sign plus LPIs

	Treated Sites		**Control Sites**	
	Bayshore Blvd @ Curlew Blvd	**Easy Bay Dr @ Missouri Ave**	**Fletcher Ave @ 15th St**	**Fletcher Ave @ Bruce B Downs Blvd**
City	**Dunedin**	**Largo**	**Tampa**	
Designated Crosswalk	NB/WB	WB/SB	NB/WB	EB/NB
Designated Right Turn "From" Approach	EB/NB	NB/WB	EB/NB	SB/EB
Lane Configuration on "From" Approach*	• EB: L1/T1/R1 • NB: L1/T1/R1	• NB: L2/T3/R1 • WB: L2/T2/R1	• EB: L1/T1/TR1 • NB: L1/TR1	• SB: L2/T3/R1 • EB: L2/T2/R1
Functional Classification	Urban Minor Arterial	Urban Principal Arterial / Urban Minor Arterial	Urban Minor Arterial / Urban Local	Urban Principal Arterial / Urban Minor Arterial
Speed Limit on "From" Approaches	35mph / 40mph	45mph / 35mph	35mph / 30mph	45 mph
AADT	21,500/10,000	33,500/42,000	42,500/unknown	50,500/42,500
Blank-out Sign	EB/NB	All approaches	No	No
LPI	Crosswalk on NB	All approaches	No	No
RTOR	Allow	Allow	Allow	Allow

**L-exclusive left turn lane; T-through lane, R-exclusive right turn lane; TR-through and right turn shared lane*

4.2.2.2 Justification of Control Sites

As shown in Table 4-2, Bayshore Blvd @ Curlew Blvd and Fletcher Ave @ 15th St are medium size urban intersections on urban minor arterials with similar speed limits (30mph – 40mph). The Fletcher Ave site has a shared right turn lane, which is different from the exclusive lane at the Curlew Blvd site. The right-turn movements mainly occur on green time. The right-turn behaviors are similar on shared lanes and exclusive lanes during green time. Right-turn events that are impacted by other vehicle movements (i.e., through movements on shared lanes) were filtered in video processing. Thus, Fletcher Ave @ 15th St can be the control site for Bayshore Blvd @ Curlew Blvd.

East Bay Dr @ Missouri Ave and Fletcher Ave @ Bruce B Downs Blvd are both large intersections (AADT >= 42,000) with similar functional classification (Urban Principal Arterial/Urban Minor Arterial), lane configuration (two exclusive left-turn lanes, two or three through lanes, and one exclusive right lane), and speed limit (45 mph). Thus, the two intersections are the second pair for comparison.

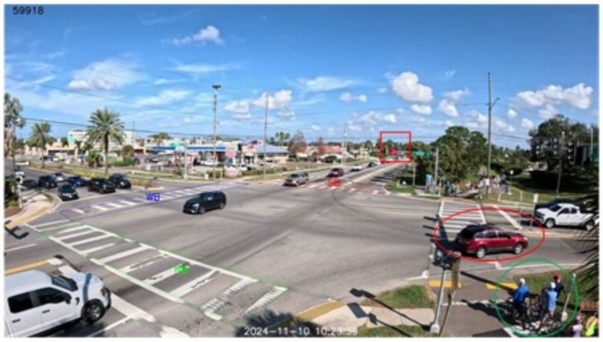
4.2.3 Field Data Collection

The field data collection is summarized in Table 4-3.

Table 4-3. Summary of Field Data Collection for Blan-out Signs plus LPI

	Treated Sites		Control Sites	
	Bayshore Blvd @ Curlew Blvd	**Easy Bay Dr @ Missouri Ave**	**Fletcher Ave @ 15th St**	**Fletcher Ave @ Bruce B Downs Blvd**
Date	11/10/2024	11/11/2024	11/9/2024	02/17/2025
Time	10am – 8pm	10am – 7pm	10am – 8pm	9am – 5pm
Weather	Clear	Clear	Clear	Clear
Data Collection Method	Video	Video	Video	Field Observation

The research team recorded videos at two treated intersections, Fletcher Ave @ 15 St, and processed the videos using CUTR's AI tools (described in section 4.1). At Fletcher Ave @ Bruce B Downs Blvd, a researcher directly observed pedestrians and right-turn vehicles in the field. The data collected are shown in Table 4-1. Two major safety measures for pedestrians involving right-turns were collected: (1) right-turn not yielding to pedestrians and (2) right-turn unsafe behaviors (conflicts or too close to pedestrians). Figure 4-9 demonstrates examples of unsafe and unyielding behaviors.



- Blankout Sign is ON
- Pedestrians have the Right-Of-Way
- The right turn vehicle **does not yield** to pedestrian's ROW

- Blankout Sign is ON
- Pedestrians have the Right-Of-Way
- The right turn vehicle is too close to pedestrians
- It is **UNSAFE**

Figure 4-9. Examples of unsafe and unyielding behaviors

The collected right-turn and pedestrian events were filtered based on the following criteria:

- Pedestrian crossings and conflicting right-turn vehicles were observed at the same time
- Excluding right-turn vehicles blocked by other vehicles while pedestrians are crossing the street
- Excluding school guard presence at treated sites

The filtered data were compared between treated sites (with blank-out sign plus LPIs) and the control site (without the treatment). The evaluation results are shown in the next section.

4.2.4 Evaluation Results

4.2.4.1 Comparison of Safety Measures

This study compared unyielding and unsafe behaviors of right-turn vehicles with and without the blank-out sign plus LPIs. The rates of safety measures are calculated as follows:

- Rate of Unsafe Behaviors—the number of unsafe events divided by the total number of events
- Rate of Unyielding Behaviors—the number of unyielding events divided by the total number of events

The safety measures are given in Table 4-4, and the comparisons of unsafe behavior rates and unyielding rates are shown in Figure 4-10.

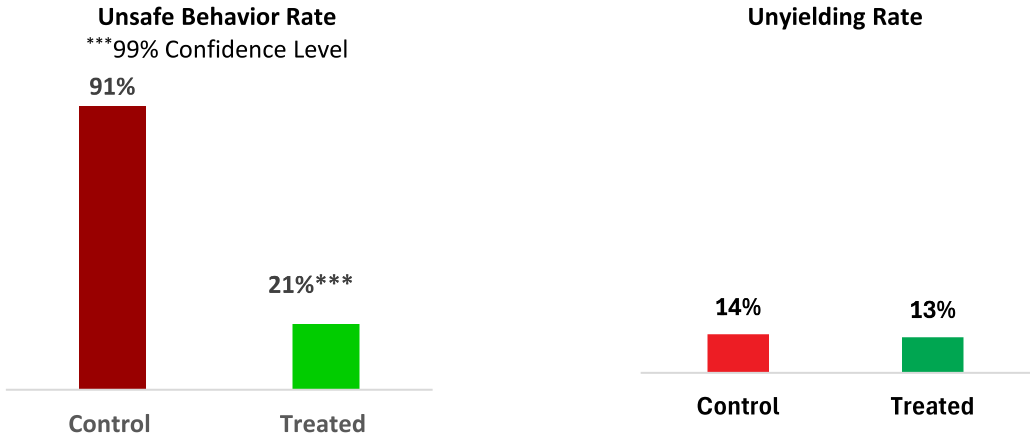
The comparison results show that:

- At Bayshore Blvd @ Curlew Rd, which is a middle sized intersection, blank-out signs (without LPI) reduced the unsafe rate by 70% (from 91% to 21%) and the unyielding rate by 1% (from 14% to 13%). The relative reductions of unsafe rate and unyielding rate are 77% (=70% ÷ 91%) and 7% (=1% ÷ 14%), respectively.

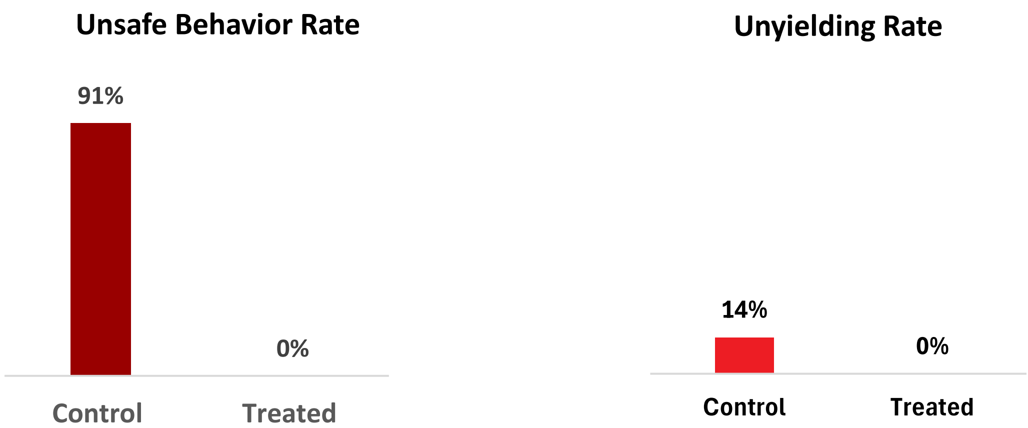
- At Bayshore Blvd @ Curlew Rd, the treatment from the combination of blank-out sign and LPI reduced the unsafe rate from 91% to 0% and unyielding rate from 14% to 0%. The relative reductions of unsafe rate and unyielding rate are 100% (=91% ÷ 91%) and 100% (=14% ÷ 14%), respectively.
- At East Bay Dr @ Missouri Rd, which is a large sized intersection, the treatment from the combination of blank-out sign and LPI reduced the unsafe rate by 34% (from 71% to 37%) and the unyielding rate by 10% (from 41% to 31%). The relative reductions of unsafe rate and unyielding rate are 48% (=34% ÷ 71%) and 24% (=10% ÷ 41%), respectively.
- The results imply that the right-turn treatment (blank-out sign) reduces unsafe and unyielding behaviors and improves pedestrian safety at signalized intersections. Compared to the blank-out sign only, the combination of blank-out sign and LPI, which displays the pedestrian "WALK" signal and the "No Right Turn" message earlier than green vehicle signals, has a more effective impact on reducing unsafe and unyielding behaviors.

Table 4-4. Comparison of Unyielding Rate and Unsafe Behaviors for Right-Turn Treatments

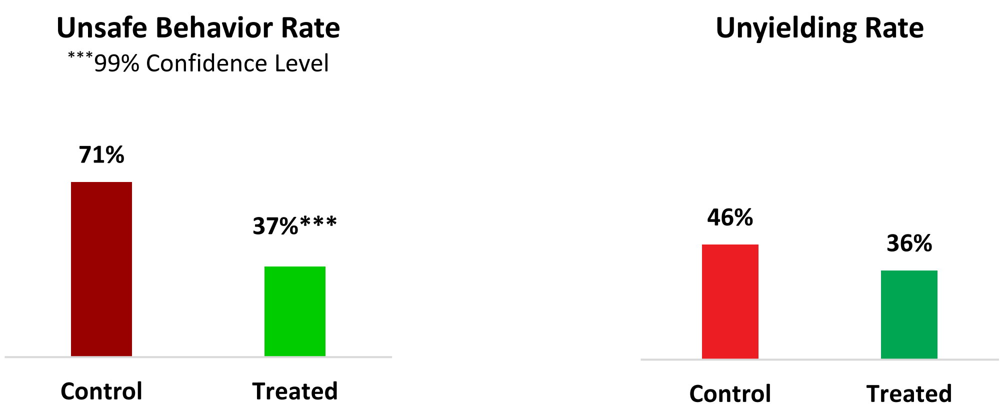
	Medium-sized Intersection			Large Sized Intersection	
Intersection	Bayshore Blvd @ Curlew Blvd		Fletcher Ave @ 15th St	Easy Bay Dr @ Missouri Ave	Fletcher Ave @ Bruce B Downs Blvd
	Treated (Blank-out)		Control	Treated	Control
	WB (w/o LPI)	NB (with LPI)			
Total Number	109	12	65	67	56
Safe	86	12	6	42	16
Unsafe	23	0	59	25	40
Unsafe Rate	**21%**	**0%**	**91%**	**37%**	**71%**
Yield	95	12	56	43	30
Unyielding	14	0	9	24	26
Unyielding Rate	**13%**	**0%**	**14%**	**36%**	**46%**



A. Bayshore Blvd @ Curlew Rd, WB (Treated, blank-out sign only) vs. Fletcher @ 15th (Control)



B. Bayshore Blvd @ Curlew Rd, NB (Treated, blank-out sign plus LPI) vs. Fletcher @ 15th (Control)



C. East Bay Dr (Treated, blank-out sign plus LPI) vs. Fletcher Ave @ Bruce B Downs Blvd (Control)

Figure 4-10. Comparison of unsafe behavior and unyielding rates for blank-out sign plus LPIs

4.2.4.2 *Pedestrian Behavior Analysis*

This study examined pedestrian behaviors at treated sites to understand their compliance with the treatments. In this study, videos that included the presence of safety crossing guards were excluded. Events in which crossing pedestrians and right-turning vehicles presented simultaneously were retained. Figure 4-11 shows the distribution of pedestrian mode at treated sites. As shown in Figure 4-11A, bicycles account for 79% of pedestrian crossing events at Bayshore Blvd and Curlew Blvd, followed by mixed groups (20%) and pedestrians (1%). The Fred Marquis Pinellas Trail, which runs along Bayshore Blvd at this intersection, attracts a large number of bicyclists.

Figure 4-11B shows the distribution of pedestrian mode at Easy Bay Dr @ Missouri Ave. Pedestrians account for 54% of crossing events, followed by bicycles (24%), and mixed groups (21%). Only one scooter was observed in this study.

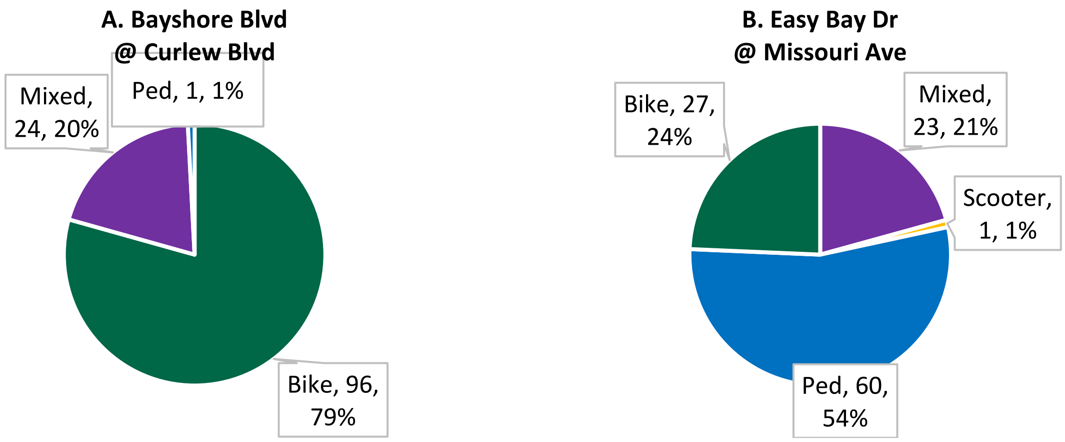


Figure 4-11. Distribution of pedestrian mode at treated sites with right-turn vehicles

The distribution of pedestrian right-of-way at treated sites is shown in Figure 4-12. Seven percent (7%) of pedestrians crossed during a RED signal (without Right-of-Way). Additionally, 7% of bicyclists and 2% of pedestrians either did not push the button or stepped into the crosswalk before the “WALK” signal was activated. Figure 4-13 shows the distribution of button-pushing behaviors. Five percent (5%) of pedestrians did not push the button when crossing the street. Among these non-pushing behaviors, 89% were bicyclists and 11% were pedestrians.

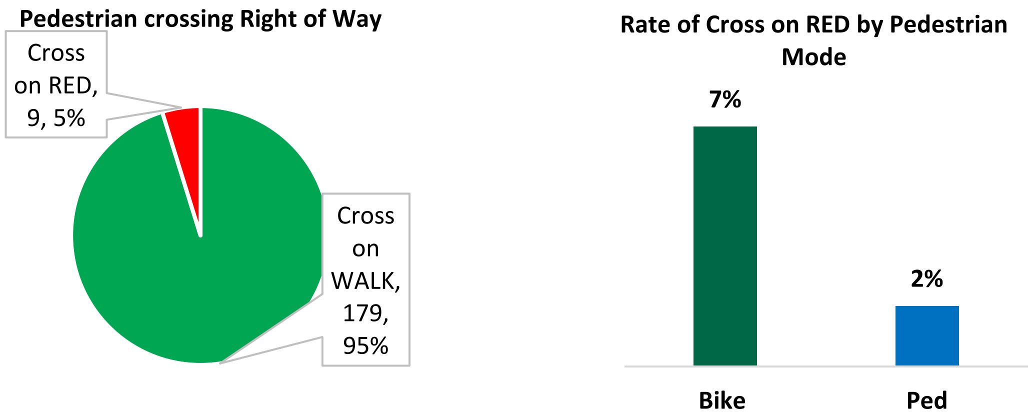


Figure 4-12. Distribution of pedestrian right-of-way (ROW)

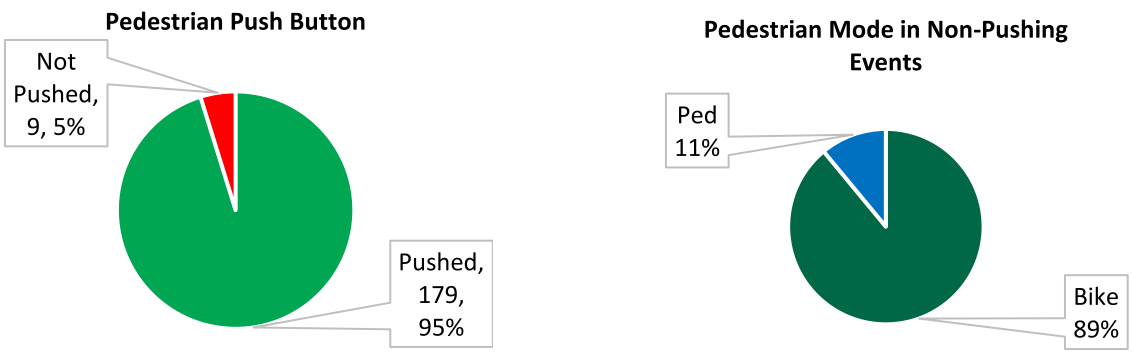


Figure 4-13. Distribution of pedestrian pushing button behaviors

4.2.4.3 Right-turn Vehicle Behavior Analysis

In field observations, the research team found that some drivers might misunderstand or ignore activated blank-out signs displaying the "No Right Turn" symbol (R3-1, Figure 4-6B). An example of continuous right-turn violations with an activated blank-out sign within one traffic signal cycle is shown in Figure 4-14. This event occurred at the intersection of East Bay Dr @ Missouri Ave, at the SB crosswalk. Five vehicles, turning from EB to SB within one traffic cycle failed to obey the blank-out sign displaying the "No Right Turn" message.

- **The first vehicle** entered the intersection when the vehicle signal was RED and conflicting vehicle movements had the right-of-way (green signal). During its turn, the blank-out sign and the pedestrian "WALK" signal were activated simultaneously. The vehicle tried to complete its right turn before a pedestrian approached although a "No Right Turn" message was displayed.
- **The subsequent vehicles** turned during the display of the blank-out sign "No Right Turn" message although the 3rd vehicle correctly yielded to the crossing pedestrian. These vehicles misunderstood or ignored the blank-out sign and behaved as they would with a normal green signal—yielding to pedestrians and looking for a gap to turn.

- **1st vehicle** turned right with an activated blank-out sign
    - Time: 12:01:09
    - Pedestrian “WALK” signal and blackout sign are activated simultaneously
    - The vehicle signal is red (the LPI is activated)
    - A pedestrian started to cross at the far side
    - The vehicle completed right turn on red.

- **2nd vehicle** turned right with an activated blank-out sign
    - Time: 12:01:12
    - Pedestrian “WALK” signal and blank-out sign are activated
    - The vehicle signal is green
    - The pedestrian stepped into the crosswalk at the far side

- **3rd vehicle** turned right with an activated blank-out sign
    - Time: 12:01:17
    - Pedestrian “WALK” signal and blank-out sign are activated
    - The vehicle signal is green
    - The pedestrian was close to the middle of crosswalk

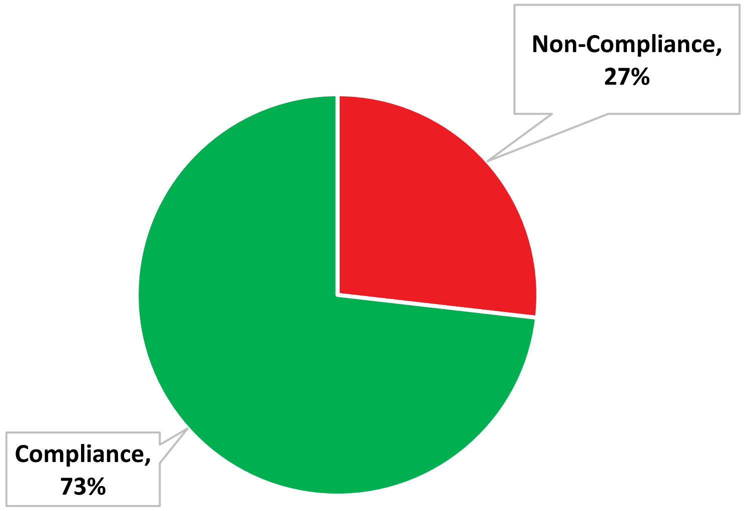
- **4th vehicle** turned right with an activated blank-out sign
    - Time: 12:01:27
    - Pedestrian "WALK" signal and blank-out sign are activated
    - The vehicle signal is green
    - The pedestrian was close to the end of crosswalk
    - The vehicle yielded to the pedestrian

- **5th vehicle** turned right with an activated blank-out sign
    - Time: 12:01:32
    - Pedestrian "WALK" signal and blank-out sign are activated
    - The vehicle signal is green
    - The pedestrian completed crossing

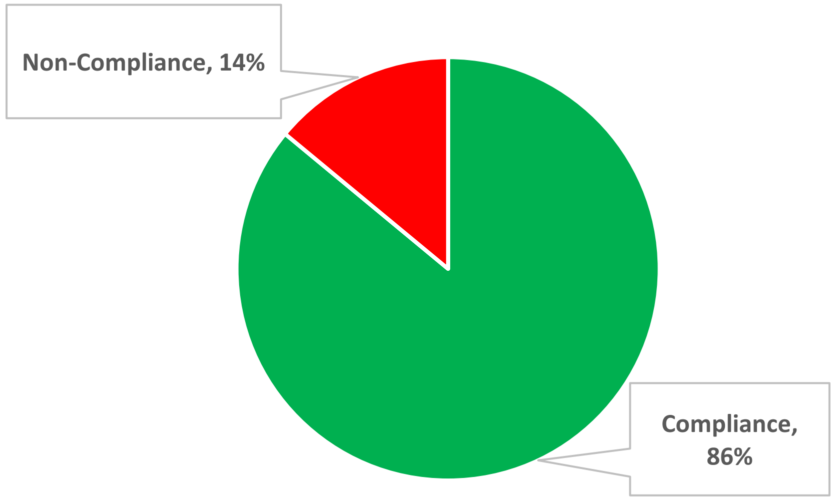
Figure 4-14. Examples of right-turn violations with an activated blank-out sign

Figure 4-15A gives the overall compliance rate of right-turn vehicles to activated blank-out signs at the two treated intersections. Results show that 73% of right-turn vehicles correctly obeyed the "No Right Turn" rule—stopping during the activation of the blank-out sign and 27% of right-turn vehicles did not follow the rule—turning during the activation of the blank-out sign. The most common violations involve cases similar to the first vehicle mentioned above—entering the intersection by the end of the red phase (RTOR is allowed) and trying to turn before the pedestrian arrives even though the blank-out sign is on.

