Final Report

Innovative Signal Timing Design and Operation Strategies to Improve Nighttime Arterial Safety

Contract Number

BED25-977-27

Final Report

Prepared for

Florida Department of Transportation

Prepared by

Center for Urban Transportation Research

September 2026

Innovative Signal Timing Design and Operation Strategies to Improve Nighttime Arterial Safety

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Project Number

BED25-977-27

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FDOT Research Center

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September 2026

Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of 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)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

Technical Report Documentation

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Innovative Signal Timing Design and Operation Strategies to Improve Nighttime Arterial Safety		**5. Report Date** 09/30/2026 **6. Performing Organization Code**
7. Author(s) Pei-Sung Lin, Yaye Keita, Zhenyu Wang, Can Cui, Ela Bialkowska-Jelinska, Rama Durga Tammayya Naidu Kolla		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Center for Urban Transportation Research (CUTR) University of South Florida 4202 E Fowler Avenue, CUT100 Tampa, FL 33620-5375		**10. Work Unit No.** **11. Contract or Grant No.** BED25-977-27
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399-0450		**13. Type of Report and Period Covered** Final Report 4/1/2025 - 9/30/2026 14. **Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

Nighttime driving presents a disproportionate safety challenge on arterial roadways, particularly in Florida, where more than half of all traffic fatalities occur after dark despite lower traffic volumes. Nighttime conditions introduce multiple risk factors, including reduced visibility, increased speeding, impaired driving, and diminished driver expectancy, all of which contribute to greater crash severity. This study investigates how innovative traffic signal timing design and operational strategies can improve nighttime safety while maintaining efficient traffic flow along arterial corridors.

The research employed a comprehensive, multi-method approach that integrates a literature review, stakeholder interviews, national case studies, and before-and-after field evaluations on selected Florida corridors. The analysis focused on signal timing strategies, including shorter cycle lengths, signal progression for speed management, early free operation, and rest-in-red control. It also evaluated pedestrian treatments such as rectangular rapid flashing beacons, pedestrian signals, and leading pedestrian intervals, together with emerging technologies including adaptive signal control, artificial intelligence-based analytics, enhanced detection systems, and connected vehicle applications. These strategies were assessed for their effectiveness in improving nighttime arterial safety.

The findings demonstrate that nighttime-specific signal timing strategies reduce risky driving behaviors, improve traffic operations, and enhance pedestrian safety. Case studies and field evaluations reveal measurable reductions in unsafe driving behavior when optimized signal timing is combined with targeted pedestrian treatments. Overall, the research concludes that integrating nighttime signal timing strategies with coordinated operations using shorter cycle lengths, targeted infrastructure enhancements, and emerging technologies are essential for achieving sustainable improvements in nighttime arterial safety.

17. Key Words		18. Distribution Statement	
Nighttime, Signal Timing and Operations, Strategies, Countermeasures, Safety, Crashes, Emerging Technologies		No restriction	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No. of Pages** 142	**22. Price**

Acknowledgements

The research team at the Center for Urban Transportation Research (CUTR) at the University of South Florida (USF) sincerely thanks Florida Department of Transportation (FDOT) Project Managers Edith Wong (PM) and Katelyn Ruka (Co-PM) for their full support, guidance, and assistance on this important research. Our appreciation also goes to FDOT Research Center Manager Mr. Darryll Dockstader, Research Development Coordinator Ms. Jennifer Clark, Performance and Workforce Coordinator Mr. Jason Tuck, and Business Systems Coordinator Ms. Ta'rika Green, for their support and assistance. We are also grateful to Neal Turner from FDOT District 1 for providing the data and information necessary to support the case study and field evaluations. Finally, the CUTR research team would like to thank all the interview participants for their time and insights.

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Executive Summary

Overview

Nighttime roadway safety remains a critical concern in the United States and particularly in Florida, where nighttime crashes account for over half of all fatalities despite significantly lower traffic volumes. Arterial corridors are especially vulnerable due to higher speeds, complex traffic movements, and interactions with pedestrians and bicyclists. This project, sponsored by FDOT, focused on identifying and evaluating innovative signal timing and operational strategies to improve nighttime safety while maintaining efficient traffic operations.

The research recognizes that traditional daytime-oriented traffic signal strategies are not well suited for nighttime conditions. Lower volumes, reduced visibility, and higher likelihood of risky driving behaviors necessitate targeted operational approaches that explicitly address nighttime risk factors.

Research Objectives and Approach

The primary goal of this study was to develop data-driven, practical guidance to improve nighttime safety on arterial roadways through optimized signal timing and operations. Specific objectives included:

- Assess current nighttime signal timing practices in Florida
- Identify innovative strategies through literature and national best practices
- Gather expert insights through stakeholder interviews
- Evaluate real-world applications through case studies and field analyses
- Develop actionable guidance for agencies

To achieve these objectives, the research used a comprehensive methodology that included:

- Literature review on nighttime crash risks and mitigation strategies
- Interviews with practitioners and experts
- Case studies from Florida and across the United States
- Field evaluations and before-and-after studies
- Development of implementation frameworks and guidance materials

Key Findings

Nighttime Safety Challenges

The study confirms that nighttime crashes are more severe and influenced by multiple interacting factors, including:

- Excessive speeding due to low traffic volumes
- Impaired driving and reduced alertness
- Risk-taking due to side-street delays or detection failures
- Reduced pedestrian visibility and driver awareness of potential pedestrian crossing locations
- Reduced roadway feature visibility

These conditions create an environment where conventional signal timing strategies may inadvertently fail to restrict unsafe behaviors, such as higher speeds under long green phases.

Effective Signal Timing Strategies

Several signal timing strategies were identified as highly effective in improving nighttime safety:

- **Short Cycle Lengths:** Reduce excessive green time, lower speeds, and improve service frequency for side streets.
- **Speed Management via Signal Progression:** Aligns progression speeds at or below posted speed limits to discourage speeding.
- **Early Free Operation:** Improves responsiveness to declining traffic demand and reduces unnecessary delays.
- **Rest-in-Red Operation:** Requires vehicles to slow or stop before receiving a green signal, reducing high-speed movements.

These strategies collectively contribute to improved driver expectancy, reduced aggressive driving, and more predictable operations.

Pedestrian Safety Improvements

Pedestrian-focused strategies were found to be critical, particularly at night when visibility is limited. Effective treatments include:

- Rectangular Rapid Flashing Beacons (RRFBs)
- Pedestrian Hybrid Beacons (PHBs)

- Midblock Pedestrian Signals and Pedestrian Signals (MPSs and PSs)
- Leading Pedestrian Intervals (LPIs)
- Dynamic Flashing Arrows (DFAs)
- Improved lighting and high-visibility crosswalks

Field studies showed increased driver yielding behavior, reduced conflicts, and improved pedestrian compliance at treated locations.

Role of Technology

Emerging technologies offer significant potential to enhance nighttime safety:

- **Adaptive signal control systems** improve responsiveness to real-time traffic conditions
- **AI-based video analytics** enable identification of near-misses and conflict patterns
- **Connected vehicle technologies** provide real-time warnings and improve situational awareness

However, implementation challenges include cost, infrastructure requirements, and the need for reliable detection systems.

Importance of Lighting and Infrastructure

Enhanced roadway lighting, particularly LED retrofits, was identified as one of the most effective interventions. Improved illumination significantly enhances:

- Driver detection of pedestrians and roadway features
- Signal visibility and comprehension
- Overall safety performance

Lighting improvements were found to be foundational, often enabling the success of other strategies.

Case Study Results

Real-world applications demonstrate the effectiveness of nighttime-specific strategies:

- **US-41 Corridor at Tallevast Road/Gaines Avenue to US-41 at 46th Avenue Drive W/Orlando Avenue in Manatee County (FDOT District 1):** Short-cycle coordination along with speed management via signal progression resulted in approximately 15% speed reduction and a 50% decrease in severe crashes, including decreases in fatal crashes (21 to 14; 33%), serious injury crashes (64 to 24; 63%), and fatal and serious bicycle/pedestrian crashes (34%).

- **Portland Rest-in-Red:** Has been implemented at high-risk nighttime intersections and corridors using long-range microwave detection and time-of-day signal control, with no quantitative safety results available yet, although preliminary agency and community feedback indicates reduced nighttime speeding and fewer high-speed intersection entries.
- **FDOT LED Lighting Retrofit for Nighttime Safety**: Resulted in a 2.0% reduction in total nighttime crashes (538 fewer crashes) and a 19.3% reduction in nighttime fatal and serious injury crashes (183 fewer crashes), while all six evaluated corridors in District 7 experienced decreases in nighttime crashes following the lighting improvements.
- **Tampa Hillsborough Expressway Authority (THEA) Connected Vehicle Pilot Program and Technologies**: Demonstrated the potential of connected vehicle technologies to improve nighttime safety by deploying 49 roadside units and more than 1,000 connected vehicles, with the Wrong-Way Entry application correctly detecting 14 of 19 events (73.7% detection rate) during evening and nighttime hours, while replacing LiDAR with thermal imaging improved pedestrian detection reliability under low-light conditions.

These findings underscore the importance of tailoring strategies to specific corridor conditions and integrating multiple treatments.

Field Evaluation Results

The field study assessed the effectiveness of innovative nighttime traffic signal timing and pedestrian treatments along Florida's US-41 and Fletcher Avenue corridors and demonstrated measurable safety and behavioral improvements under low-volume conditions. Coordinated nighttime signal timing with shorter cycle lengths and speed management via signal progression on US-41 reduced risky driving and improved driver awareness of downstream conditions, while pedestrian treatments (RRFBs and a PS) on Fletcher Avenue led to meaningful reductions in crashes and better driver–pedestrian interactions. Overall, the strategies improved safety performance while maintaining efficient traffic flow.

- **US-41 Corridor (Coordinated Nighttime Signals):**
  - Risky behaviors declined, including an **80% reduction in hard braking** (0.1% vs. 0.5%) and a **41% reduction in stopping beyond the stop bar** (1.9% vs. 3.2%).
  - **61% of drivers** reported that seeing downstream red signals discouraged speeding (vs. 7% in the control corridor).
  - Driver decision-making shifted, with **87% influenced not to speed** due to expected downstream stops.

- **Fletcher Avenue (Pedestrian Treatments – RRFBs and PS):**
  - Nighttime pedestrian crashes decreased from **12 to 3**, and bicycle crashes dropped from **5 to 0** (eliminating bicycle crashes).
  - Driver yielding rates reached 100% at the PS site and 61.1% at RRFB sites.
  - Pedestrian compliance was higher at the PS site (**83.3% push-button use; 100% crosswalk compliance**) compared to RRFB sites (**47.4% and 65.8%**).
  - Near-miss events were 0% at the PS site vs. 11.1% at RRFB locations.

Implementation Framework

The project developed a structured framework for selecting and implementing nighttime safety strategies. Key steps included:

1. Evaluate crash patterns and safety issues
2. Identify underlying causes
3. Consider operational and contextual factors
4. Select and implement appropriate countermeasures
5. Monitor performance and refine strategies

This framework ensured a systematic, data-driven approach to improving nighttime safety.

Conclusions and Implications

The findings demonstrate that improving nighttime arterial safety requires operational strategies specifically designed for low-volume, high-risk conditions rather than adaptations of conventional daytime practices. A layered approach that integrates optimized signal timing, pedestrian-focused treatments, enhanced lighting, and emerging technologies can substantially reduce crashes, improve driver behavior, enhance pedestrian safety, and maintain efficient traffic operations. The implementation framework developed through this research provides transportation agencies with practical, data-driven guidance for identifying corridor-specific safety issues, selecting appropriate countermeasures, and evaluating performance. Adoption of these strategies can support more effective investment decisions, strengthen system resilience, reduce severe crashes, and advance safer, more reliable, and sustainable nighttime transportation networks throughout Florida and beyond.

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Abbreviations and Acronyms

AADT	Annual Average Daily Traffic
ADA	Americans with Disabilities Act
AI	Artificial Intelligence
ATCS	Adaptive Traffic Control Systems
ATSC	Adaptive Traffic Signal Control
ATSPM	Automated Traffic Signal Performance Measures
CO	Co-Principal Investigator
CO-PM	Co-Principal Manager
CV	Connected Vehicle
CUTR	Center for Urban Transportation Research
FDOT	Florida Department of Transportation
FHWA	Florida Highway Administration
FLHSMV	Florida Highway Safety and Motor Vehicles
HAWK	High-Intensity Activated Crosswalk Beacon
LED	light-emitting diode
LiDAR	Light Detection and Ranging
LPI	Leading Pedestrian Interval
mph	miles per hour
MPS	Midblock Pedestrian Signal
NHTSA	National Highway Traffic Safety Administration
OBU	Onboard Unit
PHB	Pedestrian Hybrid Beacon
PI	Principal Investigator
PM	Principal Manager
PS	Pedestrian Signal
RRFB	Rectangular Rapid Flashing Beacon
RSU	Roadside Unit
SCATS	Sydney Coordinated Adaptive Traffic System
SPaT	Signal Phase and Timing
THEA	Tampa Hillsborough Expressway Authority
USDOT	United States Department of Transportation
WWE	Wrong-Way Entry
V2X	Vehicle to Everything
V2I	Vehicle to Infrastructure

1 Introduction

1.1 Project Background

Nighttime, commonly defined as the period between sunset and sunrise, when natural light levels are insufficient for normal daytime visibility (Federal Highway Administration, 2025b). However, the Florida Department of Highway Safety and Motor Vehicles (FLHSMV) more precisely defines nighttime as the period between 30 minutes after sunset and 30 minutes before sunrise (FLHSMV, 2023). Nighttime conditions present unique transportation safety challenges, particularly on arterial roadways where traffic volumes, driver expectations, and signal control needs differ substantially from daytime operations. Vulnerable road users, including pedestrians and bicyclists, face heightened risks after dark. National data consistently show that the fatality rate for nighttime crashes is significantly higher than for daytime crashes, with speeding, impaired driving, fatigue, and reduced visibility among the primary contributing factors (Federal Highway Administration, 2023a).