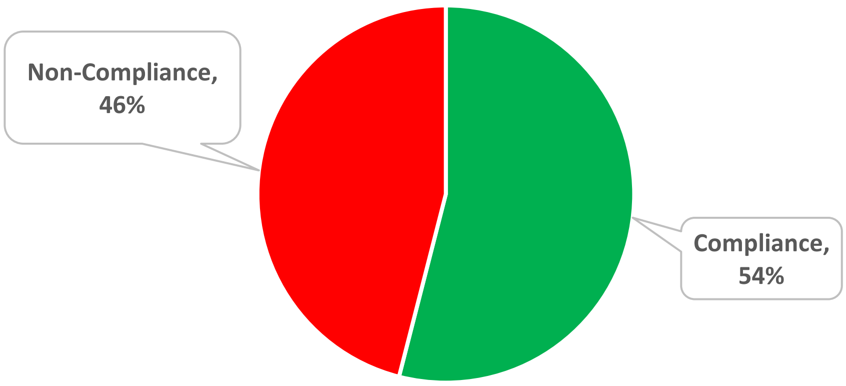
Figure 4-15B and Figure 4-15C show the compliance rates at Bayshore Blvd @ Curlew Blvd and Easy Bay @ Missouri Ave. East Bay @ Missouri Ave has a much higher non-compliance rate (46%) than Bayshore Blvd @ Curlew Blvd (14%). The high traffic demand at a large sized intersection, such as East Bay @ Missouri Ave, may result in the high non-compliance rate.



A. Overall



B. Bayshore Blvd @ Curlew Blvd



C. East Bay Dr @ Missouri Ave

Figure 4-15. Compliance rate of right turn vehicles to activated blank-out sign

4.3 Omission of Flashing Yellow Arrow and Leading Pedestrian Intervals

This section describes the evaluation of the combined countermeasures of omission of flashing yellow arrow (O-FYA) plus leading pedestrian intervals (LPIs) for pedestrian safety. The content includes treatment description, study sites, field data collection, evaluation results, and crash analysis.

4.3.1 Treatment Description

A flashing yellow arrow (FYA) is a left-turn signal that flashes to indicate that drivers may proceed with a left turn, but only after yielding to oncoming traffic and pedestrians. During a permissive left-turn movement, drivers must identify a safe gap in oncoming traffic to make their turn, while also yielding to pedestrians with the right-of-way. The complexity and demands of executing a permissive left turn can sometimes lead drivers to overlook important tasks, such as scanning for pedestrians, which may affect their ability to complete other necessary actions safely [11]. This can lead to collisions between pedestrians and left-turning vehicles, particularly during the flashing yellow arrow phase. To reduce the risk of such crashes, it is recommended to omit the permissive left-turn phase or FYA during protected and permitted left-turn operations when the pedestrian phase is active [62].

Figure 4-16 shows the operation of omission of FYA (O-FYA) during pedestrian phases:

- As shown in Figure 4-16A, if pedestrians do not push the pedestrian signal button (equivalent to traditional FYA), the signal head for left-turn vehicles displays a flashing yellow arrow. Left-turn vehicles need to yield to oncoming traffic in the opposite direction and crossing pedestrians.
- As shown in Figure 4-16B, if pedestrians push the pedestrian signal button (set a pedestrian call to traffic controller), the signal head for left-turn vehicles displays a solid

red arrow. Left-turn vehicles must stop before the stop bar and wait for a green signal. The conflicts between left-turn vehicles and crossing pedestrians are eliminated or minimized.

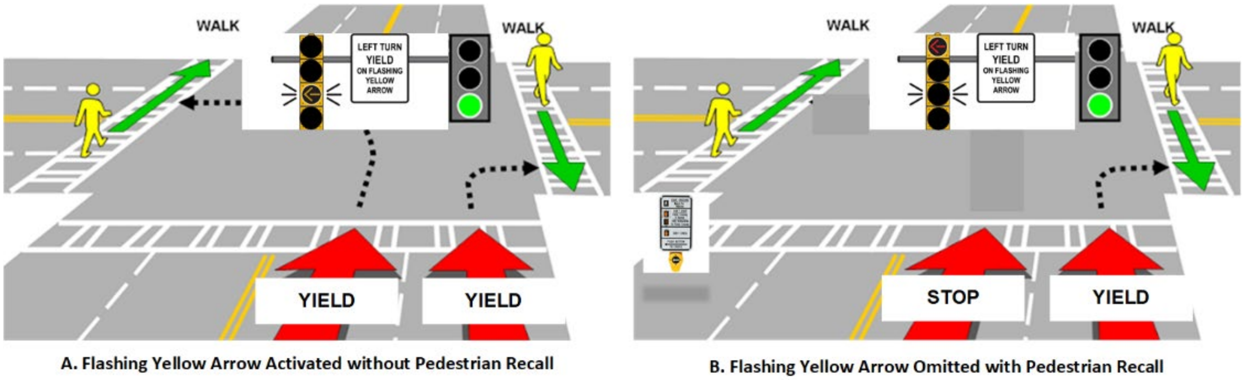


Figure 4-16. Concepts of omission of flashing yellow arrow (O-FYA)

A leading pedestrian interval (LPI) displays the WALK signal 3-7 seconds before the green signal for vehicles in the parallel direction. LPIs can help pedestrians who are slower to start crossing and increase the visibility of pedestrians crossing the street. This strategy tends to reduce conflicts between pedestrians and left- or right-turning vehicles and improve pedestrian safety at signalized intersections. The concept of LPIs is shown in Figure 4-17.

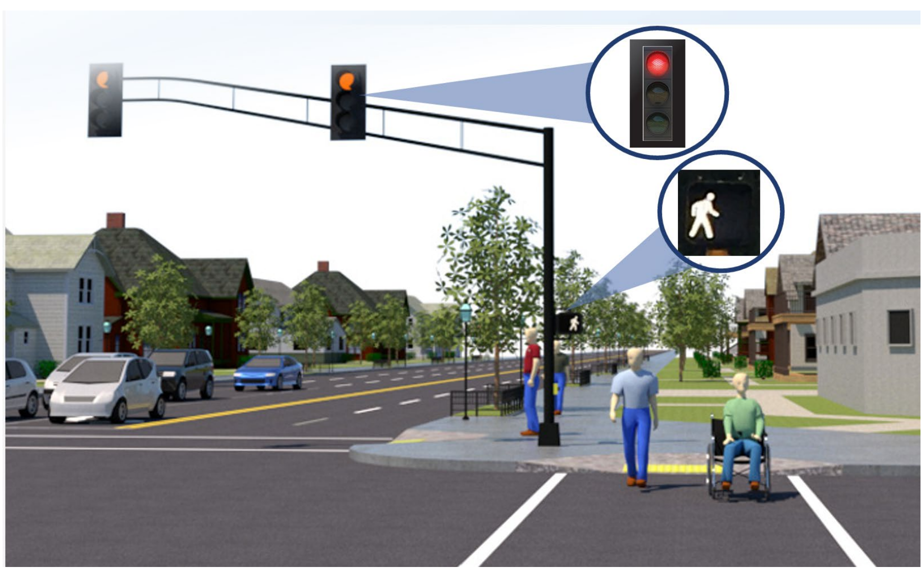


Figure 4-17. Concept of leading pedestrian intervals

Source: FHWA

This study evaluated the joint safety effects of O-FYA plus LPIs in preventing left-turn and pedestrian conflicts and improving pedestrian safety at signalized intersections. Because no implementation of the combined two treatments could be found during the study timeline, the study adopts the cross-sectional method rather than a before-after approach.

4.3.2 Study Sites

4.3.2.1 Site Characteristics

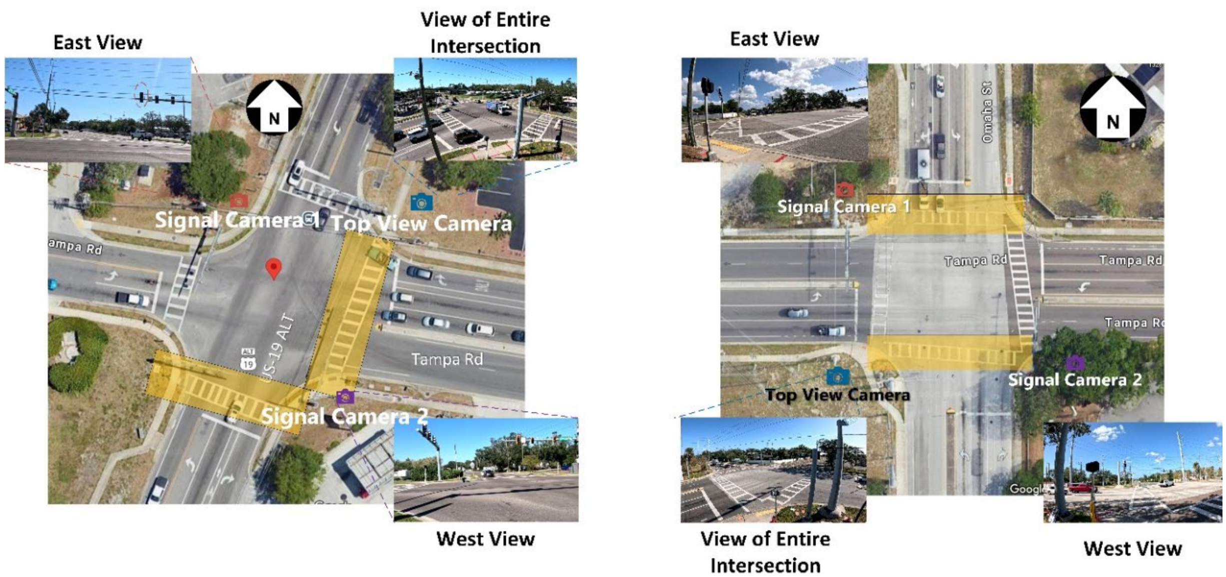
Pinellas County has implemented O-FYA and LPIs at its signalized intersections. The research team identified two signalized intersections— (1) US-19 ALT @ Tampa Rd and (2) Omaha St @ Tampa Rd, Palm Harbor, Florida—based on the following considerations:

- Equipped FYA with omission and LPIs for left turn vehicles
- Significant pedestrian volumes

The intersection of Fletcher Ave @ 15th St, Tampa, Florida, was identified as the control site based on the following considerations:

- Geometry, speed limit, and traffic patterns are similar to treated sites
- Equipped permissive left-turn signal
- Significant pedestrian volumes

The treated intersections (with the two treatments) and the control sites (without the two treatments) are shown in Figure 4-18 and Figure 4-19, respectively. Three cameras were installed to monitor left-turn vehicles and crossing pedestrians at designated crosswalks, as highlighted in the figures. The characteristics of treated and control intersections are summarized in Table 4-6.



Site 1: US-19 ALT @ Tampa Rd, Palm Harbor, FL

Site 2: Omaha St @ Tampa Rd, Palm Harbor, FL

Figure 4-18. Treatment sites for O-FYA + LPI

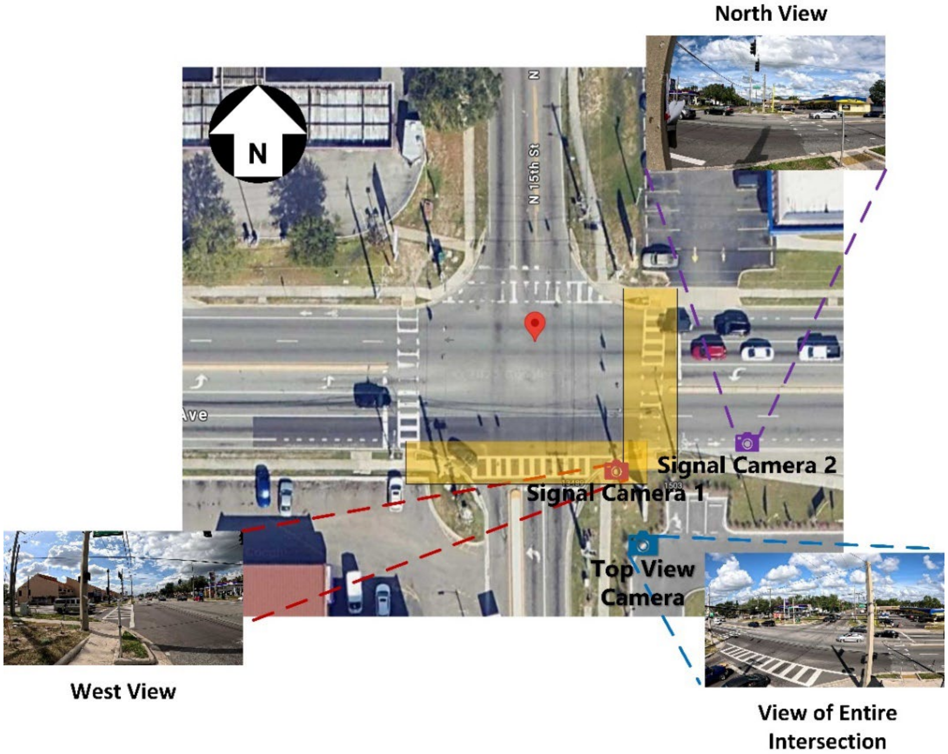


Figure 4-19. Control site: Fletcher Ave @ 15th St, Tampa, FL

Table 4-5. Summary of Study Sites for O-FYA plus LPIs

	Treated Sites		**Control Site**
	US-19 ALT @ Tampa Rd	**Omaha St @ Tampa Rd**	**Fletcher Ave @ 15th St**
City	**Palm Harbor**		**Tampa**
Designated Crosswalk	NB/WB	NB/SB	NB/WB
Designated Left Lane Approach	SB/WB	WB/EB	SB/WB
Lane Configuration on Left Turn Approach*	• WB: L1/T1/R1 • SB: L1/TR1	• WB: L1/T1/TR1 • EB: L1/T1/TR1	• SB: L1/TR1 • WB: L1/T1/TR1
Functional Classification	Urban Minor Arterial	Urban Minor Arterial	Urban Minor Arterial / Urban Local
Speed Limit	45mph/25mph	40mph/25mph	25mph/35mph
AADT	21,000/3,300	18,000/3,300	42,500/unknown
Left-Turn Phase	Protected + FYA w. Omission	Protected + FYA w. Omission	Protected + Permissive
LPI	Yes	Yes	No

**L-exclusive left turn lane; T-through lane, R-exclusive right turn lane; TR-through and right turn shared lane*

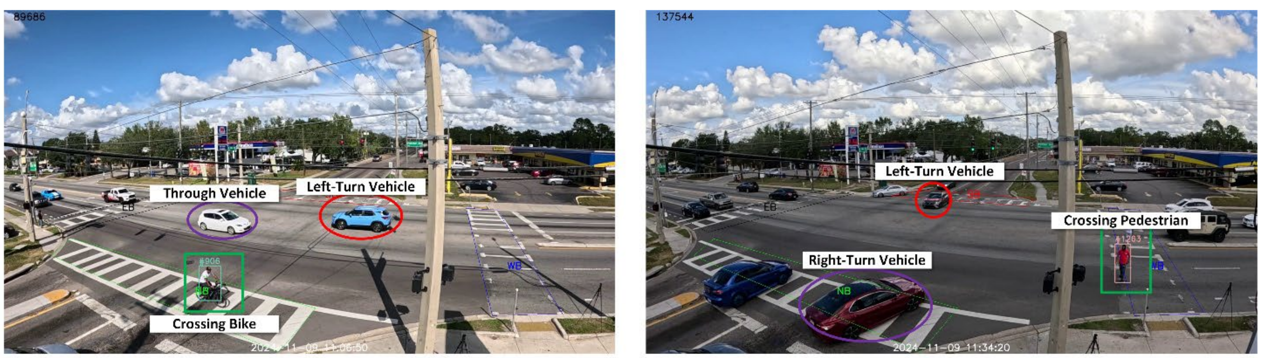
4.3.2.2 Justification of Control Sites

In a cross-sectional study, a control site serves as a benchmark to compare the outcomes observed at the treated sites. As shown in Table 4-9, the control site has the same functional classification (urban minor arterial) and the same left-turn lane configuration (one exclusive left-turn lane) as the treated sites. The speed limits of the control and treated sites are also similar (45 mph/40 mph vs. 35 mph on the major approach, and 25 mph vs. 25 mph on the minor approach).

The major difference between the control and treated sites is the annual average daily traffic (AADT). The control site's AADT is 42,500, which is higher than that of the treated sites (21,000/18,000). A high traffic volume may reduce the opportunity for left-turning vehicles to find a gap during a permissive phase. To eliminate the impact of high traffic volume on left-turn pedestrian interactions at the control site, this study selected observations at both treated and control sites based on the following criteria:

- Vehicles that were fully blocked by through or right-turn vehicles in the opposite direction were filtered out.
- Only vehicles that had an opportunity to find a gap and turn left when pedestrians were present in the crosswalk were included.

Figure 4-20 provides examples of left-turning vehicles blocked by through/right-turn vehicles while a pedestrian is crossing the street.



- Left-turn vehicle must yield to through vehicle
- No opportunity to complete left-turn during the bike cross NB

- Left-turn vehicle must yield to right-turn vehicle
- No opportunity to complete left-turn during the pedestrian cross WB

Figure 4-20. Examples of filtered left-turn observations

4.3.3 Data Collection and Analysis

The field data collection is summarized in Table 4-7.

Table 4-6. Summary of Field Data Collection for O-FYA plus LPI

Intersection	US-19 ALT @ Tampa Rd (Treated Site)	Omaha St @ Tampa Rd (Treated Site)	Fletcher Ave @ 15th St (Control Site)
Date	10/24/2024 11/03/2024	10/31/2024 11/02/2024	11/9/2024
Time	10am – 8pm	10am – 7pm	10am – 8pm
Weather	Clear	Clear	Clear

The research team processed the videos using the approach described in Section 4.1 and retrieved data as shown in Table 4-1. Two major safety measures for pedestrians involving left-turns were collected from the videos: (1) left-turn not yielding to pedestrians and (2) left-turn unsafe behaviors. Figure 4-21 demonstrates examples of unsafe and unyielding behaviors.

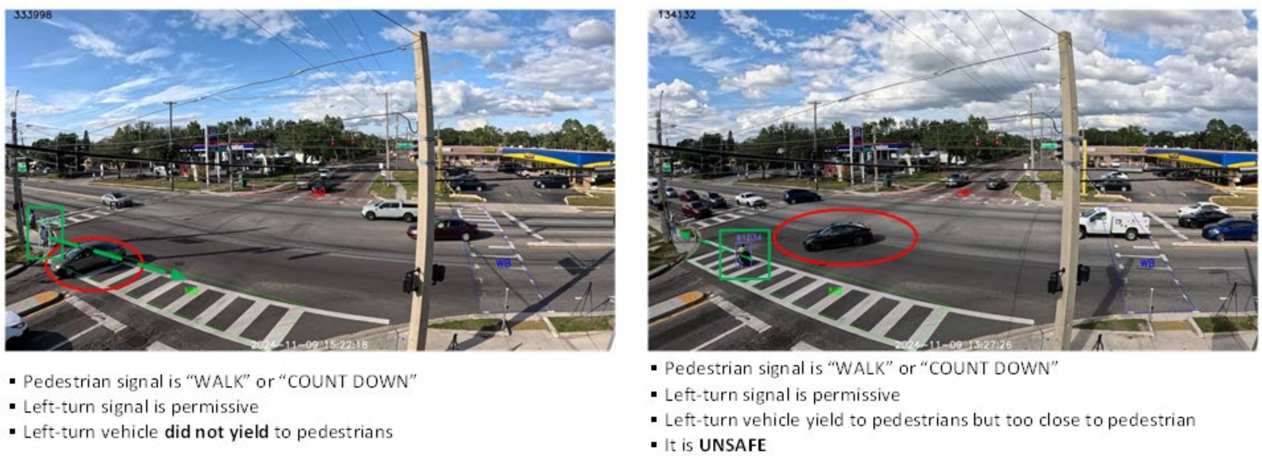


Figure 4-21. Examples of unsafe and unyielding behaviors

The collected left-turn and pedestrian events were filtered based on the following criteria:

- If left turns are permitted, left-turn vehicles and pedestrian crossings are observed concurrently
- If the FYA is omitted (left turns are prohibited), vehicles in the left-turn lanes—unaffected by opposing traffic—and pedestrians crossing at conflicting crosswalks were observed concurrently. The elimination of potential conflicts with pedestrians for these left-turn vehicles was a result of the FYA omission.
- Excluding left-turn vehicles blocked by through or right-turn vehicles while pedestrians cross the street
- Excluding school crossing guard or law enforcement presence at treated sites

The filtered data were compared between treated sites (with O-FYA plus LPIs) and the control site (without the treatment). The evaluation results are shown in the next section.

4.3.4 Evaluation Results

4.3.4.1 Safety Performance of O-FYA plus LPI

This study compared the unyielding and unsafe behaviors of left-turn vehicles with and without the treatment combination (O-FYA + LPI), as shown in Table 4-8. The comparison of unsafe behavior rate and unyielding rate is shown in Figure 4-22. Fisher's Exact Test and Bayesian analysis—both appropriate for small sample sizes—were applied to evaluate the effectiveness of O-FYA combined with LPI in reducing unsafe behaviors and unyielding behaviors, respectively.

Table 4-7. Comparison of Unyielding Rate and Unsafe Behaviors for Left-Turn Treatments

	Treated	Control
Safe	22	27
Unsafe	1	8
Yield	22	29
Not yield	1	6

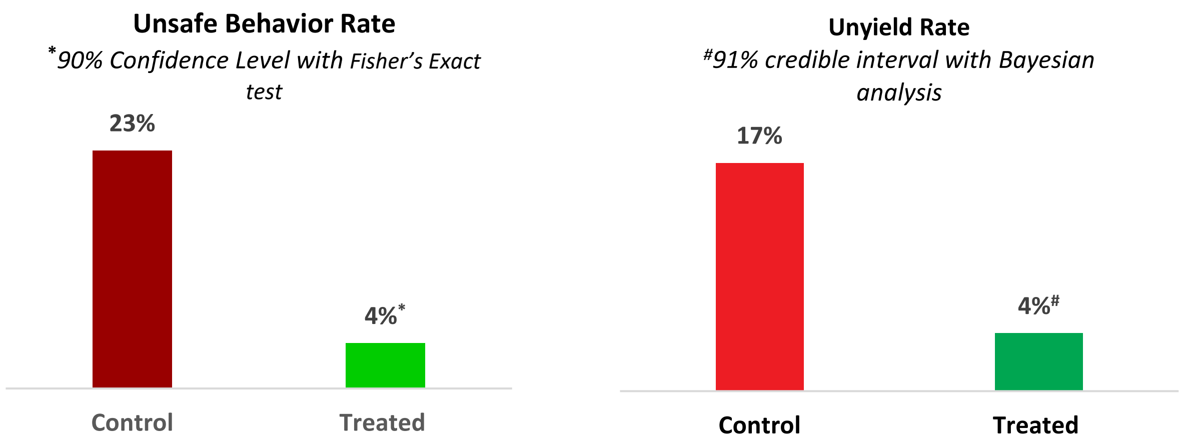


Figure 4-22. Unsafe behavior and unyielding rates with and without O-FYA plus LPI

The unsafe behavior rate was reduced by 19% from 23% (control site) to 4% (treated site), representing a relative change of 83% (= [23%-4%]/23%). This reduction is statistically significant at the confidence level of 90%. Meanwhile, the unyielding rate was reduced by 13% from 17% (control site) to 4% (treated site), implying a relative change of 76% (= [17%-4%]/17%). The Bayesian analysis strongly supports the reduction; the credible interval is 91% (91% probability that unyielding behavior is reduced). It implies that the left-turn treatment (O-FYA + LPI) improves pedestrian safety at signalized intersections significantly because the treatment separates crossing pedestrians and left-turn vehicles in time.

Only one unsafe/unyielding event was observed at treated sites (US-19 ALT @ Tampa Rd, SB), as shown in Figure 4-23. A cyclist who was intending to cross US-19 ALT (SB) pushed the button and activated the omission of FYA for left-turn vehicles from WB (turning into SB). The pedestrian "WALK" signal is on, and the left-turn signal is a solid red arrow. The left-turn vehicle that started the left turn at the end of the protected phase ran on red at the beginning of the pedestrian phase and did not yield to the pedestrian. The vehicle speed was high and unsafe for the cyclist.

Figure 4-23. Unsafe/unyielding event observed at treated sites

4.3.4.2 Pedestrian Behavior Investigation at Treated Sites

This study examined pedestrian behaviors at treated sites to understand their compliance with the treatments. In this analysis, only the events with safety crossing guard presence were excluded. Pedestrian crossing events were all kept regardless of the left-turn vehicle presence or not. Figure 4-24 shows the distribution of pedestrian mode at treated sites. It can be known that pedestrians account for 53%, followed by bicycles (37%), scooters (5%) and mixed groups (5%), respectively.

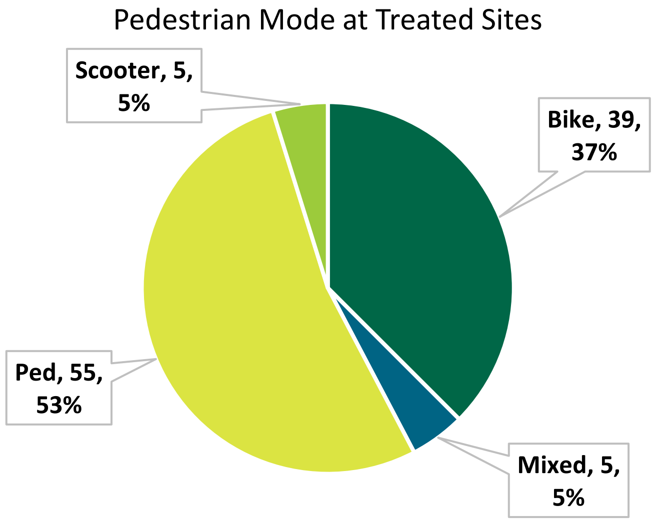
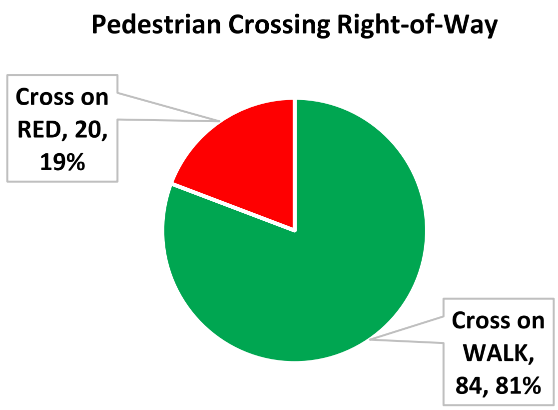


Figure 4-24. Distribution of pedestrian mode at treated sites

Pedestrians have the right-of-way (ROW) to cross the street when the pedestrian signal displays "WALK" or a count-down number as they step into the crosswalk. In contrast, when the pedestrian signal displays a "STOP" symbol, it indicates that pedestrians do not have the ROW. This study defined two pedestrian ROW events:

- *Cross on* WALK *(including count-down)*—pedestrians have right-of-way; FYA for left-turn should be omitted, and left-turn signal should be a solid red arrow; pedestrians need to push button to activate the "WALK" signal.
- *Cross on RED*—pedestrians do not have the right-of-way; protected phases or FYA for left-turn should be activated.

Figure 4-25 shows the distribution of pedestrian ROW at treated sites. Results indicate that 19% of pedestrians cross on RED (without ROW), 80% of scooters and 31% of bicycles cross the street on RED, while only 7% of pedestrians do the same.



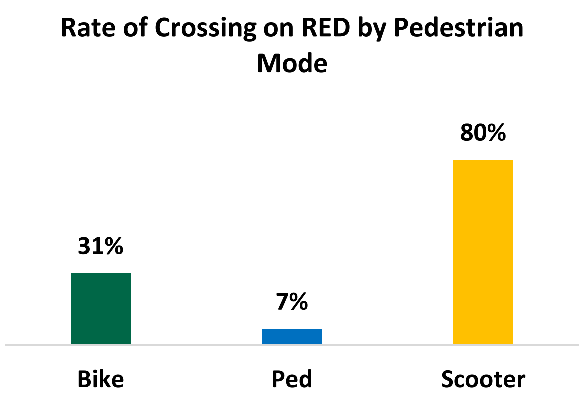


Figure 4-25. Distribution of pedestrian right-of-way (ROW)

As shown in Figure 4-26, in 13% of pedestrian observations, the push button was not activated. Among these non-pushing events, 50% are bicycles, followed by scooters (21%), and pedestrians (29%). At treated sites with O-FYA, pedestrians push the button to activate the pedestrian signal phase, which can omit FYA for left turns to minimize or fully eliminate conflicts between left-turning vehicles and pedestrians.

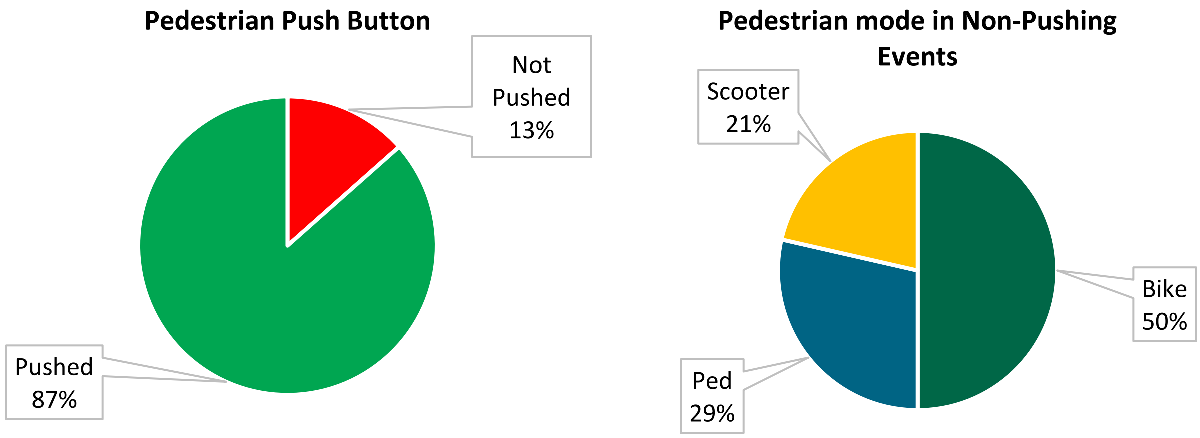


Figure 4-26. Distribution of pedestrian pushing button behaviors

Comparing Figure 4-25 and Figure 4-26, it can be observed that the rate of crossing on red (19%) is higher than the rate of not pushing the button (13%). This difference implies that 6% of pedestrians pushed the button but began crossing before the pedestrian phase was activated. A left-turning vehicle attempting to complete its turn during the protected phase may potentially conflict with the pedestrians crossing on red.

4.3.5 Before-After Crash Analysis

Since 2011, Pinellas County has implemented the "Pedestrian Protect" program, which omits permissive FYA and shows a solid red arrow for left-turning vehicles when pedestrians activate the push button. To evaluate the effectiveness of this countermeasure in reducing conflicts between pedestrians and left-turning vehicles, the CUTR team collected data from 108 signalized intersections where O-FYA was deployed between 2011 and 2018 (Figure 4-27).

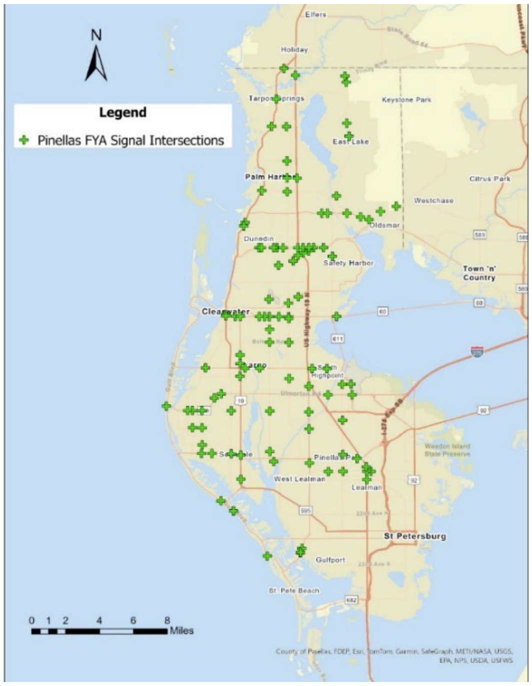


Figure 4-27. Signalized intersections in Pinellas County with deployment of omission of permissive FYA (108) (2011-2024)

After data cleaning, information from 90 signalized intersections was retained for a before-and-after analysis to assess the effectiveness of O-FYA during pedestrian phases. The dataset details whether the O-FYA is implemented at all four corners of an intersection, or at three, two, or one corner. The distribution of O-FYA across these configurations is illustrated in Figure 4-28. Approximately 29% of the signalized intersections have FYA at all four corners, 3% have FYA at three corners, 52% have FYA at two corners, and 16% have FYA at one corner.

Historical crash data from 2008 to 2023 was retrieved from the FDOT GIS Open Data Hub [131] and Signal Four system [92], based on the implementation timeline of the O-FYA. The pedestrian and bicyclist crashes involving left-turning vehicles (LT-PB) were selected from the retrieved crash data and were matched with the 90 signalized intersections.

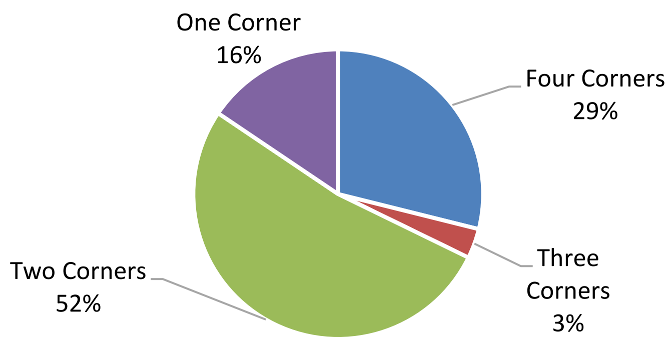


Figure 4-28. FYA corner distribution at 90 signal intersections

Based on the O-FYA layout at signalized intersections (Figure 4-28), the before-and-after crash analysis was conducted only at intersection corners where O-FYAs were implemented. The CUTR team selected a three-year evaluation period (three "before" years and three "after" years) to assess the impact of FYA implementation, acknowledging that the timeline for implementation varied across different locations. This approach was chosen to gain a clearer understanding of safety improvements and to inform future interventions.

The results show that, after three years of O-FYA implementation, the number of pedestrian-related crashes involving left-turning vehicles decreased from 17 to 5. The crash modification factor is calculated as 5/17 = 0.294, indicating a crash reduction factor of 1 - 0.294 = 0.706 (nearly 71%). The detailed breakdown of the before-and-after LT-PB crash comparison is provided in Table 4-9.

Table 4-8. Detailed Breakdown of LT-PB Crashes before and after FYA Implementation

FYA Corners	Signal ID	FYA First Date	Before 3 Years	After 3 Years
Four Corners	497	2013	0	1
	1554	2014	1	0
	78	2015	1	0
	92	2016	2	0
	797	2017	1	1
	80	2020	1	1
	763	2022	3	0
Three Corners	781	2021	2	0
Two Corners	570	2014	0	1
	617	2014	0	1
	212	2017	1	0
	886	2020	1	0
	678	2016	1	0
	949	2018	2	0
	44	2018	1	0
Total Crashes			**17**	**5**
Crash Reduction			**12**	
Crash Reduction Factor			**71%**	

By omitting the permissive FYA during pedestrian phases, conflicts between turning vehicles and pedestrians are expected to be eliminated. As a result, the project team anticipated no crashes following the implementation. However, to understand the causes of the five crashes that occurred after the implementation of FYA omission, a detailed analysis was conducted using police crash reports from the Signal Four system [5] and Google Map Street View. A summary of the results is presented in Table 4-10 and outlined in the following bullet points. Figure 4-29 illustrates the two types of crash lane positions considered.

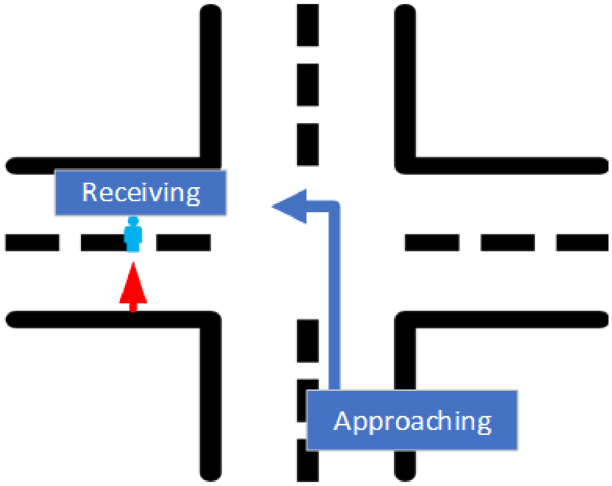


Figure 4-29. Layout of receiving and approaching corners

Table 4-9. After-Crash Analysis (After 3-year FYA implementation)

	Intersection	Date/Time	Environment	Injury Severity	Right of Way	Narrative Description from Police Crash Report
1	Roosevelt Blvd @ 58th St	Apr 29, 2015/ 6:29	Cloudy/ Daylight	Possible Injury	Pedestrian	• FYA omitted (RED for left turn) • Pedestrian at crosswalk with "WALK" signal
2	49th St @ 62nd Ave N	Apr 30, 2018/ 14:25	Clear/ Daylight	Incapacitating	Bicyclist	• FYA omitted (RED for left turn) • Bicyclist at crosswalk with "WALK" signal • Hit and run
3	66th St @142nd Ave	Mar 2, 2016/ 19:47	Clear/ Dark-Unknown Lighting	Non-Incapacitating	Driver	• FYA or Green for left turn • Pedestrian did not push button or crossed without "WALK" signal
4	Alt 19 @ Klosterman Rd	Mar 22, 2022/ 7:08	Clear/ Daylight	Possible Injury	Driver	• FYA or Green for left turn • Pedestrian did not push button or crossed without "WALK" signal
5	49th St @ 144 Ave.	Nov 10, 2016/ 17:54	Clear/ Dusk	Non-Incapacitating	Driver	• FYA or Green for left turn • Pedestrian did not push button or crossed without "WALK" signal

The analysis of the five crash reports reveals that (Table 4-10):

- All five post-implementation crashes occurred in the receiving lanes at intersections without bike lanes.
- According to police crash reports, two of the crashes (40%) involved drivers failing to yield to their right of way. However, crash reports did not clearly indicate whether these

crashes involved left-turn-on-red (pedestrian "WALK" signal was ON, FYA was omitted). It is speculated that the vehicles in the two crashes ran into the intersection at the end of the protected left turn signal and tried to complete the left turn after the pedestrian "WALK" signal was on.

In the other three crashes (60%), pedestrians stepped into crosswalks without a "WALK" signal. A possible reason is that pedestrians did not activate the push button or activated the push button but stepped into the crosswalk before the "WALK" signal activated. In these cases, drivers had the right-of-way (FYA was ON).

4.4 Automated Pedestrian Detection

This chapter describes the evaluation of automated pedestrian detection at signalized intersections, including treatment, data collection, and evaluation results.

4.4.1 Treatment

The City of Sarasota installed the DERQ AI platform for automated pedestrian detection at 16 signalized intersections in March and April 2024. As shown in Figure 4-30, automated pedestrian detection cameras are installed along Fruitville Rd, Bayfront Dr, Mount St, Washington Blvd (US-301), and Tamiami Trail (US-41) in Sarasota.

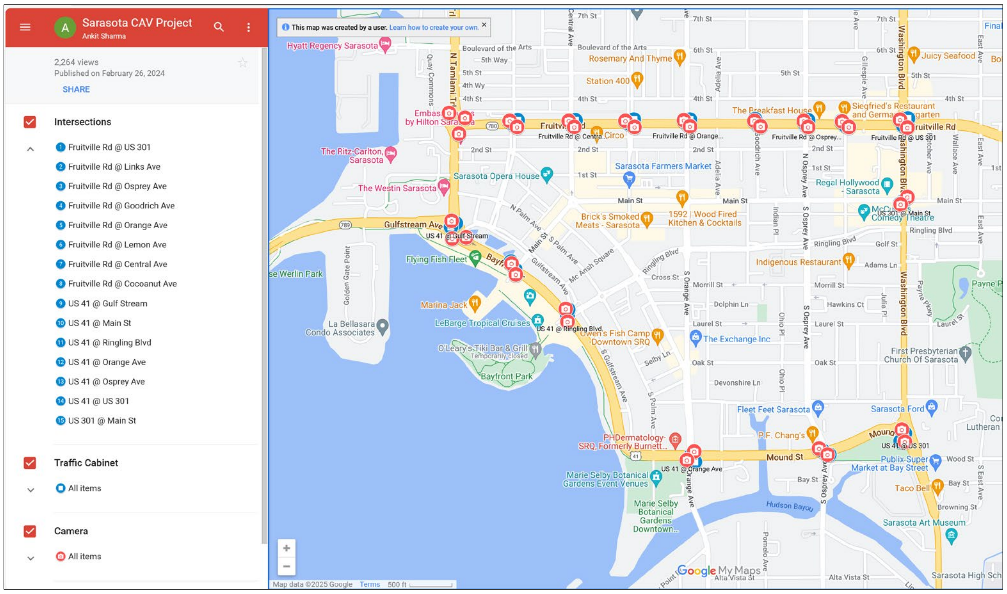


Figure 4-30. Automated pedestrian detection intersections in Sarasota County

The working scheme of automated pedestrian detection is shown in Figure 4-31. The image processing algorithm detects pedestrians in designated areas. Once the system determines that pedestrians are waiting for the pedestrian phase, the system will set a pedestrian call on the approach on which pedestrians intend to cross. This automation mechanism prevents unsafe pedestrian crossing behaviors—crossing streets without pedestrian phase—and reduces potential conflicts between pedestrians and turning vehicles.