Despite accounting for only about one-quarter of total vehicle miles traveled, nighttime driving is associated with nearly half of all traffic fatalities nationwide. Florida is among the states most affected by nighttime crashes, ranking third nationally behind Hawaii and California. Nighttime crashes account for 58.3% of all traffic crashes in Florida, with a disproportionately high share of fatal and serious injury crashes occurring after dark. For example, along the four-mile Fowler Avenue corridor in Tampa, 60% of fatal and serious injury crashes and 50% of non-motorized crashes occurred during nighttime hours, even though traffic volumes were lower than during the day (Florida Department of Transportation, 2024a). These statistics highlight the need for targeted nighttime safety strategies and operational improvements. According to Florida crash statistics from Signal Four Analytics (Signal4 Lab, 2025):

- In 2019, 1,794 of 3,191 fatalities (56%) occurred at night.
- In 2020, 1,845 of 3,342 fatalities (55%) occurred at night.
- In 2021, 2,156 of 3,745 fatalities (58%) occurred at night.
- In 2022, 2,017 of 3,550 fatalities (57%) occurred at night.
- In 2023, 1,820 of 3,168 fatalities (57%) occurred at night.
- In 2024, 1,667 of 2,971 fatalities (56%) occurred at night.

Figure 1-1 and Figure 1-2 show that crashes are disproportionately concentrated during nighttime hours (8:00 p.m. to 8:00 a.m.), particularly on weekends, with nighttime crashes accounting for nearly half of all reported incidents. Collectively, these findings underscore

the disproportionate frequency and severity of nighttime crashes and reinforce the need for targeted strategies to improve safety along arterial corridors in Florida, particularly within FDOT D7.

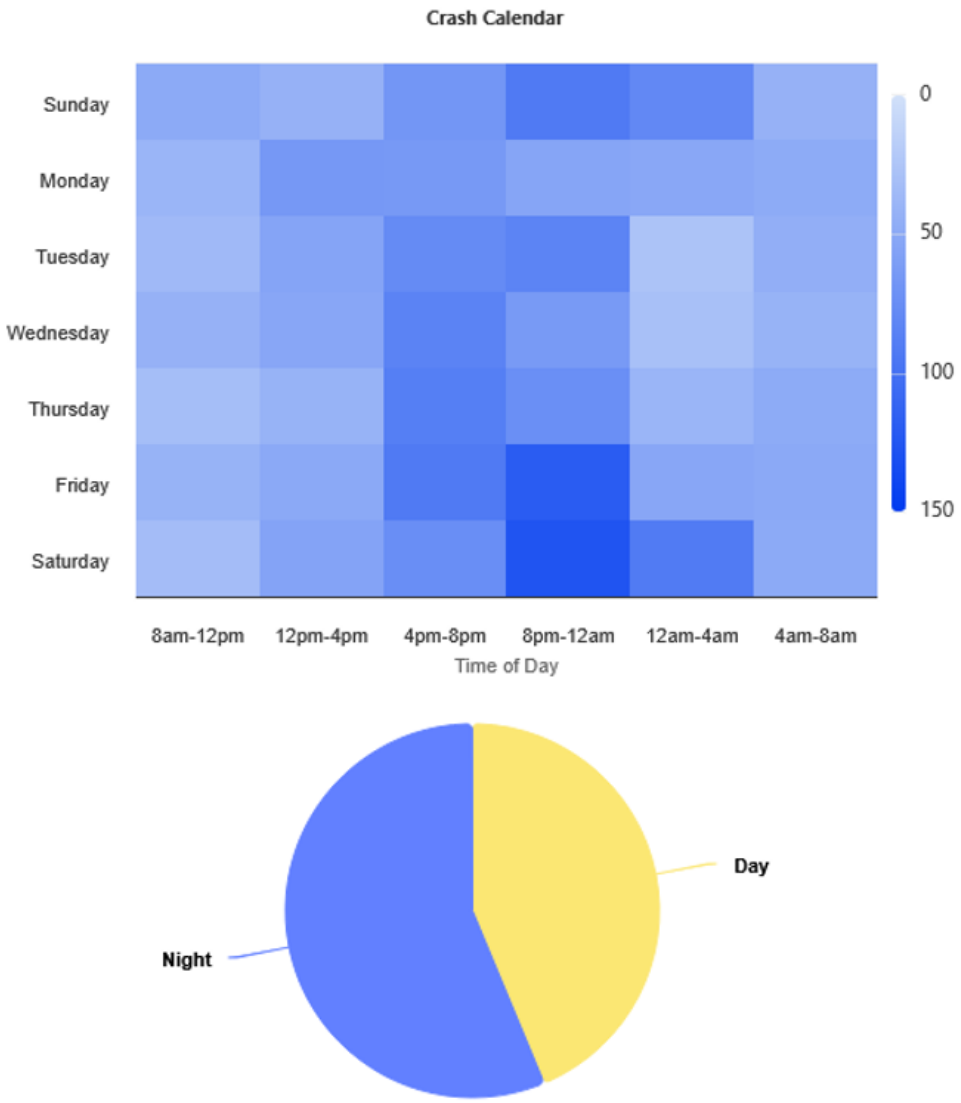


Figure 1-1. Fatal crash distribution by day, time, and light condition on arterial roads in Florida, 2024

Source: Signal4 Lab (2025)

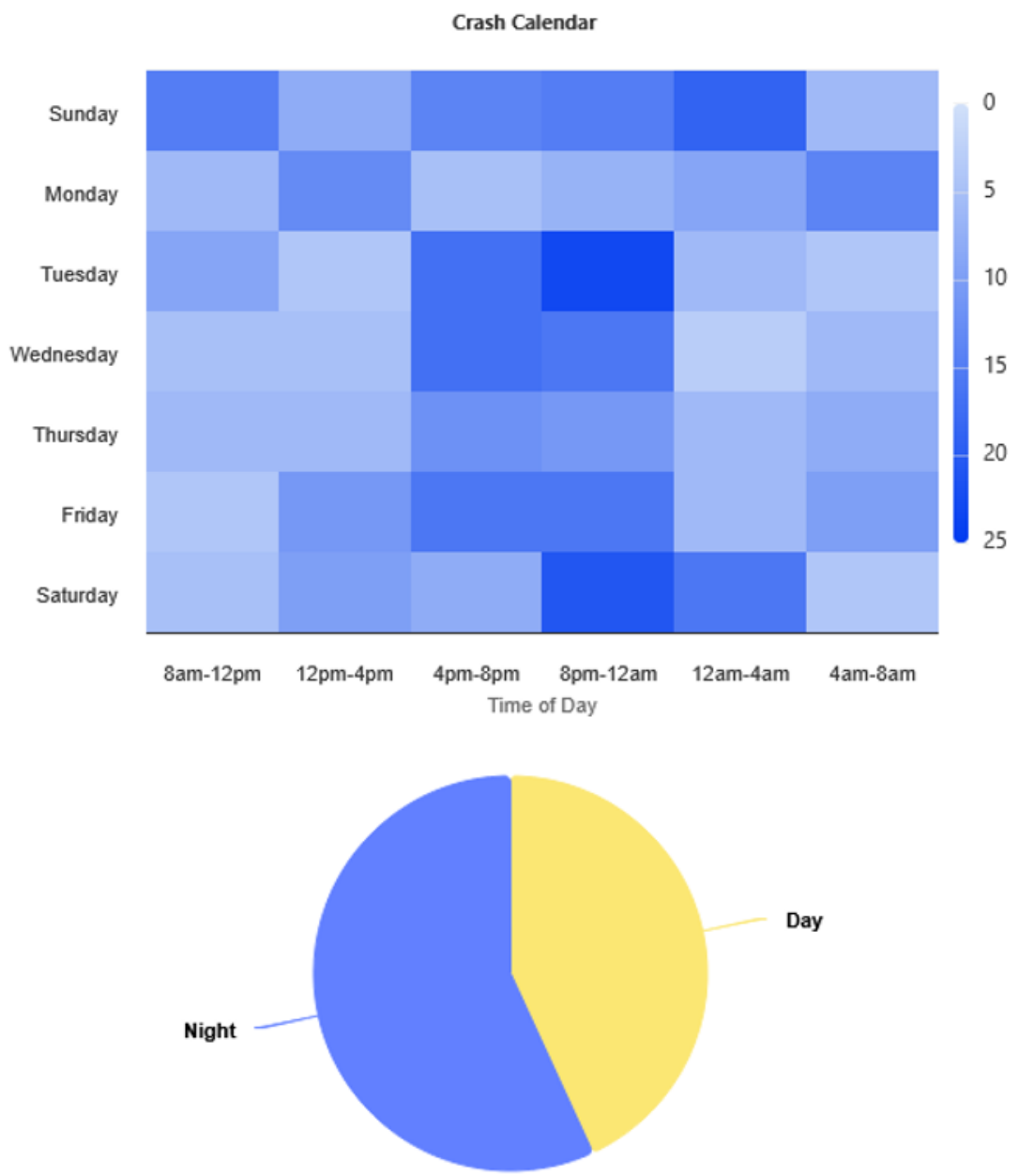


Figure 1-2. Fatal crash distribution by day, time, and light condition on arterial roads in FDOT D7, 2024

Source: Signal4 Lab (2025)

In Florida, the proportion of fatal crashes involving speeding and aggressive driving that occurred during nighttime hours was 61%, 63%, and 61% in 2020, 2021, and 2022, respectively. FDOT D7 exhibited a similar, albeit increasing, trend, with 56%, 59%, and 65% of these fatal crashes occurring at night during the same period. Notably, District 7's 65% nighttime share in 2022 exceeded the statewide average, highlighting the need for

targeted regional safety interventions. Fatal crashes associated with speeding are particularly prevalent on non-highway urban and suburban roadways.

To address these critical safety challenges, this FDOT-sponsored project investigated the role of engineering solutions, with a particular focus on traffic signal design and operations, in improving nighttime safety along arterial roadways. Signalized intersections serve as critical nodes within arterial networks; therefore, optimizing signal timing and implementing signal-related operational strategies can help reduce nighttime crash risk while maintaining efficient traffic flow.

Potential strategies include adjusting signal coordination and progression, deploying actuated signal control, eliminating nighttime flashing operations, and implementing rest-in-red (dwell-on-red) operations. Additional approaches involve the use of advanced technologies such as video analytics, computer vision, adaptive signal control systems, Artificial Intelligence (AI), connected vehicle (CV) technologies, and other emerging innovations. These technologies offer opportunities to enhance situational awareness, improve traffic operations, and reduce crash risk during nighttime periods. Through the evaluation of these strategies and technologies, the project sought to identify effective and practical solutions for improving both safety and operational performance on Florida's arterial roadways.

1.2 Research Objectives

The primary objective of this research project was to identify, assess, and evaluate traffic signal timing and operational strategies that can enhance safety and improve operational performance during nighttime conditions on Florida's arterial roadways. The project aimed to provide FDOT and local agencies with evidence-based recommendations and practical guidance to support policy development, planning, and operational decision-making related to nighttime traffic management. The specific objectives of the project were as follows:

- **Assessing Current Practices:** Understand the existing nighttime signal timing design and operation practices used in Florida.
- **Investigating Innovative Strategies:** Explore innovative traffic signal timing design and operation strategies from the literature that can enhance nighttime arterial safety in Florida.
- **Gathering Best Practices:** Obtain insights on best practices for nighttime traffic signal timing design and operation strategies through interviews with selected national experts and transportation agency professionals.

- **Conducting both Case Studies and Before-after Studies:** Perform both case studies and before-after studies to illustrate the implementation of innovative traffic signal timing design and operation strategies, along with their results and findings.
- **Developing Guidance Materials:** Create guidance materials on how to implement recommended innovative signal timing design and operation strategies to reduce nighttime fatalities, injuries, and crashes on urban and suburban arterials in Florida.

1.3 Structure of the Report

This report is organized into seven chapters:

- Chapter 1 introduces the research problem, objectives, and report structure.
- Chapter 2 presents a comprehensive review of the relevant literature.
- Chapter 3 summarizes the findings from stakeholder interviews.
- Chapter 4 synthesizes lessons learned from national case studies.
- Chapter 5 describes the before-and-after and field evaluation methodologies and presents the corresponding results.
- Chapter 6 provides guidance and recommendations for implementing nighttime signal timing and operational strategies.
- Chapter 7 presents the study conclusions and recommendations.