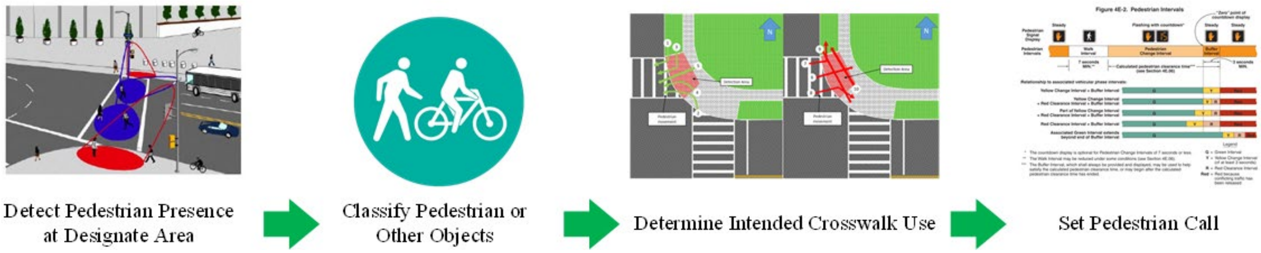


Figure 4-31. Working scheme of automated pedestrian detection in Sarasota County

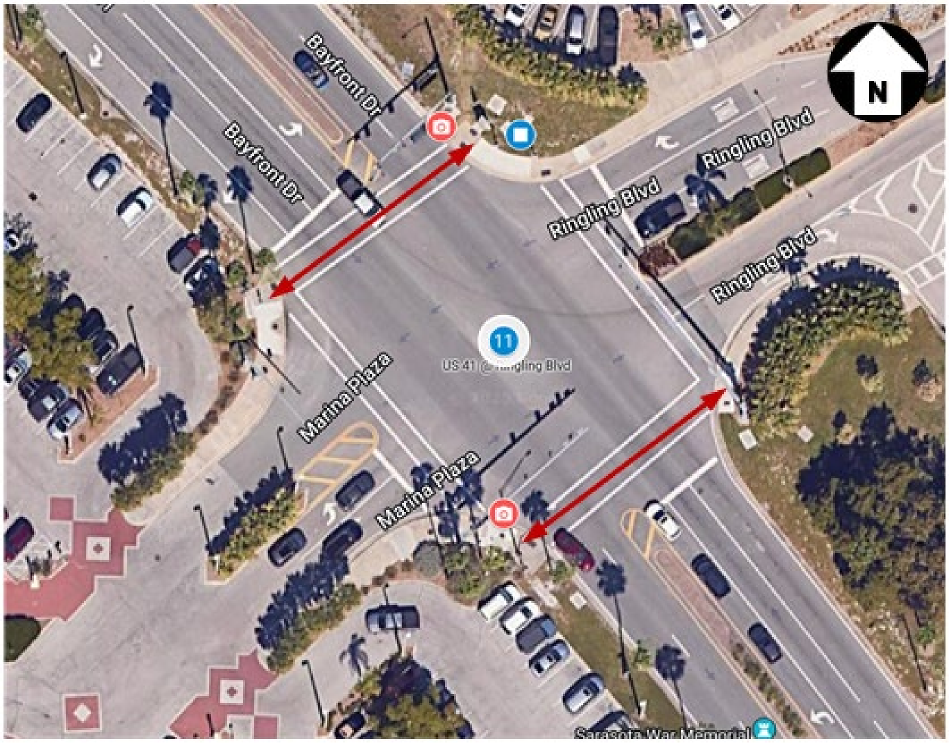
Due to the impacts of hurricanes in 2024, the City of Sarasota postponed its deployment of leading pedestrian intervals (LPIs) at 16 intersections and was out of the project timeline. Thus, this study evaluated automated pedestrian detection only based on the field data collection in Sarasota.

4.4.2 Data Collection

Field observations were conducted at one intersection selected from 16 sites in Sarasota based on the following criteria:

- The automated pedestrian detection system is working properly, and
- Significant pedestrian volumes.

Figure 4-32 shows the intersection layout for field data collection. Automated pedestrian detection is activated on EB and WB at US-41 & Ringling Blvd. The field views of WB and EB are given in Figure 4-33.



Approach with Activated Pedestrian Detection

Pedestrian Detection Camera

Figure 4-32. Study site for automated pedestrian detection in Sarasota (US-41 & Ringling Blvd)

WB Crosswalk **EB Crosswalk**

Figure 4-33. Field view of detected crosswalks (WB and EB)

Researchers observed pedestrian crossing events on the approaches with activated pedestrian detections. One event may include one or more pedestrians who cross an approach simultaneously. The field data collection was conducted in two stages: before and after the installation of pedestrian detection cameras. The data collection covered the daytime on a single day with good weather conditions. The field data collection is summarized in Table 4-11.

Table 4-10. Summary of Field Data Collection at Sarasota Sites

Category	Item	Description
Pedestrian Crossing Behavior	Push Button	If a pedestrian or a pedestrian group push button when they cross the street, record an event of "push button"
	Cross on Walk	If a pedestrian or a pedestrian group cross the street with "WALK" signal, record an event of "cross on walk"
	Cross on Red	If a pedestrian or a pedestrian group cross the street with non-"WALK" signal, record an event of "cross on red"
Data Collection Date	Weather Condition	Daytime and Clear
	Before	March 23rd, 2024
	After	February 16th, 2025

4.4.3 Evaluation Results

The research team compared the following pedestrian behavior measures that are related to pedestrian safety before and after the implementation of automated pedestrian detection at the study site:

- *The rate of pedestrian pushing button*—the number of pushing button events divided by the total number of events
- *The rate of pedestrian crossing on "WALK"*—the number of crossings on "WALK" events (regardless pushing or not pushing button) divided by the total number of events
- *The rate of pedestrian crossing on "RED"*—the number of crossings on "RED" events (regardless pushing or not pushing button) divided by the total number of events
- *The rate of pedestrian crossing on "WALK" after pushing button*—the number of pushing button and crossing on red events divided by the number of pushing button events
- *The rate of pedestrian crossing on "RED" after pushing button*—the number of pushing button and crossing on red events divided by the number of pushing button events
- *The rate of pedestrian crossing on "WALK" without pushing button*—the number of pedestrians crossing on walk but not pushing button events divided by the number of not pushing button events
- *The rate of pedestrian crossing on "RED" without pushing button*—the number of pedestrians pushing button and crossing on red divided by the number of not pushing button pedestrians

Chi-square tests were applied to examine the difference significance of safety measures before and after the installation of automated pedestrian detection. Table 4-12 summarizes the comparisons and the change of pedestrian behaviors is shown in Figure 4-34.

Table 4-11. Comparison of Pedestrian Behaviors Before and After Automated Pedestrian Detection

Events	Before		After		Significance
	Number	Rate	Number	Rate	
Push the button	274	83%[1]	192	66%[1]	>99%
Do not push button	57	17%[1]	99	34%[1]	
Cross on "WALK" signal	302	91%[1]	281	97%[1]	>95%
Cross on "RED" signal	27	8%[1]	10	3%[1]	
Cross on WALK after pushing button	262	96%[2]	188	98%[2]	*Insignificant**
Cross on RED after pushing button	9	3%[2]	4	2%[2]	
Cross on WALK without pushing button	40	70%[3]	93	93%[3]	>99%
Cross on RED without pushing button	18	32%[3]	7	7%[3]	
Total Observations	331		291		

**Fisher's Exact test is applied; [1]The denominator is total observations; [2]The denominator is the number of pushing button events; [3]The denominator is the number of not pushing events.*

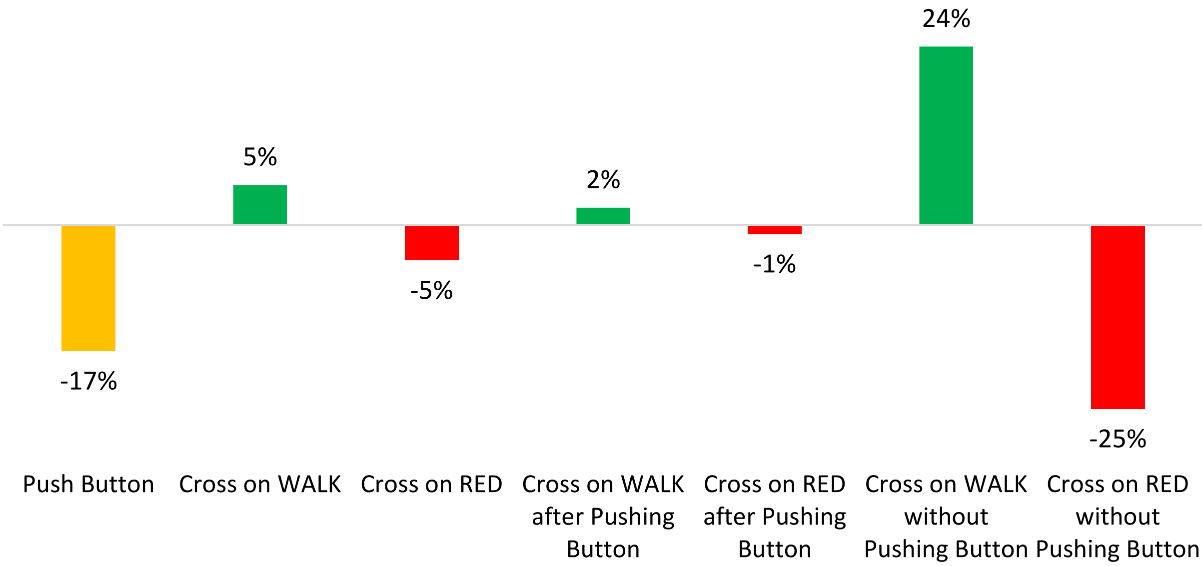


Figure 4-34. Change of pedestrian behaviors after implementing automated pedestrian detection

Based on the comparison results, the following findings can be obtained:

- On average, the rate of pedestrian crossing on "RED" is reduced by 5% and the rate of pedestrian crossing on "WALK" is increased by 5%. This indicates that automated pedestrian detection significantly lowers the risk of pedestrian behaviors—crossing on "RED"—and improves pedestrian safety at signalized intersections.

- More specifically, the treatment greatly prevents pedestrians from losing their right-of-way if they don't push the button. The rate of crossing on WALK without pushing the button is increased by 24% and the rate of crossing on RED without pushing the button is reduced by 25%.
- The safe pedestrian behaviors after pushing the button (crossing on WALK) are at a high level in both the before and after stages (96% vs 98%). The treatment slightly improves pedestrian behavior after they push the button. The rate of crossing on WALK after pushing the button is increased by 2% and the rate of crossing on RED after pushing the button is decreased by 1%.
- It is interesting to find that the rate of pushing the button decreased by 17% after implementing automatic pedestrian detection. This behavior change is caused by some pedestrians who had been familiar with the detection system after a 10-month implementation of automated pedestrian detection at this signalized intersection.

Even with automated pedestrian detection, a small portion of pedestrians (3%) tended to cross the street on RED. An example of a group of pedestrians crossing on RED with a detection event is shown in Figure 4-35.

- There was a group of pedestrians who arrived at the intersection, the pedestrian signal was red, and the parallel vehicle sign was green.
- The detector detected the pedestrian group and sent a pedestrian call to the traffic controller.
- This call would activate the pedestrian phase in the next cycle.
- Pedestrians did not wait for the "WALK" signal in the next cycle and crossed the street on RED.

Figure 4-35. An example of pedestrians in group crossing on RED with pedestrian detection

4.5 Pilot Deployment Summary and Findings

This pilot deployment included three pedestrian safety countermeasures at signalized intersections: (1) blank-out sign with "NO TURN ON RED" message + LPI, (2) Omission of Flashing Yellow Arrow (O-FYA) + LPI, and (3) automated pedestrian detection. The behavioral data of pedestrians and turning vehicles, as well as their interactions, were collected at seven signalized intersections (two for Blank-out Sign + LPI, two for O-FYA + LPI, one for automated pedestrian detection, and two for control sites) selected in Pinellas County, Hillsborough County, and the City of Sarasota. Advanced AI tools were used to process the videos to identify critical scenes and retrieve safety measures. Two safety measures—(1) unsafe interactions between right-turn vehicles and crossing pedestrians, and (2) turning vehicles not yielding to crossing pedestrians—were compared between treated sites (with the treatments of blank-out sign + LPI or O-FYA + LPI) and control sites (without the treatments). For automated pedestrian detection, a before-and-after study was conducted to compare pedestrian behaviors (pushing button, crossing on WALK, and crossing on RED). In addition, a crash comparison that involved pedestrian and left-turn vehicles was applied on 90 signalized intersections before and after the implementation of O-FYA in Pinellas County to address O-FYA's safety effects. The findings, identified issues, and suggestions are given in the following sections.

4.5.1 Key Findings

Major findings from the cross-sectional and before-after studies were obtained as follows:

Blank-out Sign with "No Right Turn" message + LPI

- Blank-out sign + LPI, which increases pedestrian visibility in crosswalks and likely conflicts with right-turn vehicles during pedestrian crossings, improves pedestrian safety related to right turns at signalized intersections.
- The treatment of blank-out sign + LPI significantly reduced right-turn vehicles' unsafe behaviors, such as conflicts or being too close to pedestrians. The reduction of unsafe behaviors is 34% (48% improvement) at a large-sized intersection and 91% (100% improvement) at a middle-sized intersection. The treatment of blank-out sign + LPI also reduced right-turn vehicles' unyielding behaviors by 10% (24% improvement) at large-sized intersections and by 14% (100% improvement) at a middle-sized intersection.
- The combination of blank-out sign and LPI has more significant safety effects compared to blank-out sign only, either in unsafe behavior or in unyielding behavior reduction.

Omission of Flashing Yellow Arrow (O-FYA) + LPI

- O-FYA + LPI, which increases pedestrian visibility in crosswalks and minimizes conflicting left-turn vehicles during pedestrian crossings, improve pedestrian safety related to left-turn vehicles at signalized intersections.

- The treatment (O-FYA + LPI) reduced left-turn vehicles' unsafe behaviors (conflicts or too close to pedestrians) by 19% (83% improvement) and left-turn vehicles' unyielding behaviors by 13% (76% improvement).
- A simple crash comparison in Pinellas County using 3 years of pedestrian crash data before and after the O-FYA deployments shows that pedestrian crashes related to left-turn crashes were reduced by nearly 71% after implementing O-FYA. This finding supports the safety effects of O-FYA + LPI.

Automated Pedestrian Detection

- Automated pedestrian detection, which automatically activates pedestrian phases, significantly reduced the risk of pedestrian behaviors—crossing on "RED"—and improves pedestrian safety at signalized intersections
- Automated pedestrian detection is greatly effective when pedestrians do not use the push button. In this situation, automated pedestrian detection increased the rate of crossing on WALK by 24% and reduced the rate of crossing on RED by 25%.

4.5.2 Notable Points and Observations

This study identified some potential issues in field observations:

- A small portion of pedestrians cross on RED (3% - 19%) at the treated sites. These risky behaviors make pedestrians lose protection from the treatments (O-FYA, blank-out sign, LPI, and automated pedestrian detection). The dangerous behaviors may be caused by not activating the push button or crossing earlier than when the "WALK" signal is shown.
- Most events in which the push button was not activated involve bicycles and scooters (>70%) when they cross the street on crosswalks. Relatively high speeds of bicycles and scooters are contributors to this phenomenon.
- Some drivers misunderstand or ignore the blank-out sign with a "No Right Turn" message and make right turns during the "No Right Turn" display (27%). This phenomenon is more serious at large-sized intersections with high traffic.
- Automated pedestrian detection increased the rate of crossing during the "WALK" signal; however, this treatment also reduced the rate of pushing the button. This change in pedestrian behavior may result in potential risks: pedestrians who become accustomed to automated pedestrian detection may not push the button at other intersections without the treatment, potentially increasing the likelihood of crossing on "RED". More studies may be needed.

5 Development of Guidelines and Toolbox

This chapter presents an overview of the development of guidelines and the creation of a toolbox aimed at reducing pedestrian crashes involving turning vehicles at signalized intersections. The guidelines and toolbox were developed by integrating findings from literature reviews, in-depth interviews, and pilot deployments to identify best practices, effective safety countermeasures, and innovative technologies. The chapter begins with a summary of key insights from the literature review, stakeholder interviews, and pilot testing, followed by guidance on selecting and implementing appropriate countermeasures and technologies. It concludes with an introduction to the toolbox and instructions for its use.

5.1 Summary of Research Results and Findings

This section presents research findings on countermeasures used to reduce the crash risk between pedestrians and turning vehicles at signalized intersections. It includes best engineering practices and proven safety treatments, innovative countermeasures or technologies, and presents how countermeasures can be combined to synergistically improve pedestrian safety.

5.1.1 Best Engineering Practices and Proven Safety Countermeasures

Signalized intersections are complex infrastructure elements designed to accommodate all road users, including pedestrians, bicyclists, and drivers. Given the diverse physical, cognitive, and sensory abilities of road users, various roadway and traffic factors must be considered to address their needs. To enhance pedestrian safety at intersections, the following key measures should be implemented whenever feasible within the given context and constraints [25]:

- Minimize pedestrian exposure to high-speed or high-volume traffic.
- Maximize visibility between pedestrians and motorists by ensuring pedestrian crossings intersect traffic flow as perpendicularly as possible.
- Reduce vehicle speeds at conflict points by minimizing corner radii to slow turning vehicles.
- Mitigate conflict or crash frequency and severity by using traffic controls or strategies to separate movements in time.
- Provide adequate signal timing to ensure pedestrians can fully clear crosswalks before conflicting vehicle movements begin.

The Federal Highway Administration (FHWA) categorizes countermeasures to improve pedestrian safety into the following classes: the walking environment, road design, intersection treatment, traffic calming, traffic management, signs and signals, and other measures [74]. Intersection-related crashes involving turning vehicles and summaries of various countermeasures designed to enhance pedestrian safety and mitigate conflicts with turning vehicles are discussed next.

5.1.1.1 Signal Treatments

Pedestrian Traffic Signals

Installing pedestrian traffic signals at a signalized intersection effectively reduces the number and severity of crashes involving pedestrians. It can reduce pedestrian crashes by 11.8% and pedestrian-related fatality and injury crashes by 24.5% [45]. Traffic signals should provide enough time for pedestrians to cross and a sufficient clearance interval, using a walking speed of three feet per second as recommended in the MUTCD, with a maximum up to four feet per second. In areas with a high concentration of older people or children, a lower speed of less than four feet per second should be used to determine the pedestrian clearance time [74].

Signals are particularly important at high pedestrian, highly congested intersections, high-speed roads, and multiple lane roads. Where pedestrian traffic is regular and frequent, pedestrian phases should come up automatically. Pedestrian actuation should only be used when pedestrian crossings are intermittent. Signal cycles should be kept short (ideally 90 seconds maximum) to reduce pedestrian delay. Pedestrians are very sensitive to delays, and a 30-second maximum wait time is ideal. Marked crosswalks at signals can encourage pedestrians to cross at the signal and help dissuade motorists from encroaching into the crossing area [74].

Pedestrian Push Button

Pedestrian push buttons allow pedestrians to request a crossing phase. Pedestrian push buttons are appropriate where pedestrian activity is infrequent and pedestrian signal phasing is not warranted on a full-time basis. Push buttons may also be used with pedestrian signals to provide a quicker WALK interval with extended WALK time for safer pedestrian crossing. Pedestrian safety can be enhanced by pedestrian push buttons only if they are correctly installed and maintained. Many agencies resist installing pedestrian push buttons because they are either infrequently used or often used improperly by pranksters wishing to disrupt traffic flow [74].

Accessible Pedestrian Signals

Accessible pedestrian signals (APS) enhance crossing performance for blind pedestrians by providing auditory and tactile cues that improve judgment and reduce crossings that begin during the DON'T WALK signal. They help decrease delays, increase the likelihood of completing crossings before the signal changes, and support safer navigation. APS also benefits sighted pedestrians by prompting faster crossing starts.

5.1.1.2 Pedestrian-Related Traffic Control Signs

The TURNING VEHICLES YIELD TO PEDESTRIANS sign instructs drivers making turns to yield the right-of-way to pedestrians crossing the roadway. This sign serves as a reminder that, when executing a turn, drivers must slow down or stop to ensure that pedestrians can safely cross. Its purpose is to reduce conflicts and enhance pedestrian safety at intersections. When evaluated, their implementation resulted in significant increases in driver compliance for both male and female drivers, with a confidence level of 95% [12].

The TURNING VEHICLES STOP FOR PEDESTRIANS sign indicates that drivers making turns must come to a complete stop and yield the right-of-way to pedestrians. It could be used in a jurisdiction where statutes or ordinances specifically require that a driver turning at a signalized intersection must stop for a pedestrian who is legally within a crosswalk.

5.1.1.3 Restricting or Eliminating Turning Maneuvers

Restricting or eliminating turning maneuvers is a proven countermeasure for reducing crashes at signalized intersections, particularly those involving pedestrians and turning vehicles [38]. For pedestrian-vehicle collisions, potential solutions include restricting or eliminating right or left turns at specific locations.

Right-turn vehicles: Using a NO TURN ON RED (NTOR) static sign, which prohibits right turns at red lights, has proven effective, achieving a 90.9% compliance rate after implementation [12].

Left-turn vehicles: Implementing dedicated left-turn phases synchronized with WALK/DON'T WALK signals enhances pedestrian safety by reducing conflicts between turning vehicles and pedestrians.

5.1.1.4 Crosswalk Visibility Enhancements

Lighting improvements are key FHWA-proven safety countermeasures that enhance visibility, comfort, and safety of pedestrian crossings. Adequate lighting improves drivers' ability to stop in time. Intersection lighting can reduce pedestrian crashes by 42%. High-visibility crosswalks can reduce pedestrian injury crashes by up to 40%. Agencies should prioritize lighting at intersections with high nighttime crash rates, heavy traffic, and significant pedestrian activity [89, 132].

5.1.1.5 Intersection Geometry

Improved Right Turn Slip Lanes and Slow Turn Wedge Calming Treatment

Improving the existing right turn slip lanes with tight turning radii, along with 90-degree crosswalks, high-visibility markings and signage, and pork chop islands for pedestrian refuge can provide clear sightlines for pedestrian visibility. These features slow turning vehicle speeds, shorten crosswalks, and enhance visibility, making them ideal for intersections with high turning volumes. They have been shown to increase pedestrian yielding by 7% overall and 32% at night while reducing right-turn speeds by 20.3%–22.5% (3.9–4.2 mph) [8].

Left Turn Traffic Calming Treatments

Left-turn traffic calming treatments are simple intersection upgrades to provide a raised/restrictive median or slow-turn wedge to address the turning vehicle and pedestrian crashes caused by left-turning vehicles. In New York City, pedestrian injuries have decreased at a faster rate compared to nearby similar areas due to left turn traffic calming treatments. In

Chicago, the percentage of drivers yielding to pedestrians increased from 73% to 94% due to such treatments [69, 133].

Curb Extension or Radius Reduction

Traffic calming methods involve the implementation of physical design elements and other measures on existing roads to reduce vehicle speeds and enhance safety for pedestrians and cyclists. Curb extensions are one such traffic calming measure, where sections of the curb extend into the roadway. These extensions tighten the turning radius, effectively reducing vehicle turning speeds, shortening pedestrian crossing distances, and improving sightlines between pedestrians and motorists [2].

Diagonal Crosswalk/Pedestrian Scramble

A diagonal crosswalk allows pedestrians to cross an intersection in any direction, including diagonally, without conflicting with vehicle movements. During this exclusive pedestrian phase, extended walk time is provided to accommodate diagonal crossings. Pedestrian signals, accessible pedestrian signals, and pavement markings clearly guide and support this crossing option. This treatment was implemented in Miami at SR 5/Brickell Avenue and SE 8th Street, improving pedestrian connectivity and enhancing safety [78].

5.1.1.6 Education

Education plays a vital role in pedestrian safety. States and cities implementing strong educational programs report declines in fatalities. FHWA recommends public education campaigns focused on intersection safety, emphasizing the dangers of red-light running, speeding, and failing to yield to pedestrians [74].

5.1.1.7 Law Enforcement

The NCHRP report highlights the safety benefits of enforcement measures, showing significant reductions in red-light violations and crashes. In Portland, Oregon, red-light running violations decreased by 69–93%, while in Virginia Beach, Virginia, violations dropped by over 69% within 13 months of activating red-light cameras. Similarly, in San Diego, California, crashes caused by red-light running fell by 8%, with a 16% reduction at intersections equipped with cameras. Although these findings are promising, further research is needed to fully assess the long-term impact of red-light enforcement programs. Additionally, in Washington, D.C., increased police enforcement has played a key role in improving pedestrian safety and significantly reducing annual fatalities among both vehicle occupants and pedestrians over the past decade, though other contributing factors may also influence these outcomes [17].

5.1.2 Innovative Countermeasures or Technologies

Beyond the previously mentioned countermeasures, additional strategies and technologies can further mitigate conflicts between pedestrians and turning vehicles. These include leading pedestrian intervals (LPIs), NTOR blank-out signs, omission of permitted left turns during protected-permissive left-turn (PPLT) operations, automated pedestrian detection (APD) systems, and other advanced solutions. The following sections provide a detailed overview of each measure.

5.1.2.1 Leading Pedestrian Intervals

LPIs are an effective, low-cost safety countermeasure that provides pedestrians with a three to seven-second head start before vehicles are allowed to turn, significantly reducing pedestrian-vehicle conflicts at signalized intersections. Field evaluations in Florida, Pennsylvania, and New York have demonstrated the effectiveness of LPIs, with reductions in pedestrian-vehicle crashes of up to 60%. A study conducted in downtown St. Petersburg, Florida, confirmed that LPIs virtually eliminated conflicts for pedestrians at the start of the WALK interval. Similarly, long-term crash analyses in New York City and Pennsylvania further validated the safety benefits of LPIs [134]. Implementation of LPIs is cost-effective. The CMF analyses showed a benefit-cost ratio ranging from 1:2 to 1:5 based on data from multiple cities, including Chicago, New York City, Charlotte, and Toronto [57].

LPI enhances safety by [89]:

- Improving the visibility of pedestrians to drivers making turns across the crosswalk.
- Reducing conflicts between pedestrians and vehicles.
- Increasing the likelihood of drivers yielding to pedestrians.
- Enhancing safety for pedestrians who may be slower to start into the intersection.

LPIs are essential at intersections with heavy right- or left-turning traffic, where frequent conflicts between vehicles and pedestrians pose significant safety concerns. Many agencies have integrated LPIs into their urban traffic systems as part of initiatives like Vision Zero, modernizing signal controllers, and optimizing traffic networks to support widespread deployment. Although isolating the effects of LPIs from other safety measures can be challenging, data shows improvements in pedestrian safety, leading to their expansion at feasible locations. However, some agencies remain cautious due to mixed results, particularly regarding conflicts with right-turning vehicles. Consequently, not all agencies implement LPIs universally. In these cases, their effectiveness is assessed individually during signal retiming studies.

Pedestrian surveys indicate that LPIs improve compliance with traffic signals, enhancing overall safety. However, some pedestrians are unaware of the additional crossing time provided, highlighting the need for increased public awareness. Despite this, the widespread adoption of LPIs demonstrates their proven effectiveness in reducing pedestrian-vehicle conflicts and enhancing safety at signalized intersections.

The Urban Street Design Guide further emphasizes the integration of LPIs with other pedestrian safety measures at high-risk intersections. These include installing pedestrian safety islands, eliminating channelized right-turn lanes, and incorporating curb extensions and tight corner radii to improve pedestrian visibility and reduce exposure time. The combined implementation of these strategies ensures a comprehensive approach to pedestrian safety at signalized intersections.

5.1.2.2 No Turn on Red Blank-out Signs

An NTOR blank-out sign is an illuminated traffic control device that activates only when specific conditions, such as pedestrian presence in the crosswalk, are met. At other times, the sign remains unlit, minimizing unnecessary restrictions on vehicle movement while enhancing pedestrian safety. Activated by pedestrian push buttons or automated detection, these signs help reduce conflicts between right-turning vehicles and pedestrians, particularly during high-traffic periods.

A 2019 study found that NTOR blank-out signs achieved a driver compliance rate of 77.5%. Their clear, enforceable messages are especially effective in high-conflict areas, offering flexibility by permitting right turns on red when cross-street traffic is light and no pedestrians are present [12].

However, implementation must account for structural factors, such as overhead support and wind load capacity. In Florida, NTOR blank-out signs are strategically placed at key intersections to address pedestrian safety concerns, with activation schedules that can be adjusted based on traffic patterns and time of day. These signs can be seamlessly integrated into traffic signal controllers using adaptive logic.

5.1.2.3 Omission of Permissive Left Turns During Protected/Permissive Left-turn Operations

A PPLT operation allows vehicles to turn left during both protected phases (green arrow) and permissive (flashing yellow arrow (FYA)) phases. The protected left turn phase provides a green, yellow, or red arrow signal indication for left-turning vehicles while stopping both oncoming traffic and parallel pedestrian crossings to eliminate conflicts [58]. The permissive phase offers greater flexibility, especially when traffic volumes are low for both oncoming and left-turning vehicles. However, it might cause safety issues for pedestrians crossing the road. While agencies like the Alaska DOT allow permissive phasing during off-peak times, studies in North Carolina suggest a slight decrease in safety when intersections shift from protected-only to PPLT operation with FYA.

Omitting the permissive left turn during pedestrian phases improves safety by prioritizing pedestrians while maintaining traffic flow efficiency. According to the 2024 FDOT Traffic Engineering Manual, this approach is recommended at intersections with documented pedestrian-yielding issues during permissive left-turn phases. When a pedestrian call is detected during a permissive phase, the FYA either terminates early if time remains in the through phase or is deferred until the next cycle if not. This strategy is common where PPLT signals coincide with frequent pedestrian conflicts. For example, Pinellas County, Florida, implemented this practice at Alt 19 and Tampa Road following school crossing guard feedback and observed pedestrian-bicycle conflicts. Previously, a five-section signal head was used; currently, agencies use both five- and four-section signal heads [17, 119]. FYAs can be restricted or confined to a particular lane movement (e.g., just the left turn lane) when using a dedicated four-section signal head. The use of a four-section signal head instead of a five-section signal head for a FYA left-turn signal is recommended to ensure driver clarity and safety.

5.1.2.4 Automated Pedestrian Detection Technology

APD uses advanced technologies to detect pedestrians in real-time, enhancing road safety and traffic signal efficiency. Common detection methods include radar, infrared, ultrasonic sensors, and video processing, with ongoing advancements improving their accuracy and reliability. Each technology varies in cost, accuracy, installation, maintenance, and accessibility. APD systems detect pedestrians waiting at crosswalks and automatically signal traffic controllers to initiate the WALK phase, providing additional protection and improving traffic flow. According to the FHWA Pedestrian Safety to Congress report [130], APD enhances safety by controlling traffic signals based on pedestrian presence, prohibiting vehicle turns when pedestrians are in crosswalks, activating nighttime lighting, and adjusting pedestrian calls to reduce delays.

Advanced APD systems further improve pedestrian safety and reduce vehicle delays through call extension and cancellation functions. Call extensions lengthen the WALK phase if a pedestrian remains in the crosswalk, while cancellations terminate requests if a pedestrian leaves the detection zone and does not return within a set timeframe. For example, thermal machine vision systems, identified as the most accurate in 2019, use passive infrared and image processing to detect pedestrians in any lighting condition. FLIR TrafiOne sensors provide 24/7 real-time detection, function in complete darkness and glare, and integrate with traffic signal controllers to dynamically adjust signals.

Despite their benefits, APD systems face challenges, including occasional false detections and occlusion issues caused by streetlights and infrastructure, which can impede effectiveness. Detecting pedestrians in joint waiting areas is particularly difficult, as AI algorithms struggle to determine pedestrian intent and place calls accurately. While detection accuracy can reach approximately 85%, thermal cameras have not consistently met performance standards across agencies. Further research is needed to address these challenges and optimize detection reliability in complex environments.

APD can reduce reliance on pedestrian push buttons, but this may introduce safety concerns at other nearby signalized intersections. To mitigate these risks, agencies can install APD on all intersection approaches and also implement detection technologies at nearby intersections. If full deployment is not feasible, adding a push button locator tone can provide an auditory cue to remind pedestrians to press the button. These measures enhance pedestrian safety and accessibility.

5.1.2.5 Other Technologies

Innovative pedestrian safety technologies are advancing rapidly, with AI-driven systems improving intersection management and real-time traffic monitoring. AI-powered pedestrian detection systems monitor crosswalks, predict pedestrian movements, and dynamically adjust crossing times to optimize traffic flow. For example, crossing phases can be truncated when pedestrians clear intersections early; however, this approach requires 100% confirmation to ensure safety. Additionally, AI video analytics and radar conflict analytics are being explored to enhance real-time traffic monitoring, though upgrading existing traffic controllers to support these technologies may take years.

Connected vehicle technology represents another key advancement, enabling communication between vehicles, bicycles, and pedestrians to improve safety. Geofencing enhances this system by limiting safety alerts to pedestrians within designated zones, reducing unnecessary notifications. For example, Sarasota's connected vehicle integration involves traffic controllers transmitting signal phase and timing (SPaT) data to a DERQ processor, which tracks object speed and trajectory. This data is converted into personal safety messages (PSMs) and broadcast via roadside units (RSUs) mounted above traffic signals. Future applications aim to integrate smartphone apps that interact with these systems, providing pedestrians with real-time alerts about signal phases and potential conflicts.

AI-driven computer vision is also transforming transportation safety by enabling machines to interpret visual information from images and video feeds. Automated video analytics help transportation agencies monitor traffic in real time, detect incidents, analyze traffic patterns, and identify near-miss events, supporting data-driven safety improvements. For example, researchers at New Jersey academic institutions have developed tools that streamline monitoring processes and provide actionable data for proactive safety measures. As machine learning and deep learning techniques continue to advance, computer vision is expected to play a growing role in pedestrian detection, traffic management, and autonomous systems.

5.1.3 Combination of Countermeasures and Technologies

The innovative countermeasures and technologies can be implemented as a single solution at the intersection, but also with other countermeasures. It is often needed to further improve or enhance pedestrian and bicycle safety at the signalized intersections by considering the proper combination of countermeasures and technologies in a cost-effective manner. The findings from the project show that combining these treatments, particularly LPIs with NTOR and APD, as well as LPIs with omission of permissive left turns and APD, improves driver compliance, minimizes pedestrian-vehicle interactions, and allows signal timing to adapt based on real-time pedestrian presence. The following sections provide details on the effectiveness of combining LPI, NTOR blank-out sign, omission of permissive left-turn phase, and APD.

5.1.3.1 LPI and NTOR Blank-out Sign

LPI and NTOR blank-out signs work together to enhance intersection safety. LPIs provide pedestrians with a head start, allowing them to begin crossing before vehicles receive a green signal. When an NTOR sign is installed, vehicles are not permitted to turn right on a red light, further reducing the risk of conflicts between turning vehicles and pedestrians. Together, these measures ensure that pedestrians have sufficient time to cross safely and that turning vehicles are effectively kept in the right-turn lane until it is safe to proceed.

Florida's statewide LPI study recommended supplementing LPIs with NTOR or TURNING VEHICLES YIELD TO PEDESTRIANS signage due to inconsistent driver-yielding behaviors. The combination of LPIs with NTOR blank-out signs is common, though this is not a standard practice yet. Driver compliance with LPIs is often low when blank-out signs are absent, particularly in areas with aggressive driving behavior, where drivers prioritize turning over yielding to pedestrians.

5.1.3.2 LPI and Omission of Permissive Left Turn

Integrating LPIs with the omission of permitted left turns for FYA signals during protected plus permissive left-turn operations when pedestrian calls are received establishes fully protected left-turn operations, improving both vehicle control and pedestrian safety. In this configuration, the LPI provides pedestrians with a head start to cross before any vehicular movement is allowed, while eliminating the permissive phase ensures that left-turning vehicles are not allowed to turn when pedestrians cross streets. This approach minimizes conflicts between pedestrians and left-turning vehicles by clearly segregating pedestrian and vehicular phases, resulting in reduced crash risks and improved overall intersection safety.

5.1.3.3 LPI and APD

The combination of LPI and APD improves intersection safety by optimizing timing and responsiveness. LPIs provide pedestrians with a head start before vehicles receive a green signal; however, if a pedestrian does not push the button, the LPI is not activated. APD detects pedestrian presence and can activate LPI and extend the crossing phase when needed, allowing the signal system to dynamically adjust crossing times for improved safety and efficiency.

5.1.3.4 NTOR Blank-out Sign and APD

Dual-message blank-out signs like NTOR and TURNING VEHICLES YIELD TO PEDESTRIANS, combined with APD systems significantly improve driver awareness and compliance with pedestrian crossing rules. The integration of APD with dual-message blank-out signs further enhances safety by ensuring drivers are alerted to pedestrian presence and required yielding actions.

5.1.3.5 Omission of Permissive Left Turn and APD

Combining omission of permissive left turn and APD can improve pedestrian safety. APD can trigger the omission of the permissive left-turn phase during protected plus permissive left-turn operations when pedestrians are present to cross streets but do not press pedestrian push-buttons. This combination can eliminate a common conflict between left-turn vehicles and pedestrians at signalized intersections. At the same time, APD systems monitor pedestrian activity in real time and can adjust signal timings to extend crossing intervals when needed, ensuring that pedestrians have adequate time to cross safely.

5.1.3.6 NTOR Blank-out Sign and Omission of Permissive Left Turn

In some cases, the NTOR blank-out sign is activated when the permissive left-turn phase is omitted. This measure ensures that left-turning vehicles must wait for a protected phase, reinforcing compliance with traffic control. By reducing conflicts at the intersection and clarifying driver expectations, it helps improve overall traffic flow. Ultimately, this combination enhances both pedestrian safety and overall intersection efficiency.

5.1.3.7 NTOR Blank-out Sign, LPI, and APD

The combination of NTOR blank-out signs, LPI, and APD countermeasures provides integrated strengths of individual countermeasures, eliminates most conflicts between turning vehicles and pedestrians, and provides effective improvements in pedestrian safety.

5.1.3.8 Education and Public Awareness

To promote compliance with new traffic control measures, implement education, outreach, and digital campaigns when introducing permissive left turn omissions, NTOR Blank-out Signs, and LPIs to ensure pedestrians cross only on the WALK signal. Educate drivers on NTOR blank-out signs, emphasizing the need to stop completely when activated, and incorporate this training into driver's license testing. Additionally, conduct targeted law enforcement at high-noncompliance intersections to reduce violations and improve safety.

5.2 Guidelines for Selection and Implementation of Countermeasures and Technologies

This section introduces guidelines for selecting countermeasures to enhance pedestrian safety at signalized intersections. Drawing on best practices, interview results, and field study findings, these guidelines outline processes for selecting and implementing strategies that minimize conflicts between pedestrians and turning vehicles. Key countermeasures include LPI, NTOR blank-out signs, omission of permissive left-turn phases, and APD. These measures aim to assist transportation professionals in designing safer, more efficient intersections tailored to specific urban environments.

5.3 Guideline Development Process

The development of these guideline recommendations involves a thorough and multi-faceted approach. It begins with an extensive analysis of relevant literature, drawing from the latest research and best practices in the field. This is complemented by interviews with a wide range of professionals, researchers, and vendors, whose insights help inform the guidelines. Additionally, field studies were conducted to observe real-world conditions and validate the findings. Together, these methods ensure that the recommendations are evidence-based, practical, and tailored to address current challenges and needs.

5.3.1 Selection of Countermeasures

A systematic approach is essential for effectively enhancing pedestrian safety at signalized intersections. The process (Figure 5-1) begins by identifying key safety concerns, followed by an analysis of intersection characteristics and features. The final step involves selecting appropriate countermeasures to address conflicts between pedestrians and turning vehicles, ensuring a tailored and impactful solution.

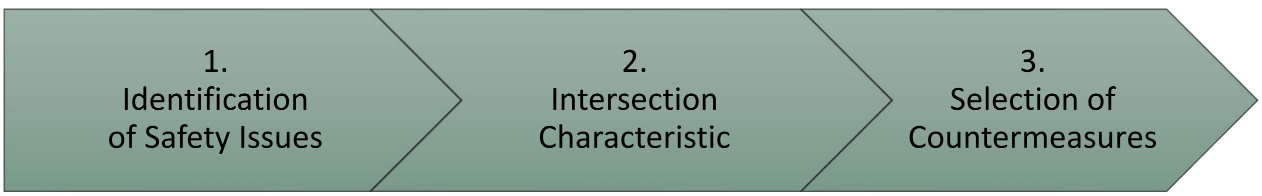


Figure 5-1. Countermeasures selection process

1. Identification of Safety Issues. Examples of safety concerns include:
   - **Excessive speeds.**
   - **Noncompliance with traffic control** (e.g., drivers failing to yield or stop, pedestrians disregarding the signals).
   - **Inadequate visibility.**
2. Intersection Characteristics. Traffic volume, vehicle speeds, and number of lanes are some of the intersection features that may be considered.
   - **Traffic Volumes**: Encompassing all users, higher traffic volumes can increase the complexity of crossing scenarios.
   - **Vehicle Speeds**: Elevated speeds, particularly at conflict points, can exacerbate the severity of pedestrian-vehicle interactions.
   - **Number of Lanes**: The presence of multiple travel lanes can introduce additional risks, necessitating more robust safety interventions.
3. Selection of Countermeasures.

Selecting appropriate countermeasures for an intersection requires a thorough evaluation of multiple factors to ensure effectiveness, safety, and feasibility. Beyond assessing the factors outlined in Steps 1 and 2, which shape the traffic environment and influence driver behavior regarding stopping or yielding to pedestrians, a further examination of additional elements is crucial. By considering these factors, transportation professionals can design tailored solutions that enhance pedestrian safety at each specific intersection. The following criteria should be considered when selecting pedestrian safety countermeasures at signalized intersections. Suggested implementation locations for these countermeasures are provided below and illustrated in Figure 5-2.

5.3.1.1 LPI

LPIs are best suited for signalized intersections with high pedestrian presence, crash history, pedestrian-vehicle conflicts, and wide or complex geometries as described below.

- **High pedestrian activity**: Areas such as downtowns, transit hubs, commercial districts, near schools, parks, and senior centers.
- **Crash history involving pedestrian-vehicle conflicts:** Locations with documented pedestrian crashes, particularly those occurring at the beginning of the WALK phase.
- **High pedestrian volume and turning vehicle conflicts**: Intersections with frequent pedestrian crossings and significant right- or left-turning traffic, where yielding compliance is low.
- **Wide intersections or complex geometries**: Intersections where pedestrians need better visibility and additional time to establish presence in the crosswalk.

FDOT Traffic Engineering Manual (TEM) [135] provides informative and clear guidance on LPI location screening considerations and LPI implementation considerations. It could serve as a valuable resource for LPI location screening and implementation.

5.3.1.2 NTOR Blank-out Sign

NTOR blank-out signs should be installed at locations where turning on red poses a significant safety risk for pedestrians, but the turn restrictions need to be dynamic, meaning only active during certain times or conditions. NTOR blank-out signs can be installed at intersections with:

- **Already installed LPIs:** Locations where LPIs were installed, but conflicts persist.
- **Variable traffic conditions**: Areas where pedestrian presence fluctuates, allowing for dynamic activation to minimize unnecessary restrictions on vehicle flow.
- **Urban environments with heavy foot traffic**: Areas with dense pedestrian activity, such as downtowns, transit hubs, and commercial districts.
- **Limited driver visibility**: Locations where sightlines to pedestrians are obstructed by roadway geometry, landscaping, or parked vehicles.

- **Adaptive traffic signal systems**: Intersections equipped with advanced controllers that can integrate blank-out sign activation based on real-time conditions.

5.3.1.3 Omission of Permissive Left Turn

The implementation of omission of permissive left turns should be considered at intersections where permissive left turns create significant safety or operational issues during the protected plus permissive left-turn operations, including intersections:

- **With multiple opposing through lanes**: Where gaps in traffic are hard to judge.
- **With skewed angles**: Where visibility of oncoming traffic is limited.
- **At wide intersections:** Where left-turning drivers struggle to see pedestrians or judge distance.
- **At intersections along roads with high speeds**: Where drivers have limited time to scan area for pedestrians and monitor the incoming traffic to establish a gap to turn.

5.3.1.4 APD

Automatic pedestrian detection systems use sensors to detect pedestrians and place and/or cancel a pedestrian call based on the presence of pedestrians. The systems can also be set up to extend pedestrian crossing time when needed. These systems should be installed at intersections where:

- **Limited pedestrian compliance with pressing push buttons to cross streets**: Areas where pedestrians frequently neglect to activate pedestrian push buttons, leading to unresponsive pedestrian signals and increased crossing risks.
- **Variable pedestrian and vehicle volumes**: Intersections where traffic demand fluctuates throughout the day, benefiting from fully actuated signal control.
- **Low visibility conditions**: Intersections prone to nighttime, foggy, or glare-related visibility issues, where APD using thermal or infrared technology can improve detection reliability.
- **High pedestrian-vehicle conflict risk**: Locations with a history of pedestrian crashes or near-miss incidents, where APD can enhance safety by prohibiting conflicting vehicle movements.
- **Need for real-time adaptive signal control**: Locations where pedestrian presence should trigger signal timing adjustments, including call extensions for slower walkers and call cancellations for false detections.