2 Literature Review

Nighttime arterial safety is a multidimensional issue involving driver behavior, roadway visibility, signal operation, pedestrian exposure, and emerging technology applications. Compared with daytime operations, nighttime traffic conditions often involve lower volumes but higher crash severity, particularly along arterial corridors where higher speeds, frequent signalized intersections, pedestrian crossings, and access points coexist. The literature reviewed as part of this research project indicates that nighttime crashes are not only associated with behavioral risks such as speeding (National Center for Statistics and Analysis, 2023; National Highway Traffic Safety Administration, 2020), distraction, impairment, and fatigue, but also with infrastructure and operational conditions such as lighting quality, signal visibility (Federal Highway Administration, 2023b), and pedestrian detection (National Safety Council, 2025; Wang et al., 2020).

This chapter summarizes the key findings from the literature review and organizes them around four themes: nighttime safety issues on arterial roadways; current practices in Florida; innovative strategies and national best practices; and key findings relevant to future nighttime signal timing improvements.

2.1 Nighttime Safety Issues on Arterial Roadways

Nighttime conditions create a higher-risk operating environment for all roadway users. Reduced illumination limits drivers' ability to detect hazards, judge distances, and respond to unexpected events. These limitations are particularly important on arterial roadways, where vehicles may travel at relatively high speeds while encountering signalized intersections, turning movements, pedestrian crossings, transit stops, commercial driveways, and nighttime activity centers. Although traffic volumes are generally lower at night, crashes tend to be more severe because reduced visibility increases drivers' perception-reaction times, while higher operating speeds reduce the time and distance available to detect, respond to, and avoid potential hazards.

The literature identifies several major contributors to nighttime crash risk. Figure 2-1 illustrates the top five contributing factors of nighttime crashes in all reported crashes (8:00 p.m. to 8:00 a.m.) in Florida D7 in 2024. Distracted driving (National Center for Statistics and Analysis, 2024c) is one of the most prominent behavioral factors. Under low-light conditions, drivers already experience reduced peripheral vision, poorer depth perception, and slower hazard recognition. When attention is further diverted by phone use, navigation systems, or other in-vehicle distractions, the ability to detect pedestrians, traffic signals, and sudden roadway conflicts is significantly reduced. The review notes that distracted driving was the leading behavioral factor among nighttime crashes in FDOT D7

in 2024, exceeding speeding, impairment, and drowsy driving (National Center for Statistics and Analysis, 2024b).

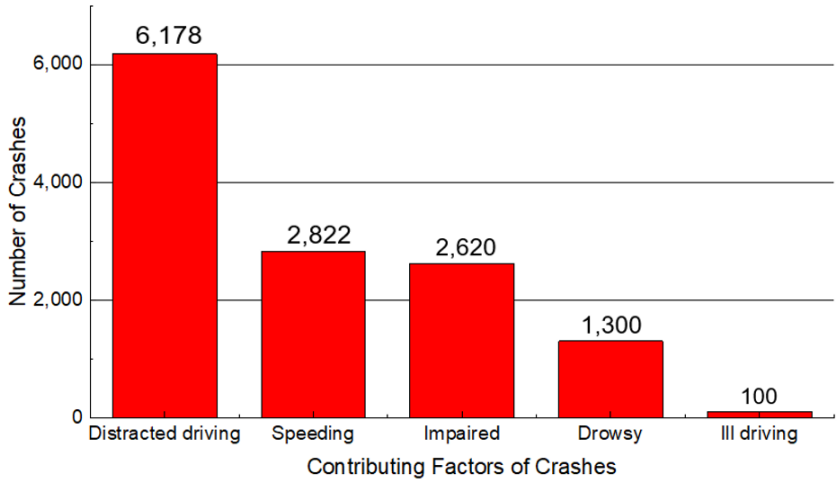


Figure 2-1. User behavior contribution to crashes at nighttime, FDOT D7, 2024

Source: National Center for Statistics and Analysis (2024b)

Recent national and Florida traffic safety data highlight the elevated risks associated with nighttime travel and several factors that contribute to severe nighttime crash outcomes:

- 45% of fatal crashes in Florida occur during nighttime hours, between 7:00 p.m. and 6:00 a.m. (Florida Department of Highway Safety and Motor Vehicles, 2024).
- 76% of pedestrian fatalities nationwide in 2024 occurred under dark conditions (NHTSA, 2025) (National Highway Traffic Safety Administration, 2025).
- 57% of passenger vehicle occupants killed in nighttime crashes were unrestrained, compared with 43% in daytime crashes (National Highway Traffic Safety Administration, 2023b).
- Alcohol impairment among drivers involved in fatal crashes is nearly three times higher at night than during the day (National Highway Traffic Safety Administration, 2023a).
- In 2024, 43% of crashes resulting in pedestrian fatalities involved a driver and/or pedestrian with a BAC of 0.01 or higher. (National Highway Traffic Safety Administration, 2025).

2.1.1 Distracted Driving

Distracted driving is a major nighttime safety concern. NHTSA data show that 43% of traffic fatalities occur between 6:00 p.m. and 6:00 a.m., and distraction contributed to 8.1% of fatal crashes nationwide in 2021(National Center for Statistics and Analysis, 2024b). This issue is also evident in FDOT District 7, where 6,178 nighttime crashes in 2024 were attributed to distraction, making it the leading crash cause during nighttime hours. Reduced visibility, fatigue, slower reaction time, and limited peripheral vision make distraction especially dangerous at night, as drivers may fail to notice pedestrians, signals, or sudden hazards. Prior studies show that texting and smartphone use at night increase lane deviation, speed, and detection failures, even when pedestrians use high-visibility retroreflective gear.

2.1.2 Speeding at Night

Speeding is another critical nighttime safety issue (Federal Highway Administration, 2023c; National Highway Traffic Safety Administration, 2020). At night, headlight illumination limits the distance within which a driver can detect and respond to hazards. When vehicles travel at higher speeds, the available stopping sight distance may be insufficient, especially on corridors with pedestrians, cyclists, driveways, or poorly lit intersections. In addition to statistical trends, spatial patterns provide further insights into the geographic distribution of nighttime speeding-related crashes. Figure 2-2 presents a combined heatmap and crash severity map for FDOT D7 based on 2024 data. The left panel illustrates crash density hotspots concentrated in Hillsborough and Pinellas Counties, particularly along key corridors such as Fowler Avenue, I-275, and US-19. The right panel shows individual crash locations by severity, where red dots represent fatal crashes, aligning closely with the identified hotspots. These patterns confirm that speeding-related fatalities are not only frequent but geographically clustered, reinforcing the need for location-specific countermeasures in nighttime signal and speed management strategies.

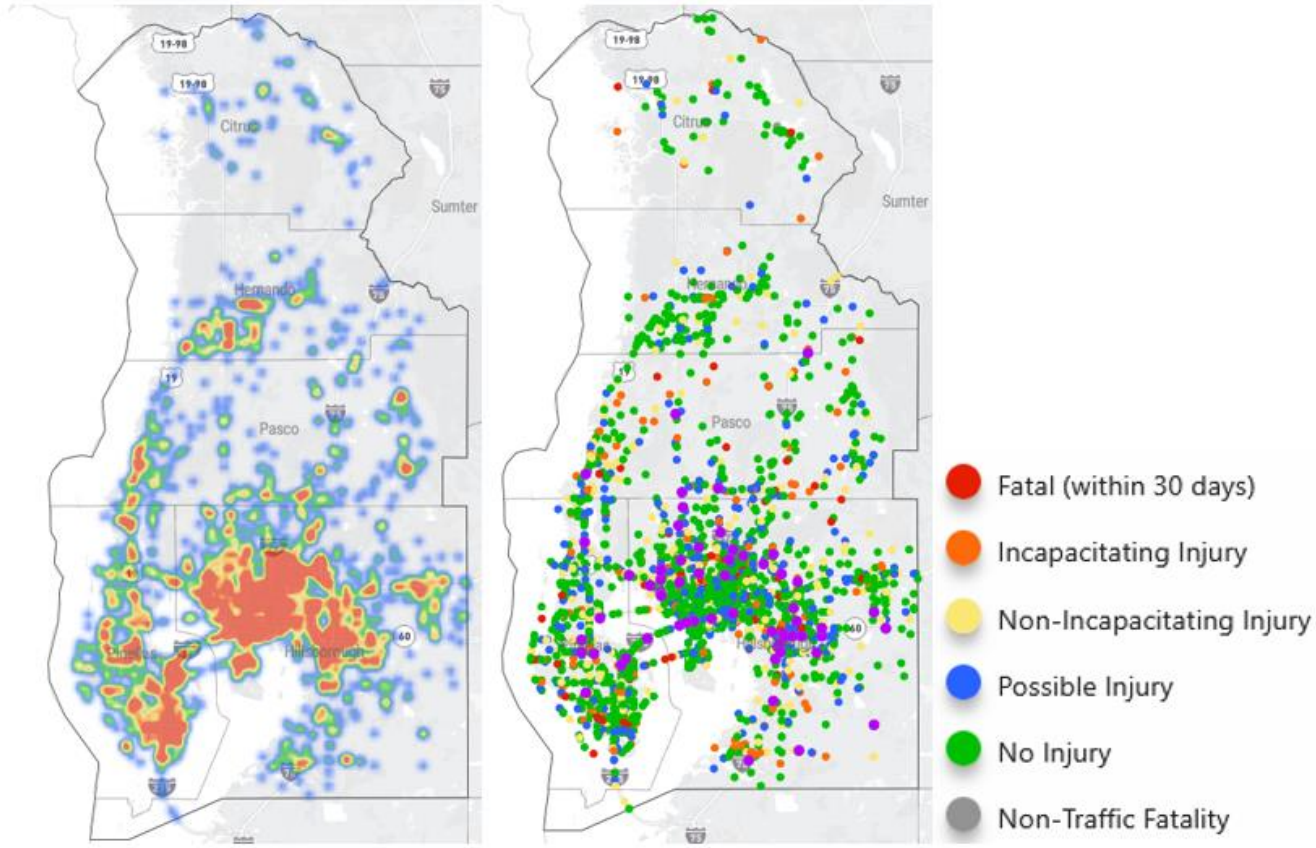


Figure 2-2. Nighttime speeding-related crash hotspots and crash severity in FDOT D7

Source: Signal4 Lab (2025)

2.1.3 Visibility and Lighting Conditions

Visibility and lighting conditions are also central to nighttime arterial safety (American Optometric Association, 2023; Federal Highway Administration, 2025a). Poor lighting at intersections, crosswalks, and midblock crossings reduces the conspicuity of pedestrians and bicyclists. Older drivers may face additional visual challenges due to reduced contrast sensitivity and increased glare sensitivity (National Safety Council, 2025). According to FHWA safety evaluations (Federal Highway Administration, 2022b):

- Nighttime crashes at rural and urban intersections can be reduced by 33% to 38% using well-designed lighting systems.
- Pedestrian-injury crashes at intersections can be reduced by 42% with proper illumination (Figure 2-3).
- Enhancements like RRFBs, reflective signage, and advanced pavement markings can reduce crash rates by 25% to 47%, depending on treatment type.

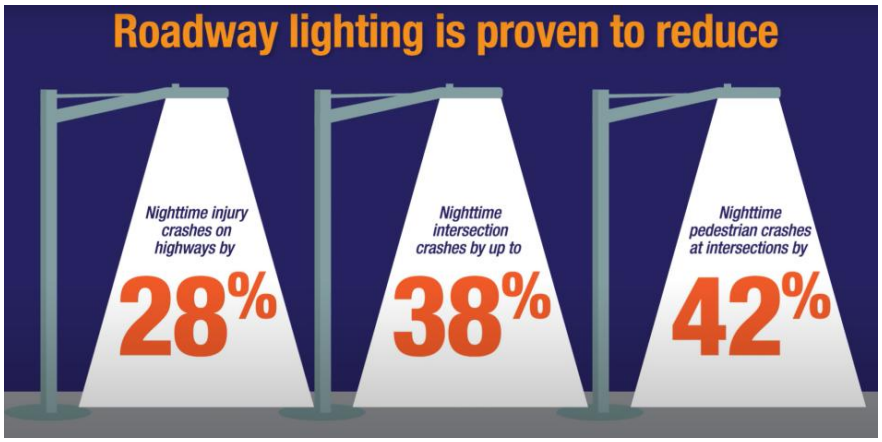


Figure 2-3. Crash reduction benefits of roadway lighting at night

Source: Federal Highway Administration (2022a)

2.1.4 Drowsy and Fatigued Driving at Night

Drowsy and fatigued driving is another important but often underreported factor (National Highway Traffic Safety Administration, 2024a). Fatigue reduces alertness, decision-making ability, and reaction time, while drowsiness can lead to momentary lapses in attention or microsleep. These risks are especially common during late-night and early-morning hours, when human circadian rhythms naturally reduce alertness. On arterial corridors, monotony, low traffic volumes, and limited lighting can further increase fatigue-related risks.

Signal timing strategies that reduce unnecessary delays, simplify nighttime phasing, and improve progression can lower driver workload, enhance driver expectancy, and support timely detection and response to potential hazards. As shown in Figure 2-4, many crashes involving drowsy drivers occurred during late-night to early-morning hours, with notable peaks between 12:00 a.m. and 6:00 a.m. These crashes are disproportionately associated with poor lighting conditions, particularly under “Dark Not Lighted” and “Dark Unknown Lighting” classifications. This pattern reinforces the role of insufficient illumination in elevating the risk of drowsy-driving-related incidents.