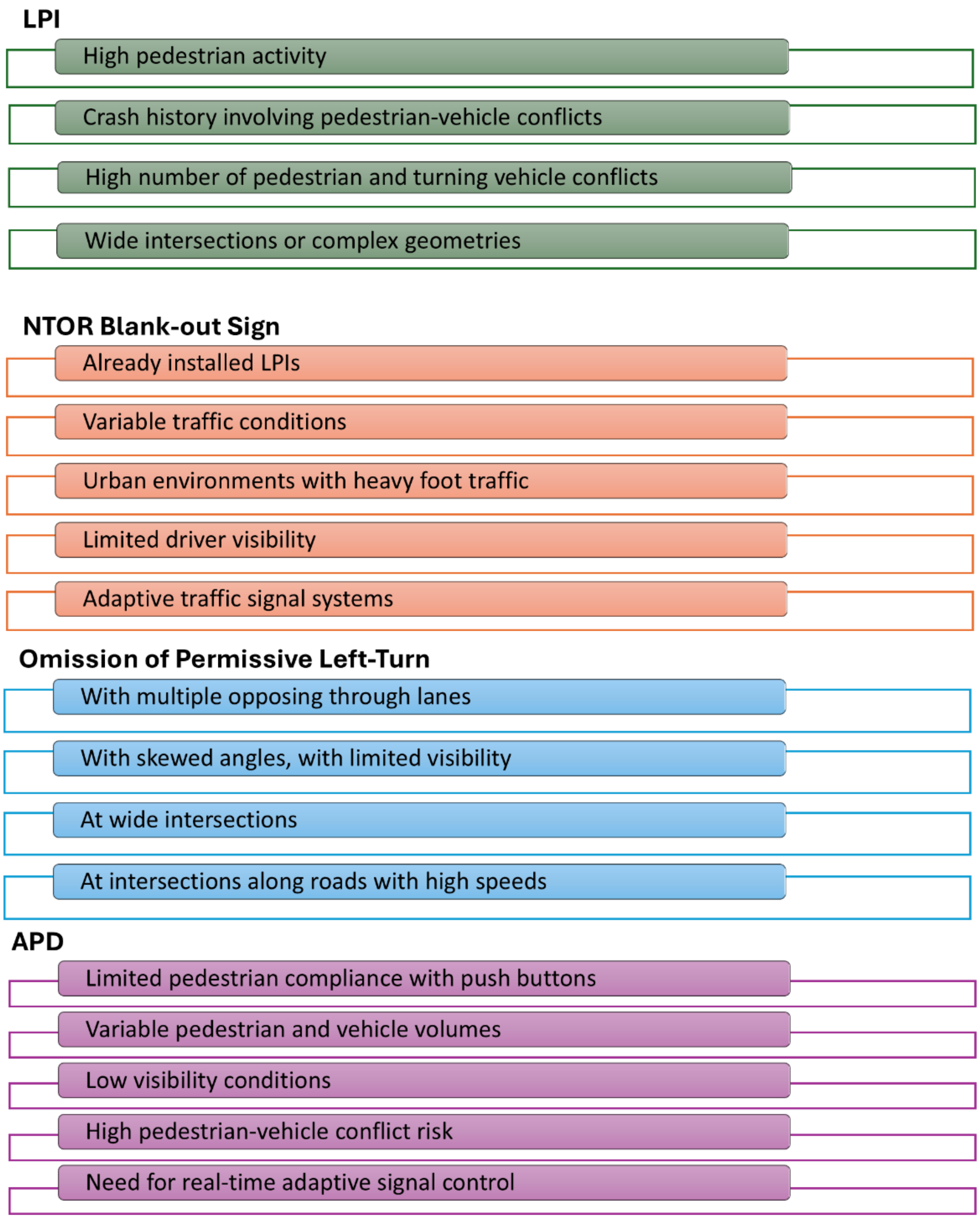


Figure 5-2. Where to implement countermeasures

5.3.2 Implementation Strategies

This subsection outlines the implementation steps for selected countermeasures and technologies at signalized intersections, designed for transportation agencies. Specific steps are provided for each countermeasure, as well as for their combinations and public awareness efforts.

(1) LPI

- Ensure signal controllers are updated to support LPI integration.

- Install LPIs at intersections or approaches with high pedestrian volumes and frequent turning movements.
- Adjust signal timing parameters by optimizing LPI duration based on intersection geometry, pedestrian crossing distances, and vehicle approach speeds.
- Integrate LPIs with proper signage to inform drivers of pedestrian priority.
- Conduct public awareness campaigns to educate pedestrians and drivers about LPI functionality.
- Consider combining LPIs with NTOR restrictions where high pedestrian conflicts exist.
- Follow FDOT LPI implementation considerations described in the TEM.

(2) NTOR Blank-Out Signs

- Install blank-out signs at intersections with high pedestrian-vehicle conflicts, particularly near schools, transit stops, and urban centers where right-turning vehicles frequently conflict with vulnerable road users.
- Ensure blank-out signs are integrated with LPI and APD to activate only when necessary.
- Position signs for maximum driver visibility, considering overhead structures and wind load constraints.
- Implement time-based activation during peak pedestrian hours where applicable.
- Monitor driver compliance and adjust signal timing or signage placement as needed.

(3) Omission of Permissive Left Turns During PPLT Operations

- Configure signal controllers to terminate FYA when a pedestrian call is activated or detected, and refer to the section FYA OMIT BY PED in the FDOT TEM for implementations.
- Provide protected-only left-turn phases at locations with frequent pedestrian crossings.
- Transition from five-section to four-section signal heads with FYA.
- Conduct signal retiming studies to evaluate the effectiveness of FYA omissions in reducing pedestrian-vehicle conflicts.

(4) APD Technology

- Integrate APD with signal controllers to automate pedestrian call requests at locations where pedestrians frequently fail to press the pedestrian push button.
- Deploy thermal vision systems, such as FLIR TrafiOne, to improve nighttime detection and reduce false negatives.
- Utilize APD to extend crossing times when pedestrians remain in the crosswalk.
- Address occlusion challenges by optimizing sensor placement and coverage.

- Evaluate detection accuracy regularly and adjust settings as needed to improve efficiency.

(5) Combination of Countermeasures and Technologies

- Pair LPIs with NTOR blank-out signs to effectively increase driver compliance and yielding to pedestrians.
- Integrate APD with LPI and NTOR blank-out signs or dual-message blank-out signs (e.g., NO TURN ON RED and TURNING VEHICLES YIELD TO PEDESTRIANS) to significantly reduce the conflicts between pedestrians and turning vehicles.
- Implement the combination of omission of FYA and NTOR blank-out signs to eliminate the conflicts between pedestrians and left-turning vehicles.
- Implement pedestrian safety islands, curb extensions, and tighter corner radii to complement LPIs and NTOR blank-out sign strategies.
- Ensure adaptive signal control systems support real-time pedestrian detection and dynamic phase adjustments.

(6) Public Awareness and Compliance Monitoring

- Develop outreach programs to educate pedestrians and drivers about LPIs, NTOR blank-out signs, omission of permissive turn, and APD strategies.
- Conduct periodic evaluations of pedestrian compliance and driver yielding behavior.
- Use automated video analytics to monitor intersection safety and identify areas for improvement.
- Collaborate with law enforcement agencies to enforce pedestrian right-of-way laws.

5.3.3 Evaluation of Effectiveness

Agencies can evaluate the effectiveness of the pedestrian safety countermeasures at signalized intersections using the following steps:

- Define evaluation objectives (establish measurable goals such as reducing crashes, improving compliance, or enhancing visibility).
- Conduct “Before” and “After” implementation data collection.
- Analyze and compare data.
- Select performance matrices (reduction in pedestrian-vehicle crashes, decrease in near-misses at crosswalks, and/or lower vehicle speeds near pedestrian crossing).
- Optimize and adjust countermeasures.
- Continue monitoring and reporting.

5.3.4 Instructions for Utilizing the Guidelines

Transportation agencies should follow a structured approach to assessing, implementing, and evaluating pedestrian safety measures at signalized intersections. This begins with identifying key safety issues through site analysis, considering factors like pedestrian volumes, turning movements, and crash history. Appropriate countermeasures should be considered for implementation and integrated with existing infrastructure.

The countermeasures include (1) LPIs for pedestrian visibility improvements, (2) NTOR blank-out signs for improving drivers' compliance, (3) omission of FYA to eliminate conflicts between the conflicts between pedestrians and left-turning vehicles, (4) APD for pedestrian detection to endure properly placing a pedestrian call, and (5) a proper combination of countermeasures 1-4 to achieve best results. Continuous monitoring and public education through outreach campaigns and enforcement programs ensure effectiveness and improve intersection safety.

The detailed steps for utilizing the guidelines are as follows:

(1) **Assess the intersection**. Identify pedestrian safety issues, such as frequent pedestrian-vehicle conflicts, low driver compliance, insufficient crossing time, pedestrian push button issues, and crash history. Conduct a site analysis that considers pedestrian volumes and turning movements.

(2) **Select appropriate countermeasures**. Match pedestrian safety issues with relevant countermeasures (e.g., use LPIs in areas with pedestrian visibility issues, implement APD for pedestrian push button issues). Consider combining multiple countermeasures for greater effectiveness.

(3) **Implement the countermeasures**. Update traffic signal controllers, install signage, and deploy selected countermeasures and technologies. Ensure proper integration of selected countermeasures with existing infrastructure (e.g., APD systems should align with pedestrian signals). Follow best practices for placement and visibility.

(4) **Monitor and evaluate effectiveness**. Use video analytics, pedestrian compliance studies, and crash data analysis to assess improvements. Adjust signal timings, detection settings, and sign placements based on observed performance. Collaborate with law enforcement and transportation agencies to refine implementation. By following these steps, agencies can ensure that pedestrian safety measures are effectively integrated and continuously improved at signalized intersections.

(5) **Educate the public**. Inform pedestrians and drivers about new safety measures through signage, outreach campaigns, and enforcement programs. Provide clear instructions on how each countermeasure works (e.g., LPIs give pedestrians a head start before vehicles move).

5.4 Development and Instructions of the Toolbox

5.4.1 Purpose, Structure, and Development of the Toolbox

The toolbox is designed to guide the selection and implementation of effective countermeasures, enhancing intersection safety and optimizing traffic operations through practical, data-driven strategies. It follows a structured approach, including an assessment of intersection safety challenges, a review of best practices and innovative countermeasures, detailed implementation guidelines, and additional resources. Developed through extensive literature reviews, interviews with professionals, researchers, and technology vendors, as well as field data collection and analysis, the toolbox provides a comprehensive framework for improving pedestrian safety at signalized intersections.

5.4.2 Description of the Toolbox

This toolbox offers a comprehensive set of strategies and countermeasures to enhance pedestrian safety at signalized intersections, particularly in areas with conflicts involving turning vehicles. Key strategies include LPI, NTOR blank-out signs, omission of permissive left turns, and APD. It provides detailed guidance on when and how to implement these countermeasures, as well as how to combine two or more for improved effectiveness. Step-by-step instructions are provided to guide agencies through the assessment, selection, and implementation process, making it a practical resource for mitigating pedestrian-vehicle conflicts. By following the recommendations outlined in this toolbox, transportation professionals can create safer and more efficient intersections that better protect pedestrians while maintaining smooth traffic operations.

5.4.3 Instructions for Utilizing the Toolbox

This toolbox is designed for traffic safety practitioners, including planners, designers, engineers, and safety analysts, to identify pedestrian safety issues and implement effective countermeasures at signalized intersections. It offers a series of guiding questions to help practitioners determine appropriate actions. The following steps, outlined in Figure 5-3 and detailed below, provide a structured approach to mitigating pedestrian-vehicle conflicts, enhancing visibility, and improving overall intersection safety.

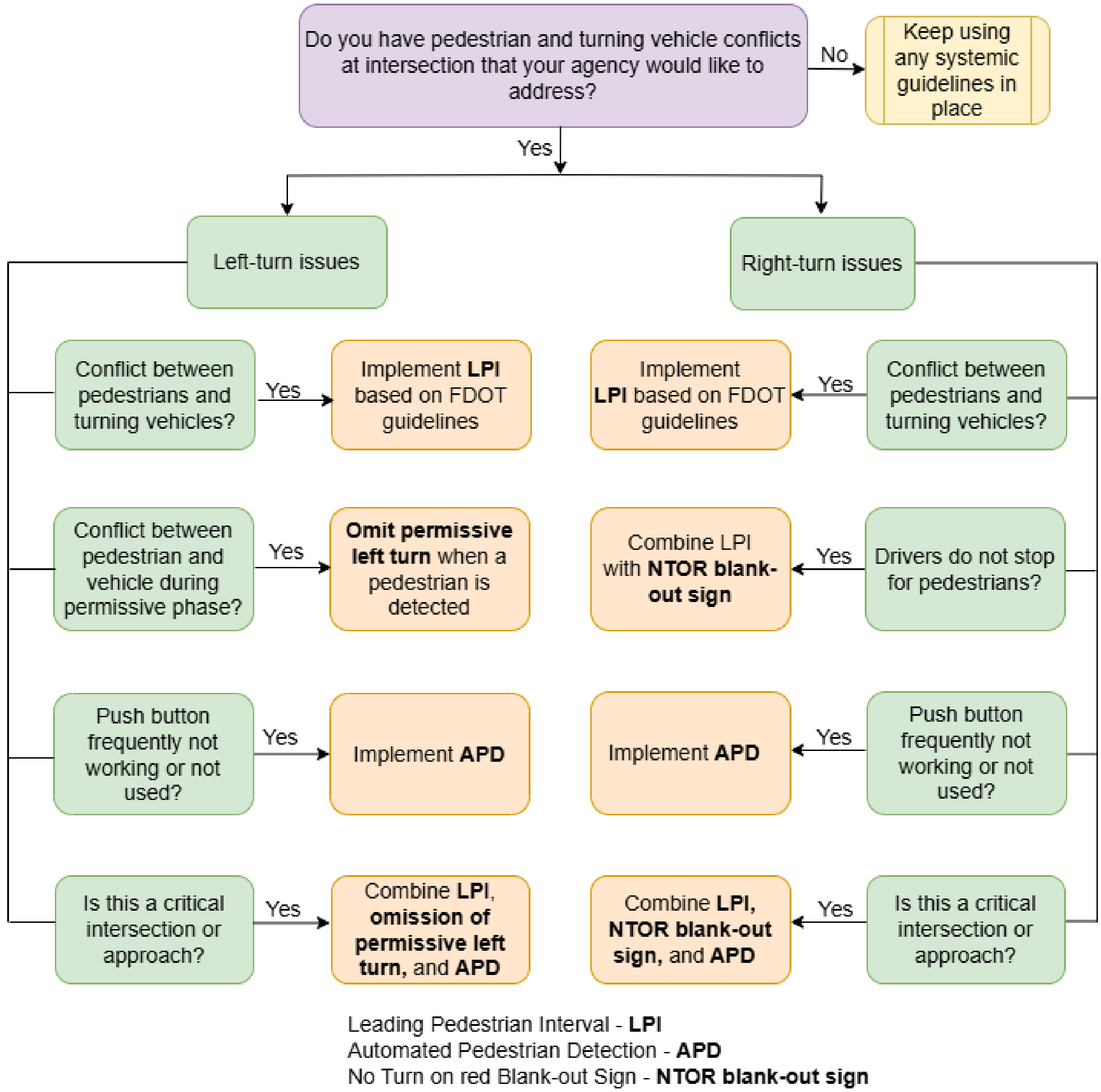


Figure 5-3. Countermeasure selection flowchart

1. Identifying Intersection Safety Challenges

The process begins by assessing whether pedestrian-vehicle conflicts, low visibility, or failure-to-yield issues exist at a given intersection. If no issues are identified, agencies should continue following existing systemic guidelines. If safety concerns are present, practitioners must determine whether the primary issue involves left-turning or right-turning vehicles based on intersection characteristics. A thorough safety assessment, including conflict analysis, should be conducted to guide the selection of appropriate countermeasures. Key steps in this identification process are illustrated in Figure 5-3.

2. Addressing Left-Turn Issues

- **Step 1:** Assess if issues are related to visibility of pedestrians, high turning vehicle volumes, or others.
  - *If yes, implement **LPI** following FDOT guidelines to give pedestrians a head start before vehicles turn.*
- **Step 2:** Determine if the intersection has a protected/permitted left-turn phase.
  - *If yes, **omit the permissive left-turn phase** when a pedestrian is detected.*
- **Step 3:** Check for frequent push-button issues, such as failures or a lack of activation.
  - *If yes, implement **APD** to improve pedestrian crossing activation.*
- **Step 4:** Assess whether the intersection is critical (e.g., high crash risk).
  - *If yes, **combine** the omission of permissive left-turns with APD for enhanced safety.*

3. Addressing Right-Turn Issues

- **Step 1:** Evaluate if issues are related to visibility of pedestrians, high turning vehicle volumes, or others.
  - *If yes, implement a **LPI** following FDOT guidelines to give pedestrians a head start before vehicles turn.*
- **Step 2:** Verify if the intersection has vehicle yielding or stopping issues.
  - *If yes, i*nstall a **NTOR Blank-out Sign** per FDOT's Traffic Engineering Manual to restrict turning movements when necessary.
- **Step 3:** For enhanced safety, combine **LPI and NTOR Blank-out Signs** by displaying the restriction during the LPI phase and preceding yellow and red intervals.
- **Step 4:** Determine if push-button issues are common at the intersection.
  - *If yes,* implement **APD** to reduce pedestrian delays and improve crossing reliability.
- **Step 5:** At critical intersections, maximize safety by combining **LPI, NTOR Blank-out Signs, and APD** for comprehensive pedestrian protection.

4. Countermeasure Selection and Comparison

Figure 5-3 presents a countermeasure selection flowchart to assist in decision-making, and Table 5-1 compares pedestrian safety countermeasures based on the specific intersection issues they address. The table categorizes four key countermeasures—LPI, NTOR blank-out signs, permissive left-turn omission, and APD—based on common pedestrian safety concerns such as turning vehicle fails to yield, limited visibility, signal timing conflicts, high-speed turns, driver distraction or inattention, pedestrian incompliance, complex intersection geometry, inadequate signage or markings, heavy traffic volumes, and pedestrians do not frequently push the button. A checkmark indicates each countermeasure's effectiveness for a given issue. LPI is highly effective in addressing most concerns, while APD is ideal for locations with pedestrians frequently failing to press the push button to cross streets, limited visibility, driver distraction or inattention, complex intersection geometry, inadequate signage or markings, heavy traffic volumes, as it detects them automatically. NTOR blank-out signs help mitigate right-turn conflicts, particularly on high-speed roads with heavy right-turn volumes. This comparison guides practitioners in selecting the most suitable solutions to enhance pedestrian safety and traffic efficiency.

Table 5-1. Pedestrian Safety Issues and Countermeasures

Countermeasure → **Issue ↓**	**Leading pedestrian Interval**	**NTOR blank-out sign**	**Omission of permissive left-turn**	**Automated pedestrian detection**
Turning vehicle fails to yield	✔	✔	✔	
Limited visibility	✔	✔		✔
Signal timing conflicts, such as concurrent green for turning vehicles and walk signal	✔	✔	✔	
High-speed turns	✔	✔	✔	
Driver distraction or inattention	✔	✔	✔	✔
Pedestrian noncompliance				✔
Complex intersection geometry	✔	✔	✔	✔
Inadequate signage or markings	✔	✔		
Heavy traffic volumes	✔	✔	✔	✔
Pedestrians do not frequently press push-button to cross streets				✔

5.4.4 Examples of Utilizing the Toolbox

A city transportation agency identified a high-risk intersection where frequent pedestrian-vehicle conflicts were occurring, particularly involving left-turning vehicles. To enhance pedestrian safety, the agency followed the structured approach outlined in the toolbox to assess the intersection, select appropriate countermeasures, and implement them effectively.

Step 1: Identifying Intersection Safety Challenges

The agency conducted a detailed site analysis, which revealed a high number of pedestrian conflicts due to low driver compliance and inadequate yielding by left-turning vehicles. Pedestrian push-button issues were also noted, leading to inconsistent crossing opportunities.

Step 2: Selecting Countermeasures

Based on the identified challenges, the agency selected a combination of countermeasures for maximum safety benefits. They implemented LPI to give pedestrians a head start before vehicles turned and omitted the permissive left-turn phase when pedestrians were detected. Additionally, they installed an APD system to ensure accurate pedestrian activation without requiring manual push-button use.

Step 3: Implementation

Traffic signal controllers were updated to accommodate LPIs, and new signage was installed to inform drivers of the changes. The APD system was integrated with existing pedestrian signals, ensuring seamless operation. The agency followed best practices for placement and visibility to optimize effectiveness.

Step 4: Monitoring and Evaluation

Following implementation, the agency monitored the intersection using video analytics and pedestrian compliance studies. Initial findings showed improved pedestrian compliance and reduced pedestrian-vehicle conflicts. Based on observed performance, minor adjustments to signal timing were made to further enhance safety.

Step 5: Public Education and Awareness

To ensure public understanding, the agency launched an outreach campaign, including informational signage and community engagement efforts. Drivers and pedestrians were educated on the new measures, reinforcing safe crossing behavior and compliance with traffic signals.

By utilizing the toolbox's structured approach, the agency successfully improved pedestrian safety at the intersection, demonstrating the effectiveness of data-driven, well-implemented countermeasures.

5.4.5 General Resources

The toolbox was developed using information from the following sources. Safety practitioners are encouraged to consult these resources for further details on pedestrian safety measures and best practices.

LPI:

FDOT Traffic Engineering Manual (TEM) 2025: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/traffic/trafficservices/studies/tem/tem-2025/2025-fdot-traffic-engineering-manual.pdf?sfvrsn=a7778316_1

Leading Pedestrian Interval, FHWA-SA-21-0.32: https://highways.dot.gov/safety/proven-safety-countermeasures/leading-pedestrian-interval

Leading Pedestrian Interval, PEDSAFE: http://www.pedbikesafe.org/pedsafe/countermeasures_detail.cfm?CM_NUM=12

Intersection and Crossing. Toolbox Section 5, Hawaii DOT: https://hidot.hawaii.gov/highways/files/2013/07/Pedest-Tbox-Toolbox_5-Intersections-and-Crossings.pdf

Leading Pedestrian Intervals (LPIS) and Accessible Pedestrian Signals (APS), POLARA: https://polara.com/guide/leading-pedestrian-intervals

NTOR Blank-out Sign:

Evaluation of static and dynamic no right turn on red signs at traffic signals, Day, C.M., 2024: https://mdl.mndot.gov/_flysystem/fedora/2024-06/202417.pdf

Omission of Permissive Left Turn:

FDOT Traffic Engineering Manual (TEM) 2025: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/traffic/trafficservices/studies/tem/tem-2025/2025-fdot-traffic-engineering-manual.pdf?sfvrsn=a7778316_1

Left-turn Treatment Guidelines for Signalized Intersections, Colorado DOT, 2023: https://www.codot.gov/safety/traffic-safety/assets/documents/left-turn-treatment-guidelines-2023-revised2.pdf

Evaluating Permitted/Protected Versus Protected Left-turn Signals in Louisiana, Thapa et al 2022: https://www.ltrc.lsu.edu/pdf/2022/FR_669.pdf

Permissive/Protected Left-Turn Phasing, FHWA-SA-09-015: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://rosap.ntl.bts

.gov/view/dot/41466/dot_41466_DS1.pdf&ved=2ahUKEwiVs_WN2qOMAxUAQzABHdnfAD04ChAWegQIFBAB&usg=AOvVaw1EW1BoxZesNGwTK2L105oK

APD:

Automated Pedestrian Detection, PEDSAFE:
http://www.pedbikesafe.org/pedsafe/countermeasures_detail.cfm?CM_NUM=11

General links:

FDOT Transportation Symposium Traffic Engineering Manual, FDOT 2019:
https://transportationsymposium.fdot.gov/User/ClassPresentation?classFileName=2019%20Symposium%20-%20PonceKnox%20-%20Traffic%20Eng%20Manual.pdf

Improving Intersections for Pedestrians and Bicyclists, FHWA 2022:
https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-06/fhwasa22017.pdf

Signalized Intersections: Informational Guide, FHWA 2004:
https://www.fhwa.dot.gov/publications/research/safety/04091/04091.pdf

The Crash Modification Factors Clearinghouse, FHWA
https://cmfclearinghouse.fhwa.dot.gov/index.php

Toolbox of Pedestrian Countermeasures and Their Potential Effectiveness, FHWA 2018:
https://highways.dot.gov/media/11816

6 Conclusions and Recommendations

This chapter outlines the conclusions and recommendations of the project. It provides an overview of the background issues, describes the process undertaken, and summarizes the results. The conclusions synthesize the key insights and findings, while the recommendations offer actionable strategies for enhancement.