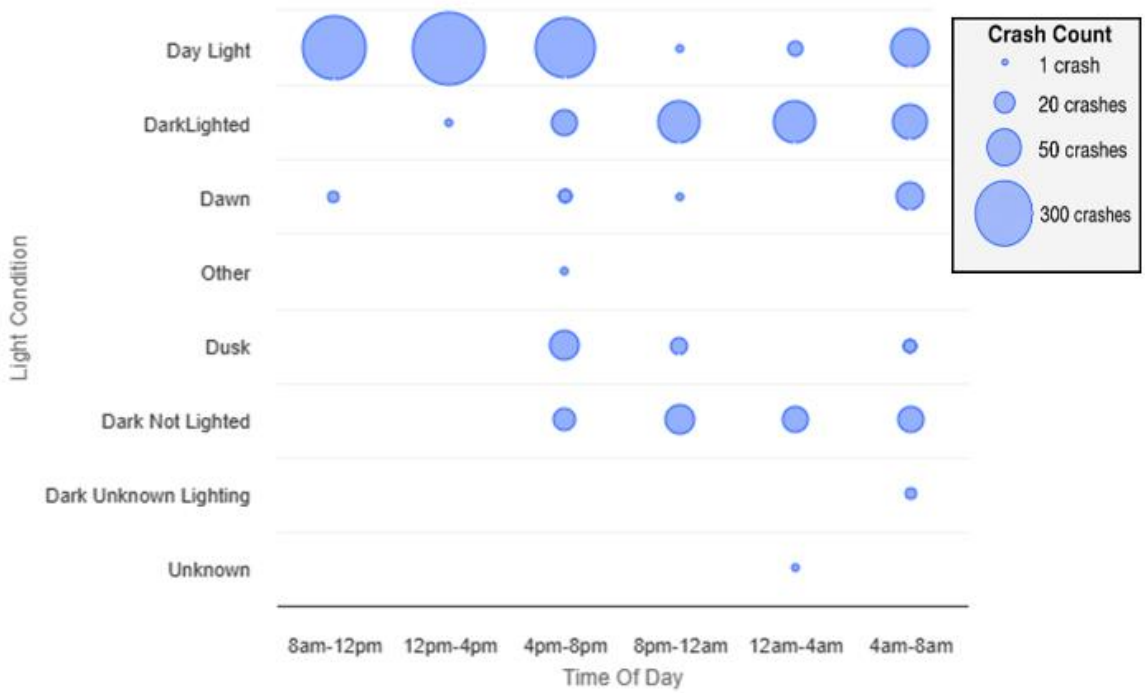


Figure 2-4. Distribution of drowsy driving crashes by time of day and lighting conditions in FDOT D7, 2024

Source: Signal4 Lab (2025)

2.1.5 Impaired Drivers

Impaired driving is also disproportionately associated with nighttime travel (Florida Department of Transportation, 2024b; National Highway Traffic Safety Administration, 2024b). Alcohol or drug impairment reduces coordination, judgment, reaction time, and visual perception. These effects are especially dangerous at signalized intersections, where drivers must recognize signal indications, anticipate turning conflicts, and respond to pedestrians or cyclists. Impaired drivers may be less capable of responding to complex signal patterns or unexpected changes. Countermeasures such as dwell-on-red operations, red-light running detection, reflective backplates, and improved signal visibility can help mitigate some of these risks when combined with enforcement and education (National Center for Statistics and Analysis, 2024a). Among all 21,048 nighttime crashes (8:00 p.m. to 8:00 a.m.) reported in FDOT D7 in 2024, 1,777 involved alcohol, accounting for nearly 9% of all nighttime incidents. This underscores the elevated risk associated with impaired driving during dark hours (see Figure 2-5).

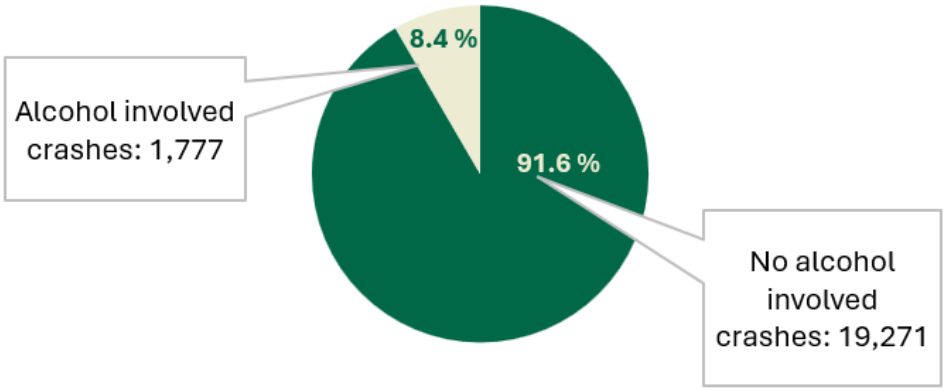


Figure 2-5. FDOT D7 alcohol involved in nighttime crashes

Source: Signal4 Lab (2025)

2.1.6 Other Contributing Factors

Other contributing factors include poor retroreflectivity of signs and pavement markings, adverse weather conditions such as rain, reduced nighttime enforcement visibility, and animal crossings. Rain can further reduce the visibility of pavement markings and signs while making roadway surfaces slippery, thereby increasing stopping distance and reducing vehicle control. While these factors may be less emphasized than speeding or impairment, they can increase risk by reducing driver guidance, lowering compliance with traffic control devices, or introducing unexpected hazards into the nighttime driving environment. Overall, the literature suggests that nighttime safety problems are the result of interacting behavioral, environmental, and operational factors rather than a single cause.

2.2 Current Practices in Florida

Florida has implemented a range of nighttime safety practices that combine signal timing, pedestrian-focused control, lighting improvements, and smart detection technologies. These practices reflect a shift from traditional nighttime operations toward more data-driven, context-sensitive, and pedestrian-oriented strategies.

2.2.1 Nighttime Signal Retiming for Speed Management in FDOT District 1

One important Florida practice is nighttime signal retiming for speed management (Florida Department of Transportation – District One, 2022). The FDOT District 1 study on US-41 between Tallevast Road and Orlando Avenue demonstrates how signal timing can be used as a low-cost operational countermeasure. The strategy included shorter cycle lengths, reduced progression speeds, compressed green bands, leading pedestrian intervals, and overnight coordinated signal patterns. These adjustments were intended to reduce incentives for high-speed progression, create more predictable platoons, and improve

pedestrian crossing opportunities. The implementation produced reductions in average speeds, a decrease in fatal and serious injury crashes, and no pedestrian or bicyclist fatalities during the overnight signal pattern period.

2.2.2 Pedestrian-Focused Signal Control Strategies

Florida agencies have also expanded pedestrian-focused signal control strategies, including RRFBs, PHBs, and Midblock Pedestrian Signals (MPSs) (Alachua Chronicle, 2023; Federal Highway Administration, 2024; Fitzpatrick et al., 2021; myCollier Newsletter, 2022). MPSs are currently used in Florida under FHWA-approved experimental conditions and are not included as a standard treatment in the MUTCD. These treatments are especially relevant at uncontrolled or midblock crossings where nighttime pedestrian visibility is limited, and traditional signal control may not be warranted. RRFBs improve driver awareness through high-intensity flashing indications. PHBs provide a pedestrian-activated stop control sequence at high-risk crossing locations. MPS treatments provide formal signalized midblock crossings with countdown timers, high-visibility markings, audible cues, and enhanced lighting for pedestrians safely.

Several Florida examples demonstrate how these treatments have been used in practice. St. Petersburg has deployed RRFBs at Pinellas Trail crossings, where driver yielding rates increased substantially after activation. FDOT District 1 and District 2 have planned or installed PHBs (Figure 2-6) at midblock crossings and nighttime pedestrian generators. Gainesville, Cocoa Beach, Miami-Dade County, and Pinellas County have also implemented or planned pedestrian-focused crossing systems that combine signal control, lighting, and detection technologies. A 2025 study led by Ahsan (Ahsan et al., 2025)evaluated pre- and post-installation crash patterns at 14 MPS sites across Florida. The study found that MPS deployments achieved a 26–33% reduction in high-speed crash incidence compared with locations with PHBs and RRFBs, while also demonstrating superior deceleration effects and vehicle behavior modulation. These examples show that Florida's pedestrian safety practices are increasingly tailored to the needs of nighttime and midblock crossing environments.

Figure 2-6. Midblock PHB installed on US-41 in Lee County, FL (FDOT / Lee County Outreach, 2024)

Source: myCollier Newsletter (2022)

Automatic or passive pedestrian detection systems represent another important Florida practice. These systems can detect pedestrian presence, place a pedestrian call when the push-button is not used, cancel unnecessary calls when pedestrians leave before crossing, and extend clearance time for slower pedestrians. This type of detection is especially useful at night because it reduces reliance on manual push-button actuation and improves the responsiveness of signal control to actual pedestrian behavior.

2.2.3 AI Video Analytics for Pedestrian Safety: City of Sarasota Smart City Initiative

The City of Sarasota has received international recognition for its innovative use of AI-powered video analytics to enhance pedestrian safety and manage traffic more intelligently. As part of its broader "Smart City" initiative, Sarasota integrated artificial intelligence into traffic cameras deployed at urban intersections to detect and analyze pedestrian–vehicle interactions in real time (Figure 2-7).

System Coverage: AI video systems have been installed at 16 downtown intersections, with plans to expand the program to 90 signalized locations across the city.

Key Features:

- Detection of near-miss incidents involving pedestrians and vehicles
- Monitoring of illegal pedestrian crossings and red-light violations
- Observation of vehicle speed and lane deviation behaviors
- Real-time data collection to support signal timing optimization and safety interventions

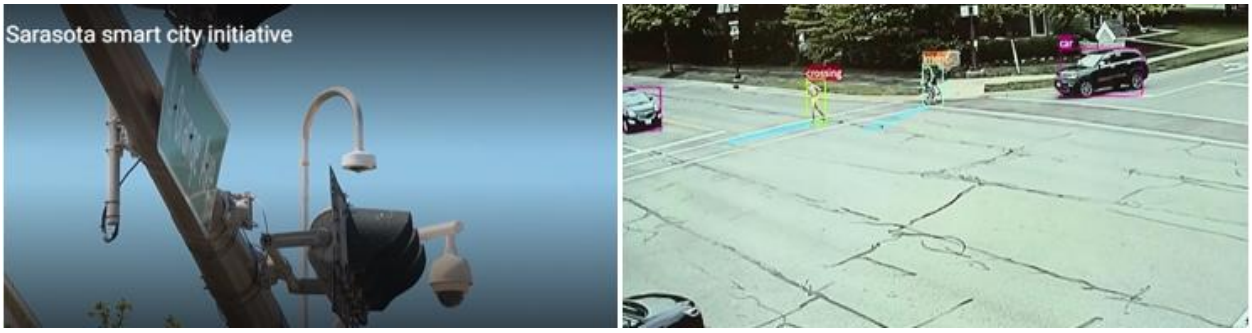


Figure 2-7. AI video analytics deployed at intersections in Sarasota's "Smart City" initiative

Source: Fox13 News, Sarasota Smart City Initiative

By leveraging continuous video-based data streams, the city can make data-driven signal adjustments, recommend targeted enforcement strategies, and improve roadway design. These efforts are aligned with Sarasota's commitment to achieving "Target Zero"—a long-term vision of eliminating all serious traffic injuries and fatalities. This Smart City deployment illustrates how video analytics can transition from passive monitoring to proactive safety management, providing actionable intelligence for municipal transportation departments.

2.2.4 FDOT LED Lighting Retrofit

Lighting improvements have also played a major role in Florida's nighttime safety efforts. FDOT District 7's lighting assessment using the Advanced Lighting Measurement System measured lighting levels and uniformity across roadway segments and overlaid them with nighttime pedestrian crash locations, as shown in Figure 2-8. This diagnostic approach supported targeted lighting interventions. LED lighting retrofits were associated with reductions in nighttime crashes, and FDOT's broader LED retrofit initiative upgraded many high-risk intersections statewide, including more than 400 intersections in District 7.

Figure 2-8. Enhanced nighttime visibility through FDOT LED lighting retrofits at intersections

Source: FDOT

2.2.5 Planned Smart Signal Corridor: SR-60 V2X and Pedestrian Detection Integration

Florida has also begun moving toward connected and smart corridor applications. The planned SR-60 West Coast Smart Signal Corridor in Pinellas County is designed to integrate advanced traffic controllers, pedestrian detection, CCTV coverage, roadside units, cellular on-board units, and vehicle-to-infrastructure safety applications. Although still in the planning stage, this project illustrates how Florida agencies are preparing to combine adaptive signal control, pedestrian detection, and CV communications to improve safety and responsiveness, particularly under low-visibility nighttime conditions.

2.3 Innovative Strategies and National Best Practices

While Florida has made significant strides in enhancing nighttime arterial safety through localized signal timing strategies, additional insights can be drawn from innovative practices implemented across the United States. This chapter explores national best practices that have demonstrated measurable benefits in improving nighttime traffic operations, safety, and sustainability.

Drawing from national best practices, this chapter organizes advancements into four categories: (1) signal timing-based safety improvements, (2) lighting-based visibility enhancements, (3) pedestrian-focused control solutions, and (4) emerging technologies and innovation techniques. Each subsection presents promising practices supported by

field evidence or pilot implementations, offering actionable guidance for improving safety outcomes during nighttime hours.