Florida faces significant pedestrian safety challenges, particularly at intersections and during interactions with turning vehicles. The Florida Department of Transportation (FDOT) is dedicated to addressing these issues through research, pilot programs, and effective countermeasures. This report, part of a larger project, includes a literature review identifying best practices and innovative technologies aimed at reducing pedestrian fatalities, injuries, and crashes at signalized intersections.

Literature Review Findings

The literature review identified various contributing factors to pedestrian and turning vehicle conflicts and outlined solutions involving engineering, law enforcement, and education strategies. It also explores innovative technologies such as Leading Pedestrian Intervals (LPI), No Turn on Red blank-out signs, omitting permitted phases when a pedestrian phase is activated, and automatic pedestrian detection (APD). Implementing a combination of LPI, blank-out signs, omitted permitted left turns, and APD is expected to significantly reduce pedestrian crashes with turning vehicles at signalized intersections.

Insights of Experts from Interviews

The results of expert interviews indicate that LPIs are popular and commonly used across the United States to improve pedestrian safety at signalized intersections, with durations varying from 3 to 10 seconds. Agencies find longer LPIs (7-10 seconds) more effective, particularly at larger intersections, while shorter durations may be inadequate. LPIs are often used in conjunction with "No Turn on Red" blank-out signs to improve drivers' compliance rate and enhance pedestrian safety, though some agencies prefer static signs for pre-timed signals, such as in urban cores or downtown areas.

Combining LPIs with additional measures, such as dual-message signs ("No Turn on Red" and "Turning Vehicles Yield to Pedestrians"), and omitting permissive left-turn phases during activation of pedestrian signals for the combined protected and permitted operations has shown promising results in improving compliance and reducing pedestrian-vehicle conflicts. For this approach, transitioning from five-section to four-section signal heads is advisable. However, this transition must account for structural factors, such as the capacity of overhead structures to support the new signs and withstand wind loads.

APD systems are especially useful at locations with high pedestrian traffic, safety concerns, and accessibility needs, reducing the reliance on manual activation. However, some challenges, such as false triggers, high costs, and maintenance requirements, make agencies cautious. False triggers are more common in the common waiting area of two crosswalks at intersection corners, but when each crosswalk has its own waiting area, pedestrian intent becomes clearer, significantly easing this challenge and increasing the pedestrian detection accuracy. Therefore, these systems are most effective at signalized intersections with distinct waiting areas for each crosswalk. Such intersections are recommended for successful implementation. Passive detection systems, which face ADA compliance issues and depend on less timely physical buttons, are seeing ongoing improvements in APS and crossing ramp designs at intersections. Advances in AI-powered technologies may lead to the broader adoption of APD systems in the future. Overall, the implementation of APDs has great potential to improve pedestrian safety at signalized intersections and mid-block crossings.

Technologies such as fisheye cameras, LIDAR, and thermal sensors are employed for intersection coverage, with AI-enhanced optical systems offering advanced capabilities by learning pedestrian behavior and predicting intentions. AI video analytics and radar conflict analytics are being explored to improve traffic control, though integrating these into existing systems may take years. Additionally, advancements like ultra-wideband (UWB) short-range wireless communication technology highlight the potential for enhancing pedestrian safety.

For nighttime pedestrian safety, experts emphasize the importance of effective street lighting. Operating streetlights at 70% brightness under normal conditions and increasing to 100% when pedestrians are detected is a recommended practice. Public outreach and reflective materials also enhance visibility. Technologies like pedestrian-activated lighting and AI-enhanced systems are under evaluation for their cost-effectiveness and impact. Measures such as speed management and protected intersections contribute to safer pedestrian environments.

Quantitative Benefits based on the Pilot Deployments

- The treatment (LPI + blank-out sign) significantly reduced unsafe behaviors among right-turning vehicles, such as conflicts or being too close to pedestrians. At a large-sized intersection, the treatment resulted in a 34% reduction in unsafe behaviors (**48%** improvement), while at a middle-sized intersection, the reduction reached 91% (**100%** improvement). Additionally, the treatment reduced right-turn vehicles' unyielding behaviors by 10% (**24%** improvement) at large-sized intersections and by 14% (**100%** improvement) at a middle-sized intersection.
- The treatment (O-FYA+LPI) reduced left-turn vehicles' unsafe behaviors (conflicts or too close to pedestrians) by 19% (**83%** improvement) and left-turn vehicles' unyielding behaviors by 13% (**76%** improvement).
- A simple crash comparison in Pinellas County using 3 years of pedestrian crash data before and after the O-FYA deployments shows that pedestrian crashes related to left-turn crashes were reduced by nearly **71%** after implementing O-FYA. This finding supports the safety effects of O-FYA + LPI.

- The use of APD systems increased the rate of pedestrian crossings on the “WALK” signal indication by 24% and reduced the rate of crossing on the “RED” signal indication by 25%, which significantly improves pedestrian safety.

Recommendations from The Pilot Study Findings

- Add Omission of Flashing Yellow Arrow (O-FYA) + LPIs to existing permissive left-turn phases without them, or add the omission function to existing FYA at intersections where significant conflicts between pedestrians and left-turning vehicles occur. This measure enhances pedestrian safety by preventing left-turn vehicles from seeking gaps in traffic while pedestrians are crossing.
- Deploy blank-out signs + LPIs at intersections with high volumes of right-turning vehicles and crossing pedestrians to eliminate conflicts and enhance pedestrian safety.
- Deploy LPIs at intersections where FYA or blank-out signs are deployed to enhance their safety functions to prevent conflicts between pedestrians and turning vehicles.
- Deploy automated pedestrian detection at intersections with high bicycle and scooter volumes or frequent instances of pedestrians crossing on “RED”.
- To ensure that pedestrians accustomed to automated pedestrian phases do not neglect to push the button at intersections or approaches without detection, the following countermeasures are recommended:
    - ✓ Deploy automated pedestrian detection systems at all approaches of an intersection.
    - ✓ Implement automated pedestrian detection systems at intersections adjacent to those where the treatment has already been deployed.
    - ✓ If the above methods are not feasible, install a “push button locator tone” at approaches or intersections without automated pedestrian detection. This system provides an automatic audio reminder for pedestrians to press the button.
- Comprehensive education, outreach, and digital campaign programs are recommended at the initial deployment of O-FYA, blank-out signs, and LPI to enhance pedestrian safety by promoting adherence to traffic signals and ensuring pedestrians cross only when the “WALK” signal is activated, even when walking with a group.
- Educational programs are needed to ensure that drivers correctly understand the 'No Right Turn' message and ‘No Turn on Red’ when these blank-out signs are activated. The most effective approach is to incorporate the blank-out sign displaying 'No Right Turn' into the driver's license test. Additionally, law enforcement activities are recommended at intersections with frequent noncompliance to reduce instances of drivers failing to stop during blank-out sign activation.

Guidance and Toolbox

1. Reducing Right-Turn Conflicts

- Install NTOR blank-out signs and LPIs at intersections with high volumes of right-turning vehicles and pedestrian crossings to reduce conflicts and improve safety.

2. Reducing Conflicts Between Left-Turn Vehicles and Pedestrians

- Omit permissive turns and install LPIs at intersections where significant conflicts occur between pedestrians and left-turning vehicles.
- Add the omission function to existing FYA to prevent left-turning vehicles from searching for gaps in traffic while pedestrians are crossing.

3. Deployment of Combined Countermeasures

- Implement LPIs blank-out signs, and/or omission of FYA for PPLT operations to achieve greater effectiveness in preventing and reducing pedestrian-vehicle conflicts.

4. Automated Pedestrian Detection

- Deploy APD at intersections with high pedestrian or bicycle traffic or where pedestrians frequently do not press the push-button and cross on a red signal.
- To address the issue of pedestrians not pressing the push-button to cross streets, consider:
    a) Installing APD at all approaches of an intersection.
    b) Deploying detection at adjacent intersections where the system is already in use.
    c) If full deployment is not feasible, add a push button locator tone at locations without detection to provide an audio reminder for pedestrians to press the button.

5. Education and Public Awareness

- Implement comprehensive education, outreach, and digital campaigns when introducing omission of permissive left turn, NTOR blank-out signs, and LPIs to encourage compliance with traffic signals and ensure pedestrians cross only when the “WALK” signal is displayed.
- Educate drivers on the NTOR blank-out signs, emphasizing the need to stop completely when activated.
- Include blank-out sign education in driver’s license testing to reinforce compliance.
- Conduct targeted law enforcement activities at intersections with frequent noncompliance to reduce violations during blank-out sign activation.

7 References

[1] Smart Growth America, "Dangerous by Design 2024," 2024. [Online]. Available: https://smartgrowthamerica.org/dangerous-by-design/

[2] L. Blackburn, M. Dunn, R. Martinson, P. Robie, and K. O'Reilly, "Improving Intersections for Pedestrians and Bicyclists Informational Guide." [Online]. Available: https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-06/fhwasa22017.pdf

[3] United States Department of Transportation, "National Roadway Safety Strategy," 2022. [Online]. Available: https://www.transportation.gov/NRSS

[4] FHWA, "National Agenda for Intersection Safety," in "FHWA-SA-02-007." [Online]. Available: https://rosap.ntl.bts.gov/view/dot/38371

[5] R. Porter, M. Dunn, and J. Soika, "A Safe System-Based Framework and Analytical Methodology for Assessing Intersections," 2021. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/67035

[6] AASHTO, "Highway Safety Manual 1st Edition," 2014. [Online]. Available: https://www.highwaysafetymanual.org/Pages/default.aspx

[7] T. Urbanik *et al.*, "Signal Timing Manual - Second Edition," National Academies of Sciences, Engineering, and Medicine, Washington, DC, 2015. [Online]. Available: https://nap.nationalacademies.org/catalog/22097/signal-timing-manual-second-edition

[8] Z. Wang, P.-S. Lin, H. Lyu, R. Rangaswamy, and S. Shindgikar, "Applying tight corner radius to improve pedestrian safety at signalized intersections," in *ICTD*, Atlanta, 2024.

[9] FHWA, "Manual on Uniform Traffic Control Devices for Streets and Highways - 11th Edition," U.S. Department of Transportation, 2023. [Online]. Available: https://mutcd.fhwa.dot.gov/pdfs/11th_Edition/mutcd11thedition.pdf

[10] R. A. Retting, M. S. Nitzburg, C. M. Farmer, and R. L. Knoblauch, "Field evaluation of two methods for restricting right turn on red to promote pedestrian safety," *ITE Journal,* vol. 72, no. 1, pp. 32-36, 2002.

[11] C. M. Richard, J. L. Campbell, and J. L. Brown, "Task Analysis of Intersection Driving Scenarios: Information Processing Bottlenecks," Federal Highway Administration, 2006. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/825/dot_825_DS1.pdf

[12] P.-S. Lin, A. Kourtellis, Z. Wang, C. Chen, R. Rangaswamy, and J. Jackman, "Understanding Interactions between Drivers and Pedestrian Features at Signalized Intersections – Phase 3," 2019. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/49952

[13] T. R. Neuman, "Guidance for Implementation of the AASHTO Strategic Highway Safety Plan," American Association of State Highway and Transportation Officials, 2003.

[14] H. Lyu, Z. Wang, P.-S. Lin, Q. Lu, P. P. Hsu, and E. Duran, "Exploring the impact of pavement friction patterns on crash injury severity using Continuous Pavement Friction Measurement (CPFM) data," presented at the 103rd Transportation Research Board (TRB) Annual Meeting, Washington, DC, 2024.

[15] K. Fitzpatrick, A. Do, R. Avelar, M. Pratt, and S. Das, "Improving Pedestrian Safety at Signalized Intersections: Impacts of Corner Radius," *Institute of Transportation Engineers. ITE Journal,* vol. 92, no. 6, pp. 37-32, 2022.

[16] K. Fitzpatrick, R. Avelar, M. Pratt, S. Das, and D. Lord, "Crash Modification Factor for Corner Radius, Right-Turn Speed, and Prediction of Pedestrian Crashes at Signalized

Intersections," Federal Highway Administration, 2022, vol. FHWA-HRT-21-105. [Online]. Available: https://www.fhwa.dot.gov/publications/research/safety/21105/21105.pdf
[17] B. Chandler, M. Myers, J. Atkinson, T. Bryer, and R. Retting, "Signalized Intersection Informational Guide," 2013. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/42546
[18] P.-S. Lin, Z. Wang, Q. Lu, and H. Lyu, "SCRIM safety data analysis and guideline development for using continuous pavement friction measurements to support prioritization of 3R and safety project selection and deployment : Deliverable 3," USF, CUTR, 2024.
[19] Centers for Disease Control and Prevention, "Pedestrian Safety," 2024. [Online]. Available: https://www.cdc.gov/pedestrian-bike-safety/about/pedestrian-safety.html?CDC_AAref_Val=https://www.cdc.gov/transportationsafety/pedestrian_safety/index.html
[20] E. Rosen and U. Sander, "Pedestrian fatality risk as a function of car impact speed," *Accident Analysis & Prevention,* vol. 41, no. 3, p. 7, 2009, doi: 10.1016/j.aap.2009.02.002.
[21] R. Sanders, "Guidance to Improve Pedestrian and Bicyclist Safety at Intersections," NCHRP, 2020. [Online]. Available: https://nap.nationalacademies.org/download/25808
[22] Governors Highway Safety Association, "Pedestrian Traffic Fatalities by State: 2021 Preliminary Data," 2021. [Online]. Available: https://www.ghsa.org/resource-hub/pedestrian-traffic-fatalities-state-2021-preliminary-data
[23] S. Monfort and B. Mueller, "Pedestrian injuries from cars and SUVs: Updated crash outcomes from the vulnerable road user injury prevention alliance (VIPA)," *Traffic Injury Prevention,* vol. 21, 2020, doi: 10.1080/15389588.2020.1829917.
[24] National Highway Traffic Safety Administration, "Traffic safety facts 2021 data: Pedestrians U.S. Department of Transportation," 2021. [Online]. Available: https://trid.trb.org/View/2192559
[25] Kittelson & Associates, Inc., "Guide for Pedestrian and Bicycle Safety at Alternative and Other Intersections and Interchanges," 2021. [Online]. Available: https://nap.nationalacademies.org/catalog/26072/guide-for-pedestrian-and-bicyclist-safety-at-alternative-and-other-intersections-and-interchanges
[26] B. Tefft, "Impact speed and a pedestrian's risk of severe injury or death," *Accident Analysis & Prevention,* 2013, doi: 10.1016/j.aap.2012.07.022.
[27] C. Jiang, R. Qiu, T. Fu, L. Fu, B. Xiong, and Z. Lu, "Impact of right-turn channelization on pedestrian safety at signalized intersections," *Accident Analysis & Prevention,* vol. 136, 2020, doi: 10.1016/j.aap.2019.105399.
[28] P. Zador, J. Moshman, and L. Marcus, "Adoption of right turn on red: Effects on crashes at signalized intersections," *Accident Analysis & Prevention,* vol. 14, no. 3, p. 14, 1982, doi: 10.1016/0001-4575(82)90033-1.
[29] R. Compton and E. Milton, "Safety Impact of Permitting Right-Turn-On-Red: A Report to Congress by the National Highway Traffic Safety Administration," National Highway Traffic Safety Administration, 1994.
[30] L. Thomas, "PBIC Webinar: Crash types series left-turn crashes involving pedestrians," 2018. [Online]. Available: https://www.pedbikeinfo.org/pdf/Webinar_PBIC_102518.pdf

[31] New York City DOT, "Left Turn Traffic Calming." [Online]. Available: https://www.nyc.gov/html/dot/html/pedestrians/turn-calming.shtml
[32] M. Sharafeldin, O. Albatayneh, A. Farid, and K. Ksaibati, "A Bayesian Approach to Examine the Impact of Pavement Friction on Intersection Safety," *Sustainability,* vol. 14, no. 19, 2022, doi: 10.3390/su141912495.
[33] Federal Highway Administration, "High Friction Surface Treatments: Project Case Study," 2014. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/41301
[34] K. Haleem, P. Alluri, and A. Gan, "Analyzing pedestrian crash injury severity at signalized and non-signalized locations," *Accident Analysis & Prevention,* vol. 81, p. 10, 2015, doi: 10.1016/j.aap.2015.04.025.
[35] J. Stipancic, L. Miranda-Moreno, J. Strauss, and A. Labbe, "Pedestrian safety at signalized intersections: Modelling spatial effects of exposure, geometry and signalization on a large urban network," *Accident Analysis & Prevention,* vol. 134, 2020, doi: 10.1016/j.aap.2019.105265.
[36] N. Y. DOT, "New York state pedestrian safety action plan," 2016.
[37] J. Fox, "Guidelines for Creating an Effective Vision Zero Action Plan," 2022. [Online]. Available: Guidelines for Creating an Effective Vision Zero Action Plan
[38] FHWA, "Intersection Safety Strategies," 2015. [Online]. Available: https://safety.fhwa.dot.gov/intersection/stop/fhwasa15085.pdf
[39] FDOT, "Intersection operations and safety." [Online]. Available: https://www.fdot.gov/traffic/trafficservices/intersection-operations.shtm
[40] FDOT, "Manual on Intersection Control Evaluation," 2024. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/traffic/trafficservices/studies/ice-materials-2024/fdot-ice-manual_2024.pdf?sfvrsn=7e23d529_5
[41] T. Bryer, "Intersection Safety Implementation Plan Process," 2009. [Online]. Available: https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-06/fhwasa10010.pdf
[42] FDOT, "PSEE (Project Suite Enterprise Edition) safety countermeasures module - how to guide," 2023. [Online]. Available: https://www.youtube.com/watch?v=JYOg84e-2io
[43] FHWA, "Pedestrian accommodations at intersections," 2013. [Online]. Available: https://safety.fhwa.dot.gov/ped_bike/univcourse/pdf/swless15.pdf
[44] NACTO, "Urban Street Design Guide," 2013. [Online]. Available: https://nacto.org/publication/urban-street-design-guide/
[45] E. Sacchi, T. Sayed, and O. Ahmed, "Developing crash modification functions for pedestrian signal improvement," in "Accident Analysis & Prevention," 2015. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S000145751530018X
[46] FDOT, "Section 653 Pedestrian Signal Assemblies." [Online]. Available: https://www.fdot.gov/docs/default-source/programmanagement/Implemented/SpecBooks/July2016/Files/653-716.pdf
[47] FDOT, "Safe Mobility at Intersections: Countdown Pedestrian Signal," 2024. [Online]. Available: https://www.safemobilityfl.com/pdfs/Countdown_Ped_Signal_Tip_Card.pdf
[48] J. Mead, C. Zegeer, and M. Bushell, "Evaluation of Pedestrian-related Roadway Measures: a Summary of Available Research," Federal Highway Administration, 2014. [Online]. Available: https://www.pedbikeinfo.org/downloads/PedestrianLitReview_April2014.pdf

[49] FDOT, "The Effects of Pedestrian Countdown Signals in Lake Buena Vista," 2000.
[50] New York City DOT, "Right Turn on Red." [Online]. Available: https://www.nyc.gov/html/dot/downloads/pdf/ssi09_rightonred.pdf
[51] FHWA, "Right Turn on Red Restrictions." [Online]. Available: https://safety.fhwa.dot.gov/saferjourney1/library/countermeasures/44.htm
[52] P.-S. Lin, A. Kourtellis, Z. Wang, and R. Guo, "Understanding interactions between drivers and pedestrian features at signalized intersections," 2015.
[53] P.-S. Lin, A. Kourtellis, Z. Wang, C. Chen, and R. Guo, "Understanding interactions between drivers and pedestrian features at signalized intersections- Phase 2," 2017.
[54] FDOT, "Turning vehicles stop for pedestrians." [Online]. Available: https://www.fdot.gov/traffic/trafficservices/signlibrary/regulatory/regulatory.shtm
[55] Signal-Tech Inc., "Turning vehicles stop for pedestrians." [Online]. Available: https://www.signal-tech.com/products/rail/light_rail_and_pedestrian_warning/56175
[56] C. Zegeer, D. Nabors, and P. Lagerwey, "Pedestrian safety guide and countermeasure selection system." [Online]. Available: http://pedbikesafe.org/PEDSAFE/countermeasures_detail.cfm?CM_NUM=24
[57] E. Goughnour *et al.*, "Safety evaluation of protected left-turn phasing and leading pedestrian intervals on pedestrian safety," 2018. [Online]. Available: https://www.fhwa.dot.gov/publications/research/safety/18044/18044.pdf
[58] S. Siby, A. Singh, and Y. Yamani, "Engineering Countermeasures for Left Turns at Signalized Intersections: A Review," *Journal of Road Safety,* vol. 33, no. 2, 2022. [Online]. Available: https://digitalcommons.odu.edu/psychology_fac_pubs/133/.
[59] NCHRP, "Accessible pedestrian signals: A guide to best practices," Washington, DC, 2011.
[60] R. van Houten, J. E. Malanefant, J. van Houten, and R. A. Retting, "Using Auditory Pedestrian Signals To Reduce Pedestrian and Vehicle Conflicts," *Transportation Research Record,* vol. 1578, no. 1, 1997. [Online]. Available: https://journals.sagepub.com/doi/epdf/10.3141/1578-03.
[61] A. Pande and B. Wolshon, *Traffic Engineering Handbook: Institute of Transportation Engineers*. 2015.
[62] FDOT, "Traffic Engineering Manual," 2024. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/traffic/trafficservices/studies/tem/tem-2024/traffic-engineering-manual-dec-2023.pdf?sfvrsn=a33268c8_4
[63] FDOT, "2024 FDOT Design Manual," 2024. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/roadway/fdm/2024/2024-fdm-complete.pdf?sfvrsn=392bd8be_21
[64] R. Ewing, "Traffic Calming State of the Practice," 1999. [Online]. Available: https://nacto.org/wp-content/uploads/Ewing-Reid-1999.pdf
[65] FHWA, "Traffic Calming : 23. Curb extensions." [Online]. Available: https://safety.fhwa.dot.gov/saferjourney1/Library/countermeasures/23.htm
[66] D. W. Harwood, "Safety effectiveness of intersection left- and right-turn lanes," 2002.
[67] FHWA, "Dedicated Left- and Right-Turn Lanes at Intersections." [Online]. Available: https://highways.dot.gov/sites/fhwa.dot.gov/files/Left-%20and%20Right-Turn%20Lanes_508.pdf