2.3.1 Signal Timing-Based Safety Strategies

Deployment of Adaptive Traffic Control Systems (ATCS)

ATCS have been widely implemented across the United States to improve signal responsiveness, reduce congestion, and enhance corridor efficiency. According to the NCHRP 20-07 Task 414 Final Report (Stevanovic et al., 2019), more than 140 ATCS deployments have been documented, with performance evaluations conducted at 70 locations. These systems vary by scale and technology, including platforms such as SCATS, SCOOT, InSync, ACS-Lite, SynchroGreen, and V-SCATS. They use different detection methods, such as video, loop, and microwave sensors, and operate with either centralized or local processing.

Reported benefits across deployments include reductions in split failures by up to 85%, crash rates by as much as 35%, and fuel consumption by 0.3% to 7%. Many systems also improve minor street access during off-peak hours, which suggests potential value for nighttime operations. Although ATCS are not specifically designed for nighttime use, their ability to adapt to low traffic volumes makes them well-suited for enhancing safety and efficiency during nighttime periods.

Rest-in-Red Signal Operations During Low-Volume Hours

Nighttime hours often correspond to lower traffic volumes but heightened crash risk due to increased speeding and reduced visibility. To address these challenges, cities are exploring signal timing strategies specifically tailored for off-peak conditions. One innovative approach is rest-in-red, a signal operation method that alters default signal behavior to encourage safe vehicle speeds and improve safety for all road users, especially pedestrians and cyclists, during low-volume nighttime hours at isolated intersections on minor or collector roadways.

The Portland Bureau of Transportation (PBOT) has deployed the Rest-in-Red strategy (City of Portland, 2025b) (Figure 2-9), which is designed to mitigate speeding and improve pedestrian safety during late-night and early-morning hours. Unlike traditional actuated signals that remain green until interrupted, rest-in-red signals default to red in all directions and only turn green when a vehicle is detected approaching the intersection. This approach ensures vehicles stop unless they are traveling within posted speed limits, thereby encouraging compliance and reducing crash risk.

The system relies on microwave detection sensors mounted on signal mast arms, capable of detecting vehicles several hundred feet away. These sensors work in coordination with

advanced signal controllers, which adjust signal timing dynamically based on time of day and vehicle presence. PBOT applies this approach primarily during off-peak hours at isolated intersections on minor or collector roadways when traffic volumes are low, but speeding risks are elevated.

PBOT first implemented rest-in-red at NE Seventh Avenue and Lloyd Boulevard, near the Blumenauer Bicycle and Pedestrian Bridge. The city is actively expanding this technology along high-risk corridors, including:

- SE Powell Boulevard (21st to 33rd Avenues), one of Portland's highest crash corridors, with implementation scheduled for summer 2024.
- 82nd Avenue, where PBOT will install new signals and upgrade existing ones in 2025 as part of a broader capital improvement plan.

The installation cost for rest-in-red ranges from $20,000 to $100,000 per intersection, depending on the condition of existing infrastructure. Funding has come from sources such as Portland's cannabis tax (for SE Powell Blvd) and Capital Improvement Projects (CIP) for other sites.

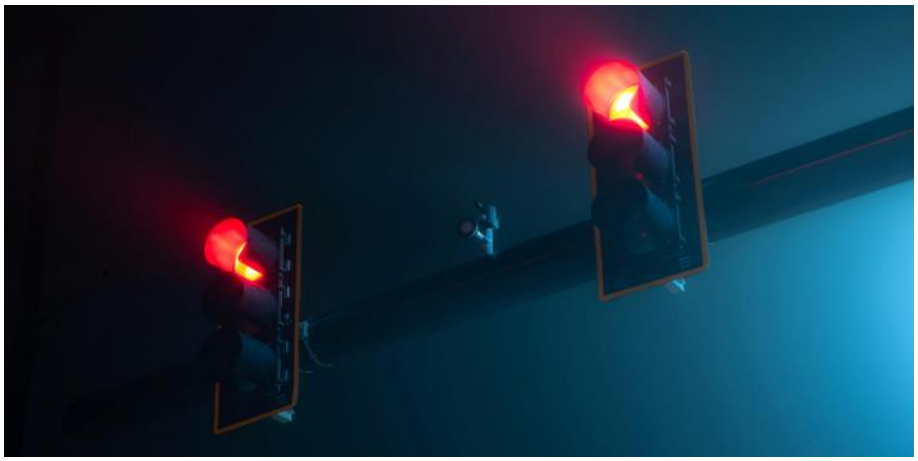


Figure 2-9. Example of rest-in-red signal display during nighttime operation
Source: City of Portland (2025b)

Rest-in-Red is embedded within Portland's Vision Zero Action Plan (2023–2025) (City of Portland, 2025a), and exemplifies a scalable, cost-effective solution for enhancing nighttime safety in multimodal urban environments.

Dynamic Flashing Yellow Arrow (D-FYA) with LiDAR Detection

D-FYA is an emerging signal control strategy designed to improve left-turn efficiency and safety by leveraging real-time vehicle detection. Unlike conventional flashing yellow arrows that operate on pre-timed cycles, D-FYA dynamically adjusts the level of left turn

protection (permissive, protected-permissive, or protected only) based on the presence and behavior of opposing through traffic.

This innovative approach integrates LiDAR-based detection technology, which continuously monitors the opposing through lanes to determine vehicle speeds, gaps, and traffic volumes. Based on the detection results, the signal controller evaluates whether sufficient and safe gaps exist for left-turning vehicles. If acceptable gaps are detected, the controller permits a flashing yellow arrow, allowing left-turn movements. If not, the signal remains in the protected red arrow phase to minimize potential conflicts.

Key Technical Components:

- ***LiDAR Sensors***: High-resolution sensors positioned at the intersection detect opposing vehicle speed, distance, and occupancy in real time.
- **Dynamic Gap Assessment Algorithms**: Signal logic dynamically evaluates safe turning gaps based on sensor input, enabling or suspending the flashing yellow phase accordingly.
- **Adaptive Phase Control**: Left-turn signal phases are activated only when safe and efficient, reducing unnecessary delays while enhancing intersection throughput.
- **Failsafe Mechanisms**: If detection is unavailable or uncertain, the system defaults to protective red arrow modes, ensuring safety remains a priority.

A LiDAR-based D-FYA system is being deployed in **Salt Lake City, Utah**, as part of a smart mobility initiative funded by UDOT. This pilot uses sensors to detect pedestrian presence and traffic gaps in real time, activating permissive left-turn functionality accordingly.

2.3.2 Lighting-Based Visibility Enhancements

A 2025 study published in the Transportation Research Record (Hu et al., 2025) evaluated the effectiveness of combining continuous crosswalk lighting, triggered illuminators, and RRFB at signalized and unsignalized nighttime pedestrian crossings. The field study was conducted at four midblock crosswalks in Kalamazoo, Michigan, and tested various configurations: RRFB only, lighting only (continuous or triggered), and a combined lighting and RRFB deployment. Key findings from this real-world study include:

- **Significant increase in driver yielding rates**: The combined lighting and RRFB treatment resulted in a 12.11% increase in driver yielding rates compared to RRFB-only or lighting-only treatments.
- **Improved speed reduction**: Drivers approaching crosswalks with integrated lighting and RRFBs were significantly more likely to reduce speed, improving reaction time and overall safety.

- **Enhanced pedestrian conspicuity**: Triggered illuminators activated by pedestrian presence made pedestrians more visible to drivers during low-light conditions, further reinforced by RRFB flashes.
- **These results demonstrate the synergistic safety benefits of integrating active warning beacons with lighting systems tailored to nighttime pedestrian needs**. The effectiveness of these combined strategies supports broader adoption in locations where night visibility and midblock pedestrian activity are both concerns.

As of 2024, similar deployments have been piloted or recommended in various state DOTs, and RRFBs are now recognized in the MUTCD as an approved countermeasure for uncontrolled crossings. In addition to combined treatments, some agencies have focused specifically on improving nighttime lighting as a standalone strategy to address pedestrian safety concerns. The Montana Department of Transportation (MDT), in partnership with Montana State University, developed a risk-based approach to improve nighttime safety on low-volume roads by integrating lighting adequacy into crash risk assessments.

Key features include:

- **Night-to-Day Crash Ratios**: Used to flag sites with potential lighting needs.
- **Field Lighting Inventories**: Assessed pole locations, luminaire types, wattage, and lighting levels via foot-candle readings.
- **PIL/CIL Criteria**: Applied MDT guidance based on traffic volumes and crash history.
- **Site Prioritization**: Locations like the 27th Street Interchange (ratio = 0.86) were recommended for lighting upgrades.
- **Context-Sensitive Design**: Lighting solutions tailored to roadway geometry and benefit-cost analysis.

2.3.3 Pedestrian-Focused Signal Control Strategies

Pedestrian safety during nighttime hours is challenged by reduced visibility, lower driver attentiveness, and increased likelihood of non-compliance with signal indications. This section highlights two types of pedestrian-oriented signal strategies that directly support nighttime safety: automated pedestrian detection systems and context-sensitive timing improvements.

Automated Pedestrian Detection Systems

Automated pedestrian detection systems represent a critical advancement in improving pedestrian safety at signalized intersections, especially under nighttime or low-visibility conditions. These systems are designed to identify the presence of pedestrians in or near crosswalks and trigger signal phase changes, such as activating the Walk interval or

extending clearance time, without requiring manual input. By doing so, they reduce reliance on push-button actuation and ensure safer, more responsive crossings for all users, particularly when visibility is limited or pedestrian behavior becomes less predictable after dark.

A more recent advancement in automated pedestrian detection the Passive Detection Phase Extension Pilot (2023–2024) in the city of Bellevue, Washington (City of Bellevue, 2025). The city deployed Ouster LiDAR sensors and Outsight spatial AI at a signalized intersection to identify pedestrians in the crosswalk in real time. The system automatically extended the green (Early Cut-Off) phase via SCATS controllers when a pedestrian was still crossing. Field results demonstrated over 90% detection accuracy and under 10% false negatives. The system is especially valuable for nighttime operations, as LiDAR does not rely on ambient light and maintains high accuracy even in low-visibility conditions. By preventing pedestrians from being stranded mid-crossing after dark, the system provides both fair access and improved nighttime safety. In 2024, the project received a $1.43 million USDOT SMART Grant to expand its implementation citywide.

Beyond Bellevue, Chattanooga, Tennessee (ITS International, 2025) has initiated the largest LiDAR-enabled pedestrian detection rollout in the United States, planning full deployment at over 120 intersections by 2025 using Ouster BlueCity technology. Early results from high-risk blocks indicate a 100% reduction in near-miss incidents.

Pedestrian Signal Enhancements

Enhancing pedestrian signal operations is a key component of nighttime traffic safety. Visibility limitations after dark increase risks for vulnerable road users, particularly at signalized intersections. Pedestrian signal enhancements, such as countdown timers, audible cues, and extended walk phases, can improve clarity, awareness, and compliance.

The San Francisco Municipal Transportation Agency (SFMTA) (San Francisco Municipal Transportation Agency, 2025) has implemented a series of pedestrian signal improvements aimed at enhancing safety, particularly during low-visibility hours such as nighttime. These upgrades focus on giving pedestrians more time and visibility to safely cross intersections.

- **Pedestrian countdown signals**: Countdown displays are installed at nearly all of San Francisco's 1,200+ signalized intersections. These signals provide pedestrians with a visual indication of how much time remains to complete a crossing, reducing uncertainty and improving decision-making during night hours.

- **LPIs**: LPIs give pedestrians a head start of at least three seconds before parallel vehicular traffic receives a green light. This design reduces the risk of conflicts between turning vehicles and crossing pedestrians. Studies cited by SFMTA indicate that LPIs can reduce pedestrian-vehicle collisions by as much as 60%.
- **Extended pedestrian crossing time**: In 2018, SFMTA adopted a citywide standard reducing the assumed pedestrian walking speed from 3.5 ft/second to 3.0 ft/second for calculating clearance intervals. This effectively increases the crossing time available, improving safety for slower pedestrians during nighttime conditions.

In the past two years, both RRFB and PHB (Caggiano et al., 2025) systems have seen significant innovation. RRFBs were formally included in the 2023 MUTCD (11th Edition) and have seen rapid market growth, with new high-intensity solar-powered units (e.g., Availed AV-400) offering wireless connectivity and better night visibility. Agencies in states like Oregon (Federal Highway Administration, 2023d) and Colorado (AVAILED TECHNOLOGIES, 2024) continue to expand RRFB use in diverse settings.

High-Intensity Activated Crosswalk beacons (HAWKs), a type of PHB, are designed to improve pedestrian safety at midblock crossings without full signal control. Meanwhile, hybrid beacons—or HAWKs—have advanced with high-intensity LEDs and clearer signaling formats to improve nighttime functionality and reduce driver confusion. Enhanced driver education, advanced signage, and data-driven near-miss analyses ensure that these devices are not only visible but properly understood and effective.

Implementation Examples:

- **California (California Department of Transportation, 2023)**: In November 2023, Caltrans activated a next-generation High-Intensity Activated Crosswalk (HAWK) system at the intersection of Lander Ave and Campbell Street in Merced County, near Hilmar High School. The upgraded beacon features enhanced LED clusters and signal phasing design, improving nighttime visibility and reducing driver confusion.
- **Virginia (City of Falls Church, 2025)**: In Summer 2024, the City of Falls Church installed three new HAWK signals at Broad Street near Oak St, Fairfax St, and Buxton St. The systems were deployed following pedestrian safety training and are expected to become operational by Summer 2025, with a specific emphasis on nighttime protection features.
- **Maryland (Montgomery County, 2025)**: The Montgomery County DOT expanded its PHB network by installing multiple midblock PHBs, such as those on Twinbrook Parkway & Halpine Rd and Bel Pre Rd, during the 2022–2023 fiscal years. These

efforts continue as part of the county's Vision Zero safety strategy to improve pedestrian visibility and protection during low-light conditions.

MPSs are specialized pedestrian signal systems installed at midblock locations, away from traditional intersections, designed to provide safe pedestrian crossing opportunities on wide or high-speed roadways. The 2023 NCHRP report Safety at Midblock Pedestrian Signals (Fitzpatrick et al., 2023) officially recognized MPS as a cost-effective safety signal system. The guidance recommended enhancements such as countdown displays, pedestrian detection, and illumination improvements.

MPS are not yet included in the MUTCD and are considered experimental by FHWA. They may present significant challenges at perpendicular multi-use trail crossings, including issues observed in FDOT D7 with following vehicles failing to stop at the flashing red signal.

Implementation Examples:

- **California**: The city of San Jose deployed midblock pedestrian signals on multilane roadways as part of its Vision Zero initiative, combining MPS with audible pedestrian cues, countdown timers, and adaptive lighting to reduce nighttime pedestrian crash risk (City of San José, 2024).
- **Utah & Texas**: According to the Crash Modification Factors Clearinghouse (Fitzpatrick et al., 2024), MPS installations in California, Utah, and Texas are associated with a 45% reduction in pedestrian-involved crashes (CMF = 0.554) and a 34% reduction in all injury crashes.

2.3.4 Emerging Technology and Innovation Techniques

Emerging technologies are increasingly transforming the way nighttime pedestrian safety is addressed. These innovations go beyond traditional signal timing and infrastructure improvements, offering real-time, adaptive, and data-driven solutions that are especially beneficial during low-visibility nighttime conditions. Recent developments have fallen into the following categories:

User-Guided Signal Control

User-Guided Signal Control (UGSC) is a next-generation signal timing approach that dynamically adjusts signal phases based on real-time detection of users—particularly pedestrians and vulnerable road users. UGSC differs from conventional ATSC by focusing on the real-time detection of pedestrian and user behaviors, rather than only adjusting to vehicle volumes. While ATSC improves corridor traffic flow, UGSC enhances individual safety and accessibility, especially during nighttime or low-volume periods when pedestrian needs may otherwise be overlooked.

Recent advances in real-time sensing, video analytics, and edge computing have enabled traffic signal systems to respond dynamically to the presence and behavior of both drivers and pedestrians. Unlike traditional pre-timed or actuated signals, user-guided signal control leverages adaptive algorithms and real-time detection data, including pedestrian presence, traffic volume, and crossing behavior, to adjust signal timing accordingly.

For example, when side streets experience low vehicle volumes, but a pedestrian is detected using infrared sensors or computer vision-based detection, the system can quickly trigger a Walk phase without requiring excessive wait times. This improves pedestrian compliance and satisfaction while reducing risky crossing behavior. Similarly, in locations with frequent vehicle activity, the system can balance mainline progression with pedestrian needs by dynamically modifying clearance intervals based on actual occupancy data.

By aligning signal responses with real-world demand using smart detection technologies, AI-powered signal controllers, and cloud-connected traffic systems, user-guided control enhances both safety and mobility, particularly at night when visibility is limited and pedestrian detection is more challenging.

Connected Vehicle-Based Pedestrian Warning Systems

Emerging applications of CV technology offer innovative approaches to detect vulnerable road users, particularly pedestrians and cyclists, who may not be easily seen by drivers. These systems leverage vehicle-to-everything (V2X) communication to identify pedestrians or micromobility users through smartphones, roadside units (RSUs), or wearable devices, and transmit real-time alerts to approaching vehicles.

Once a pedestrian is detected within a geo-fenced zone (e.g., within 200 feet of a crossing), the system can issue warnings to drivers via in-vehicle alerts or roadside message signs. These warnings can supplement traditional infrastructure-based treatments such as RRFBs, enabling more proactive and dynamic responses. For example, rather than crossing streets on red without pressing a pedestrian push-button to place a call, CV-enabled systems can automatically activate RRFBs or other signals when pedestrians do not press the button.

These CV-based strategies are especially valuable at unsignalized or midblock locations, where traditional infrastructure may be insufficient and real-time detection and broadcasting offer substantial safety benefits.

Video-Based Analytics and Computer Vision for Near-Miss Detection

Recent advancements in computer vision enable the automated identification of near-miss incidents, events where pedestrians or vulnerable road users come dangerously close to a collision without actual contact. These systems typically rely on high-resolution video feeds and AI-based object detection (e.g., YOLOv8, DeepSORT) to classify and track road users, such as pedestrians, vehicles, and bicycles.

By analyzing the spatiotemporal trajectories of these users, the system can calculate key indicators such as Time-to-Collision (TTC) or Post-Encroachment Time (PET) to determine potential conflicts. When thresholds are met, the system flags a near-miss and records the incident for review. Additional outputs such as heatmaps, annotated video clips, and behavioral reports support proactive safety planning and infrastructure evaluation. This emerging technology is particularly useful in midblock crossings and uncontrolled intersections, where traditional crash data may underestimate risk exposure.

Night Vision and Enhanced Pedestrian Detection

Night vision technologies, such as infrared (IR) thermal imaging and low-light cameras, are increasingly integrated into advanced driver-assistance systems (ADAS) and roadway infrastructure. These systems improve driver awareness during nighttime conditions by detecting pedestrians, cyclists, and other vulnerable road users (VRUs) beyond the reach of standard headlights.

By visualizing heat signatures or enhancing contrast in low-illumination environments, night vision helps drivers identify road users earlier and more clearly. Some vehicle-mounted systems can provide dashboard alerts or overlay pedestrian locations in heads-up displays (HUDs), while infrastructure-based systems can trigger responsive lighting or warnings. These technologies are particularly beneficial in areas with limited street lighting, high-speed roads, or frequent pedestrian crossings, reducing reaction time and improving overall nighttime safety.

Advanced Backup Power Systems for Traffic Signals

To maintain safe operations during power outages, especially during nighttime conditions, many jurisdictions are adopting backup power systems for signalized intersections. These systems typically consist of uninterruptible power supplies (UPS) or integrated power systems (IPS) that combine battery storage with utility grid power. To address extended utility power outages lasting hours or even days, such as those caused by hurricanes, researchers are currently studying and pilot-testing advanced backup power systems that combine solar energy with battery storage.

In the event of a utility failure (e.g., caused by storms, crashes, or equipment failure), these systems automatically activate to keep traffic signals operational for a limited duration, several hours or even days, until power is restored or personnel can intervene.

This continuity is critical at night, when dark signals can create confusion or dangerous crossing conditions for both drivers and pedestrians. Enhanced signal reliability through UPS or advanced backup power systems reduces crash risk, supports emergency response, and ensures safe passage during disruptive events.

In summary, the innovative signal strategies presented in this chapter demonstrate significant potential to mitigate nighttime crash risk by improving signal timing strategies, visibility, responsiveness, and user protection. From adaptive timing systems and pedestrian-activated beacons to LiDAR-enabled permissive left-turn controls and computer vision analytics, these solutions exemplify the integration of advanced technologies into traditional signal infrastructure. Moreover, the documented pilot implementations across Florida, Texas, Michigan, Utah, and California highlight the growing adoption of these approaches at both state and local levels. As agencies continue to face operational and budgetary constraints, the scalable and cost-effective nature of these innovations offers a viable path toward safety-first nighttime signal operations.

2.4 Key Findings from the Literature Review

The literature review indicates that nighttime arterial safety requires an integrated approach that combines signal timing, speed management, pedestrian protection, lighting, detection, and emerging technology. First, the main nighttime safety risks are strongly linked to driver behavior, especially distraction, speeding, impairment, and fatigue. However, these behavioral risks are intensified by environmental and operational conditions, including poor lighting, limited signal visibility, insufficient pedestrian detection, and low-volume nighttime signal patterns.

Second, signal timing can serve as an effective safety countermeasure rather than only an operational tool. Strategies such as reduced progression speeds, shorter nighttime cycle lengths, compressed green bands, LPIs, dwell-on-red operations, and adaptive low-volume timing can reduce speeding incentives, improve pedestrian protection, and manage intersection conflicts during nighttime hours.

Third, pedestrian safety should be a central focus of nighttime arterial operations. RRFBs, PHBs, MPS, automatic pedestrian detection, countdown timers, LPIs, and enhanced clearance intervals all address specific nighttime pedestrian risks. These treatments are particularly important at midblock crossings, multilane arterials, transit-access locations,

entertainment districts, and commercial corridors where pedestrian activity continues after dark.

Fourth, lighting and visibility improvements are essential complements to signal timing. LED retrofits, targeted intersection lighting, crosswalk illuminators, reflective backplates, larger signal heads, retroreflective signs, and high-contrast pavement markings improve the ability of drivers to detect signals, pedestrians, and roadway hazards. The literature reviewed consistently supports lighting as a proven safety countermeasure for nighttime crashes.

Fifth, emerging technologies provide opportunities for more proactive and responsive nighttime safety management. LiDAR detection, AI video analytics, CV warnings, near-miss detection, and smart corridor infrastructure can help agencies identify risks before crashes occur and adjust signal operations in real time. However, many of these technologies remain in pilot or early deployment stages and require further evaluation, funding, data integration, and interagency coordination.

Overall, the literature suggests that no single countermeasure can fully address nighttime arterial safety. The most promising direction is a layered strategy that integrates proven engineering treatments with adaptive and data-driven operations. For FDOT and local agencies, this means identifying high-risk nighttime corridors, matching treatments to specific crash patterns and user needs, and prioritizing strategies that improve speed compliance, pedestrian visibility, signal responsiveness, and operational reliability during nighttime conditions.

3 Expert Interviews

This chapter presents the results of interviews with eleven national subject-matter experts selected based on the literature review, online searches, professional networks, and the relevance of their expertise to the study objectives. It describes the interviewee selection process and summarizes expert perspectives on nighttime safety challenges on arterial roadways, general strategies for nighttime traffic signal operation, pedestrian-focused nighttime signal strategies, and emerging technology-based signal timing approaches. The chapter concludes with a summary of the key interview findings. The interview questions are provided in Appendix A.

3.1 Interview Process and Participants

The interview process followed a structured approach to ensure consistency and reliability. Experts and agency professionals were invited via email, and interviews were conducted through Microsoft Teams at mutually convenient times. A standardized interview guide was used to maintain comparability across responses while allowing for additional discussion when appropriate. Responses were transcribed, summarized, and analyzed to identify key themes and insights.

Interview invitations were sent to eleven professionals, and invitees either participated, declined, or recommended alternative experts with relevant expertise. Participants were selected based on their knowledge and experience to ensure meaningful contributions to the study goals. In accordance with the project scope, eleven individuals from state, county, local, and city transportation agencies, as well as academia and the private sector, were interviewed.

3.2 Nighttime Safety Challenges Identified by Experts

Nighttime signal operations present a distinct set of safety challenges that require careful consideration of the needs of all roadway users, including motorists, pedestrians, bicyclists, and emergency responders. This section summarizes the key issues identified by subject matter experts, with a focus on arterial roadways, where the risks are particularly pronounced.

Interviewees consistently highlighted that nighttime travel is associated with higher vehicle speeds, reduced visibility, increased risk-taking behaviors, and greater vulnerability for non-motorized users. These factors often interact, amplifying safety concerns in complex and unpredictable ways. Among the most cited challenges were:

- Higher speeds due to lower traffic volumes

- Limited visibility of pedestrians, cyclists, and roadway elements
- Reduced driver expectancy (e.g., not anticipating the presence of pedestrians at night)
- Risky behaviors such as impaired driving and red light running
- Glare from oncoming headlights and inadequate lighting infrastructure

These challenges can be broadly categorized into the following five areas: (1) Excessive Vehicle Speeds, (2) Visibility of Vulnerable Road Users, (3) Visibility of Roadway Elements and Traffic Signs, (4) Headlight Glare and Poor Ambient Lighting, and (5) Impaired Driving and Reduced Alertness. More details on each category are provided next.

3.2.1 Excessive Vehicle Speeds

During nighttime hours, especially outside of peak travel periods, reduced traffic volumes often lead to higher driving speeds. This increase in speed heightens the severity of crashes and reduces reaction time. Arterials are particularly susceptible to speeding, as wide lanes and fewer interruptions encourage faster driving. While signal timing adjustments are sometimes implemented to improve traffic flow, they may inadvertently contribute to unsafe speeds and aggressive behavior during low-volume periods.

3.2.2 Visibility of Vulnerable Road Users

Pedestrians and cyclists are significantly harder to detect at night due to poor lighting, dark clothing, and limited driver expectancy. Many drivers simply do not anticipate encountering non-motorized users after dark, especially in suburban or rural areas. This is particularly dangerous during turning movements at intersections, where sight lines are limited, and vehicle paths often conflict with pedestrian crossings. Moreover, some pedestrians and cyclists may fail to wait for appropriate signal phases, further increasing risk.