[68] New York City DOT, "Turn Calming Program." [Online]. Available: https://www.nyc.gov/html/dot/html/pedestrians/turn-calming.shtml
[69] Chicago. "Turn Calming Program." https://www.chicago.gov/city/en/sites/complete-streets-chicago/home/featured-projects-and-innovations/design-innovations/left-turn-traffic-calming.html (accessed.
[70] FDOT, "Signalized restricted crossing U-turn intersections."
[71] FHWA, "Restricted crossing U-turn intersection (FHWA-SA-14-040)," 2020. [Online]. Available: https://safety.fhwa.dot.gov/intersection/rltci/fhwasa14040.pdf
[72] W. Hughes, R. Jagannathan, D. Sengupta, and J. Hummer, "Alternative intersections/interchanges: informational report (AIIR)," 2010. [Online]. Available: https://www.fhwa.dot.gov/publications/research/safety/09060/09060.pdf
[73] J. Hummer, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen, "Restricted crossing U-turn informational guide," 2014.
[74] FHWA, "Selecting Pedestrian Safety Improvements," 2024. [Online]. Available: https://safety.fhwa.dot.gov/saferjourney1/Library/matrix.htm
[75] L. Rodegerdts, J. Bansen, C. Tiesler, J. Knudsen, and E. Myers, "Roundabouts: An Informational Guide - Second Edition," 2020. [Online]. Available: https://nap.nationalacademies.org/read/22914/chapter/1
[76] Los Angeles DOT, "Pedestrian Scramble," 2017. [Online]. Available: https://ladot.lacity.gov/sites/default/files/2022-08/exclusive-pedestrian-phase-policy-design-guide-final-2017.pdf
[77] State of New York, "Senate Bill S2515A: Establishes scramble crosswalks leading to and from school buildings during times of student arrival and dismissal," 2023. [Online]. Available: https://legislation.nysenate.gov/pdf/bills/2023/S2515A
[78] FDOT District 6, "Safety Newsletter," 2022. [Online]. Available: https://fdotsafetyresources.com/resources/safety-newsletter/safety-newsletter-issue4-march2022-web.pdf
[79] Department of Justice, "2010 ADA Standards for Accessible Design," 2010.
[80] Architectural and Transportation Barriers Compliance Board, "Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way," 2023. [Online]. Available: https://www.federalregister.gov/d/2023-16149
[81] Smart Growth America, "How street design shapes the epidemic of preventable pedestrian fatalities," 2022. [Online]. Available: https://smartgrowthamerica.org/how-street-design-shapes-the-epidemic-of-preventable-pedestrian-fatalities/
[82] American Association of State Highway and Transportation Officials, "A policy on geometric design of highways and streets," 2018.
[83] National Association of City Transportation Officials, "Transit street design guide," 2016.
[84] M. Brewer, D. Murillo, and A. Pate, "Handbook for designing roadways for the aging population," 2014.
[85] E. J. Fitzsimmons, T. E. Lindheimer, and S. D. Schrock, "Evaluation of intersection confirmation lights in medium to large communities in Iowa to reduce red light running violations," 2015.
[86] FHWA, "Proven safety countermeasures: Backplates with retroreflective borders," 2022. [Online]. Available: https://safety.fhwa.dot.gov/provencountermeasures/backplate.cfm

[87] T. Sayed, M. E. Esawey, and J. Pump, "Evaluating impact on safety of improved signal visibility at urban signalized intersections," *Transportation Research Record,* 2007, doi: 10.3141/2019-07.
[88] United States. Federal Highway Administration. Office of Safety, "Intersection proven safety countermeasure: Technical summary: Backplates with retroreflective borders," 2015. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/42807
[89] FHWA, "Proven Safety Countermeasures," 2016. [Online]. Available: https://highways.dot.gov/safety/proven-safety-countermeasures/lighting
[90] L. Chen, C. Chen, and R. Ewing, "The relative effectiveness of signal related pedestrian countermeasures at urban intersections—Lessons from a New York City case study," *Transport Policy,* vol. 32, p. 10, 2014, doi: 10.1016/j.tranpol.2013.12.006.
[91] R. Gibbons, P. Lutkevich, R. Bhagavathula, and D. Keith, "2023 FHWA Lighting Handbook," 2023. [Online]. Available: https://highways.dot.gov/sites/fhwa.dot.gov/files/2023-05/FHWA-Lighting-Handbook_0.pdf
[92] Signal Four Analytics, "Florida traffic safety dashboard," 2023. [Online]. Available: https://signal4analytics.com/
[93] Florida Department of Highway Safety and Motor Vehicles, "Driving safety: Pedestrian safety." [Online]. Available: https://www.flhsmv.gov/safety-center/driving-safety/pedestrian-safety/
[94] FHWA, "Lighting, Proven Safety Countermeasures." [Online]. Available: https://highways.dot.gov/safety/proven-safety-countermeasures/lighting
[95] R. Elvik, " Handbook of road safety measures," 2009.
[96] X. Ye, R. P. Pendyala, S. P. Washington, K. Konduri, and J. Oh, "A simultaneous equations model of crash frequency by collision type for rural intersections," *Safety Science,* vol. 47, no. 3, p. 10, 2009, doi: 10.1016/j.ssci.2008.06.007.
[97] Z. Wang, P.-S. Lin, S. Katkoori, M. Li, A. Vasili, and R. Yang, "Development of automated roadway lighting diagnosis tools for nighttime traffic safety improvement," 2020. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/55963/dot_55963_DS1.pdf
[98] FDOT, "Florida school crossing guard training guideline," 2023. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/safety/6-resources/crosswalk-safety/fscgtp-guidelines-8-2023-english-digital.pdf?sfvrsn=32b645ce_2
[99] U. S. DOT, "Safety - pedestrian in signalized crosswalk." [Online]. Available: https://www.its.dot.gov/infographs/pedestrian_signalized_crosswalk.htm
[100] A. Lam, W. Chupp, A. Chouinard, and W. G. Najm, "Safety impact assessment of the connected vehicle pilot safety applications," FHWA, Office of Transportation Management, 2022. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/63102/dot_63102_DS1.pdf
[101] M. Talas, "Connected Vehicle Pilot Deployment Program Phase 3 – system performance report - New York City," 2021. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/63102/dot_63102_DS1.pdf
[102] A. Lam, W. Chupp, W. G. Najm, J. Brewer, and D. Fallings, "Safety impact assessment of New York City connected vehicle pilot safety applications," 2022. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/63319/dot_63319_DS1.pd

[103] K. Williams, V. G. Stover, K. Dixon, and P. Demosthenes, "Access Management Manual, Second Edition," 2014.
[104] FDOT, "Multimodal access management guidebook," 2023. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/planning/systems/systems-management/document-repository/access-management/fdot-multimodal-access-management-guidebook_oct2023.pdf?sfvrsn=95abdf85_1
[105] J. S. Gluck, H. S. Levinson, and V. G. Stover, "Impacts of access management technique," Washington, DC, 1999.
[106] V. G. Stover and F. J. Koepke, "Transportation and land development," *Institute of Transportation Engineers,* 2002.
[107] H. Lyu, Z. Wang, P.-S. Lin, P. P. Hsu, and E. Duran, "Implementing high friction surface treatment (HFST) to improve intersection safety," presented at the 103rd Transportation Research Board (TRB) Annual Meeting, 2024.
[108] National Highway Safety Administration, "Pedestrian safety enforcement operations: A How-To guide." [Online]. Available: https://www.nhtsa.gov/sites/nhtsa.gov/files/812059-pedestriansafetyenforceoperahowtoguide.pdf
[109] FHWA, "Appropriate speed limits for all road users (FHWA-SA-21-034)." [Online]. Available: https://highways.dot.gov/sites/fhwa.dot.gov/files/App%20Speed%20Limits_508.pdf
[110] K. A. Eccles, "Automated enforcement for speeding and red light running," Transportation Research Board, 2012.
[111] K. Pécheux, J. Bauer, and P. McLeod, "Pedestrian safety and ITS-based countermeasures program for reducing pedestrian fatalities, injury conflicts, and other surrogate measures draft zone/area-wide evaluation technical memorandum," 2009.
[112] R. van Houten, R. A. Retting, C. M. Farmer, and J. van Houten, "Field evaluation of a leading pedestrian interval signal phase at three urban intersections," *Transportation Research Record,* 2000, doi: 10.3141/1734-13.
[113] A. C. Fayish and F. Gross, "Safety effectiveness of leading pedestrian intervals evaluated by a Before–After study with comparison groups," *Transportation Research Record,* vol. 1734, no. 1, 2010, doi: 10.3141/2198-03.
[114] P.-S. Lin, Z. Wang, C. Chen, R. Guo, and Z. Zhang, "Development of statewide guidelines for implementing leading pedestrian intervals in Florida," 2017. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv25-977-22-rpt.pdf
[115] J. Ponce and D. Knox, "Traffic Engineering Manual (TEM) updates," 2019. [Online]. Available: https://transportationsymposium.fdot.gov/User/ClassPresentation?classFileName=2019%20Symposium%20-%20PonceKnox%20-%20Traffic%20Eng%20Manual.pdf
[116] C. Zegeer and M. Cynecki, "Evaluation of countermeasures related to RTOR accidents that involve pedestrians," *Transportation Research Record,* vol. 1059, no. 5, p. 11, 1986.
[117] A. Sullivan, S. Johnes, E. Tedla, and E. Doustmohammadi, "Traffic signal design guide & timing manual," 2015. [Online]. Available:

https://www.dot.state.al.us/publications/Design/pdf/TrafficDesign/TrafficSignalManual.pdf
[118] C. Day, A. Sharma, and Oneyear, "Evaluation of static and dynamic No Right Turn On Red signs at traffic signals," 2022. [Online]. Available: https://intrans.iastate.edu/research/in-progress/evaluation-of-static-and-dynamic-no-right-turn-on-red-signs-at-traffic-signals/
[119] C. Brehmer, K. Kacir, D. Noyce, and M. Manser, "Evaluation of Traffic Signal Display for Protected/Permissive Left-Turn Control," 2003. [Online]. Available: https://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_493.pdf
[120] L. J. Johnson, "Protected-permitted left turn comparison." [Online]. Available: https://www.youtube.com/@ljthefro
[121] T. R. Board, "Traffic signal control strategies for pedestrians and bicyclists," 2022.
[122] C. Daily, "Decision-making guide for traffic signal phasing," 2020.
[123] R. L. Gordon and W. Tighe, "Traffic control systems handbook," 2005.
[124] W. Hughes, H. Huang, C. Zegeer, and M. Cynecki, "Evaluation of automated pedestrian detection at signalized intersections," 2001. [Online]. Available: https://www.fhwa.dot.gov/publications/research/safety/00097/00097.pdf
[125] P.-S. Lin, A. Kourtellis, Z. Wang, and C. Chen, "Integration of a robust automated pedestrian detection system for signalized intersections," 2019. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/64442/dot_64442_DS1.pdf
[126] A. Maxwell, J. Kennedy, I. Routledge, P. Knight, and K. Wood, "Puffin pedestrian crossing accident study," 2011. [Online]. Available: https://trl.co.uk/uploads/trl/documents/PPR507.pdf.
[127] Association of Greater Manchester Authorities, "A Before and After analysis of accidents at Puffin crossings and at signalized junctions with nearside indicators," 2007. [Online]. Available: https://www.gmtu.gov.uk/reports/rep1257.pdf.
[128] S. S. Nambisan, S. S. Pulugurtha, V. Vasudevan, M. R. Dangeti, and V. Virupaksha, "Effectiveness of automatic pedestrian detection device and smart lighting for pedestrian safety," *Transportation Research Record,* vol. 2140, p. 8, 2009, doi: 10.3141/2140-03.
[129] T. Li, S. Kothuri, K. K., X. Yang, and F. Chowdhury, "Pedestrian behavior study to advance pedestrian safety in smart transportation systems using innovative LiDAR sensors," 2023. [Online]. Available: https://nitc.trec.pdx.edu/research/project/1393
[130] FHWA, "Pedestrian Safety: Report to Congress," 2008. [Online]. Available: https://safety.fhwa.dot.gov/ped_bike/legis_guide/rpts_cngs/pedrpt_0808/pedrept_0808.pdf
[131] FDOT, "Florida Department of Transportation GIS open data hub." [Online]. Available: https://gis-fdot.opendata.arcgis.com/
[132] M. Albee and P. Bobitz, "Making our roads safer. One countermeasure at a time," 2021. [Online]. Available: https://highways.dot.gov/sites/fhwa.dot.gov/files/Proven%20Safety%20Countermeasures%20Booklet_0.pdf
[133] Chicago, "Left Turn Traffic Calming." [Online]. Available: https://www.chicago.gov/city/en/sites/complete-streets-chicago/home/featured-projects-and-innovations/design-innovations/left-turn-traffic-calming.html

[134] FDOT, "Traffic Engineering Manual Updates," 2019. [Online]. Available: https://transportationsymposium.fdot.gov/User/ClassPresentation?classFileName=2019%20Symposium%20-%20PonceKnox%20-%20Traffic%20Eng%20Manual.pdf
[135] FDOT, "Traffic Engineering Manual (TEM)," 2025. [Online]. Available: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/traffic/trafficservices/studies/tem/tem-2025/2025-fdot-traffic-engineering-manual.pdf?sfvrsn=a7778316_1

Appendix

Interview Questionnaire on Technologies and Methods for Reducing Conflicts Between Pedestrians and Turning Vehicles

This interview is part of the data collection efforts to assist the Florida Department of Transportation (FDOT) with the development of guidelines and toolbox for reducing pedestrian crashes with turning vehicles at signalized intersections. The USF-CUTR research team is interested in understanding and learning technologies and methods used by various experts to improve pedestrian safety by decreasing conflicts between turning vehicles and pedestrians at signalized intersections. The main objective of this interview is to obtain experience, suggestions, and recommendations that could assist in developing procedures to prevent pedestrian and turning vehicle crashes. Although the research team is interested to hear any countermeasures that could help reduce conflicts during turning vehicle and pedestrian interactions, the interview will focus on the technologies and methods for combining ***leading pedestrian interval***, ***automated pedestrian detection***, application of "***No Turn on Red" blank-out signs***, and advanced traffic signal control operations to allow ***omission of permitted left turns during a protected and permitted left-turn operations.***

Name, Title, and Affiliation of Respondent:

Contact Email:

Office Phone:

<u>Agency Experts</u>

1. Has your agency used the following practices to reduce conflicts between pedestrians and turning vehicles at signalized intersections?
   a) Leading pedestrian interval (LPI)
   b) Blank-out signs displaying "No Turn on Red" during red signal indications when a pedestrian call is active
   c) Blank-out signs displaying "Turning Vehicles Yield to Pedestrians" during green and yellow signal indications
   d) Blank-out signs displaying "Turning Vehicles Stop for Pedestrians"
   e) Traffic signal control operations to omit permitted left turns during a protected and permitted left turn operations when a pedestrian pushes the button or is automatically detected
   f) Automated pedestrian detection

   If yes,

   - What guidance did your agency follow while implementing this strategy?
   - How effective was this countermeasure at enhancing pedestrian safety?

- Has your agency performed any before and after study when implementing this countermeasure?
- Do you have any lessons learned to share with us?

2. Which of the implemented countermeasures or technologies has worked the best for your agency?
3. Among the listed countermeasures are there any you have not implemented yet but are planning to?
4. Has your agency combined any of the listed countermeasures (e.g., **LPI**, application of "**No Turn on Red**" **blank-out signs**, advanced traffic signal control operations to allow **omission of permitted left turns during a protected and permitted left-turn operations,** and **automated pedestrian detection)** at an intersection? How effective was the combination? Do you have any documentation or study available related to that combination?
5. Who are the vendors you have worked with when implementing the highlighted countermeasures?
6. Can you give examples of locations where you have implemented these technologies or countermeasures?
7. Do you know any organizations that have successfully combined **LPI**, application of "**No turn on red**" blank-out signs, advanced traffic signal control techniques to enable **omission of permitted left turns during a protected and permitted left-turn operations,** and **automated pedestrian detection** to reduce pedestrian and turning vehicle conflicts?
8. What countermeasures or strategies has your agency used to enhance pedestrian safety ***at night*** when dealing with turning vehicles?
9. Has your agency implemented or is planning to implement any other new or emerging technologies or strategies to improve pedestrian safety against turning vehicles at signalized intersections?
   If yes,
   i. What are those technologies?
   ii. Why do you plan to implement those technologies?
10. What are your suggestions, recommendations, or take aways from using various technologies or countermeasures for addressing pedestrian and turning vehicle related conflicts?

Consultants

1. Has your organization used or studied any of the following practices to reduce conflicts between pedestrians and turning vehicles at signalized intersections?
   a) Leading pedestrian interval (LPI)
   b) Blank-out signs displaying "No Turn on Red" during red signal indications when a pedestrian call is active

c) Blank-out signs displaying “Turning Vehicles Yield to Pedestrians” during green and yellow signal indications
d) Blank-out signs displaying “Turning Vehicles Stop for Pedestrians”
e) Traffic signal control operations to omit permitted left turns during a protected and permitted left turn operations when a pedestrian pushes the button or is automatically detected
f) Automated pedestrian detection

If yes,

- How effective was the countermeasure at enhancing pedestrian safety?
- What guidance has your organization followed while implementing the countermeasure?
- What are the lessons learned?
- Has your organization performed any before and after studies related to the countermeasure?

2. Has your organization combined any of the highlighted countermeasures (e.g., **LPI**, application of “**No Turn on Red**” **blank-out signs**, advanced traffic signal control operations to allow **omission of permitted left turns during a protected and permitted left-turn operations,** and **automated pedestrian detection**)**?**

   If yes,
   - How effective was the combination?
   - Do you have any documentation or study available related to that combination?
3. Who are the vendors or agencies you have worked with when implementing the highlighted countermeasures?
4. Can you give examples of locations where you have implemented or studied these technologies or countermeasures?
5. Do you know any organizations that have successfully combined **LPI**, application of “**No turn on red**” blank-out signs, advanced traffic signal control techniques to enable **omission of permitted left turns during a protected and permitted left-turn operations,** and **automated pedestrian detection** to reduce pedestrian and turning vehicle conflicts?
6. What countermeasures or strategies has your organization used to enhance pedestrian safety ***at night*** when dealing with turning vehicles?
7. Has your organization implemented or studied, or is planning to implement or study any other new or emerging technologies or strategies to improve pedestrian safety against turning vehicles at signalized intersections?

   If yes,
   i. What are those technologies?
   ii. Why do you plan to implement/study, or have you implemented/studied these technologies?
8. What are your suggestions, recommendations, or take aways from dealing with pedestrian and turning vehicle related conflicts?

Researchers

1. Have you researched the following countermeasures to reduce conflicts between pedestrians and turning vehicles at signalized intersections?
   (a) Leading pedestrian interval (**LPI**), (b) blank-out signs displaying "**No Turn on Red**" during red signal indications when a pedestrian call is active, (c) blank-out signs displaying "**Turning Vehicles Yield to Pedestrians**" during green and yellow signal indications, (d) blank-out signs displaying "**Turning Vehicles Stop for Pedestrians**", (e) traffic signal control operations to **omit permitted left turns during a protected and permitted left turn operations** when a pedestrian pushes the button or is automatically detected**,** (f) **automated pedestrian detection**

   If yes,
   - What were your findings related to that countermeasure and its effectiveness?
   - Have you conducted any before and after studies related to that countermeasure?
   - What methods have you used to evaluate the countermeasure and its effectiveness?
2. Have you studied the effectiveness of the combination of any of the highlighted countermeasures (e.g., **LPI**, application of "**No Turn on Red**" **blank-out signs**, advanced traffic signal control operations to allow **omission of permitted left turns during a protected and permitted left-turn operations,** and **automated pedestrian detection**)**?**

   If yes,
   - How effective was the combination?
   - Do you have any documentation available related to that study?
3. Do you know any organizations that have successfully combined **LPI**, application of "**No turn on red**" blank-out signs, advanced traffic signal control techniques to enable **omission of permitted left turns during a protected and permitted left-turn operations, and automated pedestrian detection** to reduce pedestrian and turning vehicle conflicts?
4. Have you studied any technologies or countermeasures that can help enhance pedestrian safety ***at night*** when dealing with turning vehicles?
5. Have you studied any other new or emerging technologies to improve pedestrian safety against turning vehicles at signalized intersections?

   If yes,
   - What are those technologies?
   - How effective are they?
6. What are your suggestions, recommendations, or take aways about using various technologies or countermeasures to reduce pedestrian and turning vehicle related conflicts?

Vendors

1. Do you provide any of the following?
   a) Automated pedestrian detection
   b) Blank-out signs displaying “No Turn on Red”
   c) Blank-out signs displaying “Turning Vehicles Yield to Pedestrians”
   d) Blank-out signs displaying “Turning Vehicles Stop for Pedestrians”
2. Who are your customers that bought those technologies/products?
3. Can you provide examples of locations that have one of the countermeasures/products highlighted in Question 1?
4. When designing an algorithm or a product to optimize pedestrian safety (i.e., automated pedestrian detection or blank out signs), what factors do you consider and what equipment is needed (i.e., what type of controller)?
5. What factors do you consider when calibrating signalized intersections for the safety of pedestrians?
6. Do you provide technologies or products that can enhance pedestrian safety against turning vehicles ***at night***?
   If yes,
7. What are those technologies?

What are your suggestions, recommendations, or take aways for using technologies/products to reduce pedestrian and turning vehicle related conflicts?