3.2.3 Visibility of Roadway Elements and Traffic Signs

Inadequate visibility of traffic signs, pavement markings, and roadway features is another major contributor to nighttime safety issues. Dimly lit environments, combined with faded or damaged signage, reduce a driver's ability to identify and respond to roadway cues. Signs with low retroreflectivity, small text, non-standard shapes, or poor placement (e.g., obstructed by foliage or street furniture) are especially problematic at night, particularly at higher speeds when decision time is reduced.

3.2.4 Headlight Glare and Poor Ambient Lighting

Glare from oncoming vehicle headlights, especially from high-intensity or misaligned beams, can temporarily blind drivers or reduce contrast, making it harder to detect pedestrians, cyclists, or signage. This effect is worsened in areas with poor ambient

lighting or inadequate street lighting. The combination of glare and darkness impairs depth perception and hazard recognition, increasing the likelihood of nighttime crashes.

3.2.5 Impaired Driving and Reduced Alertness

Nighttime hours see a disproportionate number of crashes involving impaired or fatigued drivers. Alcohol consumption, drug use, and sleep deprivation all contribute to reduced alertness, slower reaction times, and poor decision-making. These factors often lead to dangerous behaviors such as running red lights or making unsafe maneuvers. Compounding the issue are long signal cycles or detection failures, which may cause delays on side streets, further frustrating impaired drivers and increasing the potential for risky actions.

In summary, nighttime traffic signal operations must contend with a complex interplay of behavioral, environmental, and operational factors. The challenges identified by experts underscore the need for targeted strategies that address speed management, enhance visibility, and reduce risky behaviors, particularly on arterial corridors where nighttime crash severity is elevated.

3.3 General Nighttime Traffic Signal Timing and Operational Strategies

This section synthesizes the general nighttime traffic signal strategies discussed by the interviewed experts. Key approaches include operating signals in actuated mode to respond to real-time traffic demand, signal progression in a short cycle length, early signal free operations, and adjusting left-turn signal phasing to enhance safety during low-visibility conditions. Experts also emphasized the importance of improved street lighting and the use of "rest-on-red" operations to better manage vehicle behavior at low-volume intersections. Additional strategies were noted to support safer nighttime conditions for all users, particularly on arterial roadways.

3.3.1 Signal Operations in an Actuated Mode

Actuated signal operations respond dynamically to real-time vehicle and pedestrian demand, typically detected using technologies such as loop detectors, video cameras, or radar. During nighttime hours, a few agencies reported implementing a “Rest-in-Green” strategy, where the mainline remains green unless demand is detected on a side street. While this approach helps minimize unnecessary stops and improves traffic flow, experts noted that it can unintentionally encourage higher speeds, which may increase crash severity. Additionally, if detection systems are broken or malfunctioning, side-street users may experience excessive delays due to the lack of timely phase calls.

To better accommodate variable nighttime demand, some agencies switch to fully actuated (free) mode, often after 9:00 PM. This approach replaces flashing operations, which were historically used at night (e.g., flashing yellow on the mainline and red on the side street), but are now widely considered outdated and unsafe due to their tendency to create confusion over right-of-way and encourage risky driver's behavior. Actuated mode allows signals to serve approaches only as needed, improving responsiveness and reducing delay, particularly on arterials with lower volumes.

Interviewees emphasized the importance of context-sensitive strategies. For example, short-cycle pretimed control can be effective in dense urban environments with closely spaced intersections, where maintaining coordination and platoon progression is feasible. However, in suburban or lower-density areas, agencies typically remove coordination at night to enable more flexible and adaptive operations. In such cases, minimum green times are often adjusted, for instance, 15 seconds on the mainline, 5 to 7 seconds for left-turn phases, and about 7 seconds for side-street movements. Reducing mainline minimum green times to better align with side-street durations can help mitigate excessive speeds and enhance overall safety.

Experts also noted that short cycle lengths with minimum recall are preferred during low-volume periods to avoid overly long green phases, which can lead to sustained speeding. Shorter cycles also reduce waiting times for drivers, which can discourage red-light running and support pedestrian safety by providing more frequent crossing opportunities. For example, half-cycle operations during nighttime hours can significantly reduce delays for side-street traffic without compromising overall intersection performance. While fully actuated nighttime operations present challenges, such as maintaining detection accuracy and minimizing occasional delays, interviewees noted that, when carefully designed and implemented, these strategies offer substantial safety and operational benefits, particularly in low-volume or off-peak conditions.

Although comprehensive safety performance data comparing nighttime signal strategies remains limited, the consensus among interviewees is that approaches such as fully actuated operations and short cycles show promise in balancing traffic efficiency with the safety of all road users during nighttime conditions.

3.3.2 Signal Progression in a Short Cycle or Early Free Signal Operations

Signal progression is a key strategy used to maintain vehicle platoons, reduce erratic driver behavior, and efficiently clear queues along arterial corridors. During nighttime or other periods of low traffic demand, some agencies implement short-cycle coordination, which involves reducing signal cycle lengths while maintaining coordination. This approach helps minimize delays, improve traffic flow, and reduce stop-and-go driving. However,

interviewees noted that shorter cycles may limit the ability to maintain effective progression over long corridors, particularly when intersections are spaced farther apart.

As traffic volumes decline, typically in the evening or late at night, some agencies transition to early free operation, where signals drop out of coordination and begin to operate independently in either actuated or fully free modes. This allows signal timing to better respond to light traffic conditions, reducing unnecessary delays for vehicles on side streets or less-traveled movements. While early free operation increases responsiveness, it also removes the benefits of progression, which may impact speed management and intersection efficiency.

Interview participants emphasized the role of signal progression as a tool for nighttime speed management. Adjusting coordination plans to lower progression speeds can influence driver behavior by discouraging excessive speeding. For example, Portland's downtown grid uses a 60-second cycle length to create an 18-mph progression speed, effectively managing speeds during both day and night operations. Other agencies (e.g., the Washington, D.C. Department of Transportation) intentionally set progression speeds at about 5 mph below the posted speed limit to ensure that speeding drivers are more likely to encounter red lights, thereby encouraging compliance with safer speeds.

While two-way progression is especially difficult to implement, particularly at night when demand is low, some agencies intentionally design the system to be "bumpier" to discourage high-speed travel. Frequent stops created by short cycles can reinforce lower speeds, though the approach must be carefully balanced to avoid excessive delays or driver frustration.

Evidence from FDOT District 1 suggests that speed management through progression is more effective at night, as daytime congestion naturally controls vehicle speeds. Experts noted that with further testing and refinement, this strategy could become standard practice for nighttime operations, though broader implementation would require additional funding, staff resources, and public education to ensure success.

A critical challenge raised by several experts is determining the appropriate timing to remove coordination and shifting to free operation at night. While slower progression speeds can help manage speeds, some cautioned against setting them too far below posted limits. Drivers generally align their speed with posted signage, and lower progression speeds significantly can lead to frustration, risky maneuvers, or non-compliance. While signal timing progression is relatively straightforward on one-way streets, applying it effectively on two-way corridors remains more complex due to opposing traffic flows and varying demands.

3.3.3 Left Turn Signals to Ensure Safety of Left Turns

Improving the safety of left-turn movements requires a combination of thoughtful signal timing, intersection design, driver guidance, and adaptive technology. One of the most effective safety measures is the use of protected left-turn phases, typically indicated by green arrows, which eliminate conflicts with opposing through traffic and significantly reduce the risk of angle (T-bone) collisions. Depending on traffic volumes and intersection context, agencies may also use permissive or protected-permissive phasing to balance operational efficiency with safety. Adjustments such as leading or lagging left-turn phases and appropriately timed clearance intervals help ensure that vehicles complete their turns safely and without confusion.

Intersection geometry and layout also play a critical role in left-turn safety. Features such as dedicated left-turn lanes, medians, and channelization separate turning vehicles from through traffic, reducing conflict points and improving overall intersection performance. Adequate visibility, supported by effective lighting, clear signage, and unobstructed sight lines, is particularly important at night, allowing drivers to better judge gaps in oncoming traffic.

In addition, detection technologies and adaptive signal control systems are increasingly being used to enhance left-turn safety by adjusting signal timing in real time. Vehicle detection allows for dynamic allocation of green time based on actual demand, while pedestrian detection helps minimize conflicts with crossing movements. These tools are especially valuable during off-peak hours or nighttime operations, when traffic patterns are more variable, and the risks associated with driver fatigue or reduced visibility are elevated.

By integrating precise signal phasing, context-sensitive intersection design, clear visual guidance, and responsive control technologies, agencies can significantly improve the safety of left-turn movements for all users, including drivers, pedestrians, and cyclists.

3.3.4 Street Lighting to Support Traffic Signal Operations at Night

Street lighting is a critical component of nighttime traffic safety and plays an essential role in enhancing the effectiveness of signal operations. Interview participants consistently emphasized that visibility, rather than signal timing alone, is often the primary barrier to safe nighttime operations. In many cases, improving lighting conditions at intersections can yield greater safety benefits than signal timing adjustments, particularly in areas with high pedestrian activity or complex vehicle movements.

Adequate and well-placed lighting improves the visibility of signal heads, signs, crosswalks, and roadway geometry, enabling drivers to better recognize and respond to

traffic control devices and potential hazards. This is especially important for detecting pedestrians, cyclists, and turning vehicles, whose visibility is significantly reduced at night. Experts noted that lighting is also crucial for enhancing driver expectancy, helping motorists anticipate and interpret upcoming intersections or pedestrian crossings more accurately.

A few interviewees pointed to the value of retroreflective signal backplates, which improve the conspicuity of traffic signals by outlining the signal face with high-contrast reflective borders. This treatment has been shown to improve driver recognition and compliance, particularly under poor lighting or adverse weather conditions, and is increasingly being adopted as a low-cost safety countermeasure.

Beyond static lighting, some agencies are exploring adaptive lighting systems that adjust brightness levels based on time of day, traffic volumes, or pedestrian presence. These systems can provide enhanced illumination when it is most needed, such as during nighttime peak hours or in response to detected activity in crosswalks.

In summary, effective street lighting not only supports traffic signal visibility and compliance but also addresses broader nighttime safety concerns. When paired with other measures, such as improved signal phasing, signage, and detection technologies, lighting enhancements can significantly reduce crash risk and improve the safety and comfort of all roadway users during nighttime conditions.

3.3.5 Rest-in-Red during Light Traffic

The rest-in-red strategy is a nighttime signal operation technique aimed at reducing vehicle speeds and preventing drivers from becoming accustomed to uninterrupted green signals, an issue that can contribute to excessive speeding. While not widely adopted according to interview responses, this strategy has proven effective in select contexts such as low-volume intersections, isolated collector roads, pedestrian crossings, and locations prone to speeding, particularly where geometric features like hills and valleys or intersecting high-speed arterials are present.

The approach works by holding the mainline signal on red during low-demand periods until vehicle detection triggers a green phase. The intent is to slow down traffic, particularly at night, without unnecessarily delaying compliant drivers. It is most effective when paired with advanced detection systems, such as radar or dual-loop configurations (Figure 3-1), that can differentiate between speeding and non-speeding vehicles. In this setup, speeding vehicles are held at red, while vehicles traveling at or below the speed limit receive a green indication. This selective service can deter speeding behavior without penalizing responsible drivers.

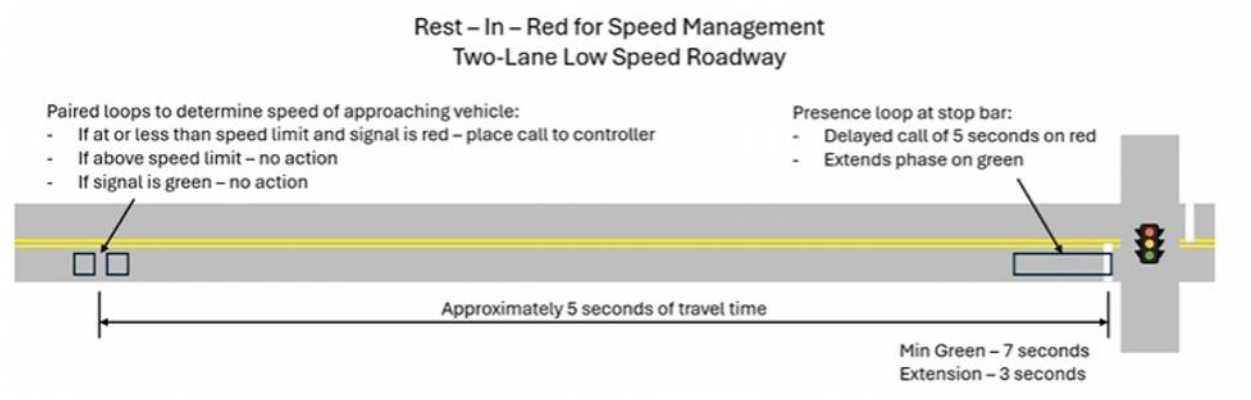


Figure 3-1. Advanced detection dual-loop configurations

Source: Peter Yauch

Detection layout plays a critical role in the success of rest-in-red. On major approaches, setback detectors are typically used to balance speed management and efficiency, while side-street detection is often limited to stop bar presence. Standard stop bar detectors alone are insufficient for speed-based control, making advanced detection capabilities essential.

Implementing rest-in-red requires careful planning, including confirming detection functionality, programming the signal controller, and defining operation hours, usually during off-peak or nighttime periods. Some locations apply it throughout the day in areas with persistent speed issues. Pilot programs, such as those conducted by DDOT, have shown mixed results. One deployment in a residential area was successful, while another using a “rest-in-pedestrian” configuration had to be reverted due to driver confusion.

Despite its potential, broader adoption of rest-in-red faces challenges, including detector reliability, layout complexity, and public perception. Confusion about the signal operation can lead to complaints or misinterpretations of malfunctions. As such, the strategy is best suited for isolated or low-volume intersections where traditional coordination offers limited safety benefits.

To maximize effectiveness, experts recommend combining rest-in-red with robust detection systems and public education efforts to clarify the purpose and expected behavior. When properly implemented, the strategy has the potential to enhance speed compliance, reduce crash risk, and improve overall nighttime traffic safety, particularly in environments where speeding is a recurring concern.

3.3.6 Other Strategies for Supporting Nighttime Safety on Arterials

Ensuring nighttime safety on arterial roadways requires not only effective signal timing but also well-maintained and fully functional infrastructure. Interviewed practitioners emphasized the importance of keeping detection systems, signal controllers, and communication equipment in proper working condition, as equipment failures can lead to skipped signal phases, missed vehicle or pedestrian calls, and increased crash risk during low-visibility conditions.

The importance of operational consistency was also noted during the interviews. Maintaining uniform timing plans 24/7 or minimizing unnecessary variation between day and night operations helps establish predictable driver behavior and reduces confusion. However, context-sensitive planning remains critical. Agencies can develop localized nighttime signal plans tailored to the specific needs of each intersection, accounting for geometry, traffic volumes, pedestrian activity, and land use. For example, nightlife corridors with high late-night demand may extend peak timing plans past midnight, while residential areas often shift to earlier nighttime plans, around 10:00 PM, to reduce conflicts.

Detection-based strategies also play a vital role in nighttime safety. Practitioners highlighted the use of dilemma zone protection (also known as decision zone protection), where setback detectors are installed several seconds upstream of the stop bar. These detectors allow the signal to extend green phases when high-speed vehicles are approaching, reducing the likelihood of red-light running and rear-end crashes. Advanced detection technologies, such as radar or video-based systems capable of speed estimation, enhance the accuracy of vehicle detection and help ensure more responsive and adaptive signal control, especially in low-light conditions.

Increased clearance intervals are another strategy cited by interviewees to improve safety by allowing more time for vehicles to exit the intersection before cross traffic is released. This adjustment is particularly useful at higher-speed intersections where drivers may misjudge yellow intervals or where nighttime visibility is limited.

Supplemental safety measures further support nighttime operations, particularly in rural or high-speed corridors. These include:

- **Advance warning flashers** to alert drivers of upcoming signalized intersections, especially on fast-moving rural approaches.
- **Blank-out signs** that activate only under specific conditions, such as “No Turn on Red” when pedestrians are present. A Minnesota DOT study found that while static “no-turn-on-red” signs generally achieved better compliance than blank-out signs,

blank-out signs were more effective at drawing driver attention to pedestrians, highlighting the value of visual enhancements during nighttime operations.

- **Retroreflective signal backplates** to enhance signal visibility and improve driver compliance.
- **Automated speed enforcement cameras**, which are used selectively to deter excessive speeding between intersections.

While the strategies highlighted in this report show promise, practitioners acknowledge a lack of extensive empirical research guiding their implementation at night. More data and field studies are needed to evaluate the effectiveness of various nighttime safety strategies and to support the development of evidence-based guidance for agencies.

In summary, effective nighttime signal operations require a multi-layered approach that combines equipment reliability, context-sensitive planning, advanced detection, and supplemental enforcement or visibility measures. Together, these strategies support safer conditions for all road users on arterial networks after dark.

3.4 Pedestrian-Focused Nighttime Traffic Signal Strategies

This section focuses on strategies specifically aimed at enhancing pedestrian safety during nighttime hours. Key measures include speed management through traffic signal operations, early free signal operation, RRFBs, and PHBs. Additionally, the section covers the use of automated pedestrian detection technologies to enable safer and more responsive crossing operations under low-light conditions.

3.4.1 Speed Management Through Traffic Signal Operations

Managing vehicle speeds through traffic signal operations is a critical strategy for improving pedestrian safety, especially at intersections and along arterial corridors. One effective method is to implement shorter signal cycle lengths, which reduces the total duration of red-green phases. Shorter cycles discourage drivers from accelerating aggressively to "beat the light," thereby reducing speed variability and promoting more consistent, predictable traffic flow.

Lower speeds at the onset of green phases decrease both the likelihood and severity of potential collisions, offering pedestrians safer opportunities to cross. In addition, more predictable vehicle behavior allows drivers greater reaction time and improves the visibility and decision-making environment for pedestrians—factors that are especially important under low-light or nighttime conditions.

By integrating these speed management techniques into nighttime signal operations, agencies can significantly reduce vehicle-pedestrian conflicts and create a safer environment for vulnerable road users.

3.4.2 Early Free Signal Operation

Early free signal operation is a traffic signal timing strategy that allows a coordinated signal to exit its preset plan before the scheduled end of the pattern. In typical coordinated systems, signals along a corridor operate on fixed cycle lengths and offsets to maintain progression, often referred to as a "green wave," which minimizes stops for vehicles traveling along the mainline.

While this coordination benefits vehicular flow during peak periods, it can become inefficient and even problematic when traffic volumes drop, particularly during off-peak hours or at night. In such conditions, maintaining strict coordination often results in unnecessary green time for the mainline, while vehicles on side streets or making turning movements face prolonged red lights.

Early free operation addresses this issue by allowing a signal to release from coordination before the official end of the plan, based on real-time traffic conditions. For example, if a peak-hour timing plan is set to run until 7:00 PM but mainline traffic volumes drop significantly by 6:40 PM, the controller can exit the plan early and shift into free or actuated mode, where signal phases are served based on detected demand rather than a fixed schedule.

This transition offers multiple safety and operational benefits, especially for pedestrians:

- Improved responsiveness to side-street activity ensures shorter wait times for pedestrians, reducing the temptation to cross against the signal due to long delays.
- Minimized driver frustration on side streets lowers the risk of red-light running, a behavior that disproportionately endangers crossing pedestrians.
- More flexible timing supports better accommodation of pedestrian phases, particularly in areas with lower nighttime vehicular demand but steady foot traffic, such as residential zones or entertainment districts.

Early free operation is typically triggered through detector inputs or volume thresholds set for coordinated phases. When real-time data indicates traffic levels no longer warrant coordination, the system transitions to a more demand-responsive mode, serving both vehicles and pedestrians more equitably.

Additionally, early free is part of a broader suite of adaptive signal strategies, including techniques like "late start" (which delays re-entry into coordination if volumes remain low).

Together, these tools provide agencies with greater flexibility during off-peak and transitional periods, allowing traffic signals to operate more efficiently and safely in dynamic environments.

In summary, early free signal operation not only improves traffic flow efficiency but also plays a critical role in enhancing pedestrian safety by reducing delays, encouraging compliance, and enabling quicker, safer crossings, especially during low-volume nighttime hours.

3.4.3 RRFB and PHB

Visual stimuli play a critical role in enhancing nighttime safety, particularly for pedestrians. Treatments such as RRFBs, PHBs, in-pavement lighting, and Leading LPIs are designed to increase pedestrian visibility and prompt more appropriate driver responses at crossings.

RRFBs (Figure 3-2) and PHBs (Figure 3-3) are especially effective at night, as they generate high-visibility signals that capture driver attention and reinforce yielding behavior. RRFBs use intense, rapidly flashing amber lights to alert drivers to the presence of pedestrians at mid-block or uncontrolled crosswalks, significantly improving driver compliance. Similarly, PHBs provide a red signal stop indication, offering pedestrians a safer crossing opportunity by giving them dedicated right-of-way at locations where standard traffic signals may not be warranted.

Figure 3-2. Rectangular rapid flashing beacon

Source: Traffic Safety Supply Company

Figure 3-3. Pedestrian hybrid beacon

Source: Federal Highway Administration

Experts consistently emphasized the value of visual pedestrian treatments in improving nighttime safety, particularly using RRFBs and PHBs. These devices are especially effective after dark due to their high visibility and conspicuous signaling, which contrast sharply with low-light roadway environments.

RRFBs, with their rapid flashing amber lights, draw driver attention from a distance and increase the likelihood that approaching vehicles will slow or stop for pedestrians, particularly at mid-block or uncontrolled crossings. PHBs go a step further by displaying a solid red indication, requiring drivers to come to a complete stop when pedestrians are present. This makes them particularly useful on high-speed or poorly lit roads, where driver awareness may be limited.

Interviewees noted that the effectiveness of RRFBs and PHBs is further enhanced when installed in well-lit areas, and some professionals recommended the use of advanced flashers or supplemental lighting to maximize driver recognition. While PHBs were seen as suitable for higher-volume roadways, RRFBs were considered more appropriate for lower-volume streets or side roads, where full signal control may not be justified. When paired with reflective signage, appropriate signal timing, and pedestrian detection, these treatments significantly improve pedestrian visibility and reinforce driver compliance, helping to reduce vehicle-pedestrian conflicts during nighttime conditions.

Regarding signal timing strategies, there were mixed opinions about the use of LPIs, which give pedestrians a few seconds of head start before vehicles receive a green indication. Some experts saw LPIs as effective at night, particularly in areas with frequent pedestrian-vehicle conflicts, as they allow pedestrians to become more visible in the crosswalk and

help moderate driver turning behavior. Others were more skeptical, suggesting that LPIs are most effective during periods of high pedestrian and vehicle volumes, and may have limited impact during low-traffic nighttime hours.

Overall, professionals agreed that context matters greatly when selecting and deploying pedestrian-focused treatments. RRFBs, PHBs, and LPIs, when thoughtfully applied and supported by good lighting and detection, can significantly enhance nighttime pedestrian safety along urban arterials and side streets alike.

3.4.4 Automated Pedestrian Detection

Automated pedestrian detection is an emerging and promising strategy for enhancing nighttime pedestrian safety, especially for vulnerable users at intersections, mid-block crossings, and locations where pedestrians may require extended crossing time. These systems use advanced sensors, such as infrared, microwave, or video analytics, to detect pedestrian presence without requiring physical push-button activation. This enables more responsive signal operations, including automatic phase calls and dynamic extension of crossing times for slower-moving individuals, such as older adults or people with disabilities.

This technology offers benefits after dark, when visibility is reduced, and pedestrians may be less likely to be seen or may avoid pressing buttons due to poor lighting or perceived safety concerns. Early pilot programs, including those by DDOT, indicate that automated detection can improve the reliability of pedestrian phase activation, reduce delay, and potentially gather valuable data on pedestrian volumes and behavior.

However, the technology remains in its early stages. Key challenges include high implementation costs, limited accuracy in distinguishing intent to cross, and environmental sensitivity (e.g., false detections caused by shadows or passing objects). Despite these limitations, many practitioners view automated pedestrian detection as a critical long-term investment for improving safety and accessibility.

While current deployment is limited and largely confined to testing or demonstration sites, continued improvements in detection accuracy and cost-effectiveness could pave the way for broader adoption, making signalized crossings safer and more adaptive—particularly during low-light and nighttime conditions when pedestrian vulnerability is highest.

3.4.5 Other Pedestrian-Focused Strategies Supporting Nighttime Safety on Arterials

In addition to signal timing adjustments, interviewees emphasized the importance of supplementary engineering strategies to further enhance pedestrian safety at night, particularly at intersections and crossings where visibility and driver awareness are

compromised. These include all-red clearance intervals, reduced speed limits, and a range of physical and visual enhancements designed to calm traffic and improve pedestrian visibility.

All-red clearance intervals provide a safety buffer by momentarily stopping all vehicle movements at the end of each signal phase. This brief pause allows pedestrians additional time to clear the intersection safely and reduces the likelihood of vehicle-pedestrian conflicts, especially in locations with longer crossing distances or higher pedestrian volumes.

Adaptive signal timing and pedestrian detection systems were also highlighted for their ability to dynamically adjust phase lengths based on real-time vehicle speeds and pedestrian presence. These systems improve responsiveness and reduce delay while prioritizing safety, particularly when demand is unpredictable or visibility is limited.

Physical and Visual Enhancements

A variety of low-cost physical and visual treatments can further reinforce driver awareness and pedestrian safety during nighttime hours:

- **Retroreflective signal backplates** improve the visibility of traffic signals by providing a high-contrast, reflective background that stands out against dark or cluttered environments. These backplates reflect headlights back toward drivers, increasing the distance at which signals, especially red and pedestrian indications, can be seen. This treatment is especially effective at night and has been shown to reduce red-light running and improve compliance.
- **Enhanced lighting** at crosswalks is critical for nighttime visibility. Proper illumination, whether from overhead streetlights, focused lighting at crossings, or integrated signal-mounted lighting, allows drivers to detect pedestrians from greater distances and helps pedestrians better assess vehicle speeds. Well-lit crossings are particularly important in areas with high foot traffic, such as near schools, transit stops, or commercial districts.
- **Speed tables placed near pedestrian crossings** act as horizontal traffic-calming devices that physically slow vehicles without requiring changes to signal timing. These raised areas of pavement encourage consistent speed reduction and improve pedestrian safety by reducing vehicle approach speeds at critical crossing points.
- **Raised crosswalks** combine visibility improvements with vertical traffic calming. By elevating the crossing to sidewalk level, these treatments make pedestrians more visible and force drivers to reduce speed through vertical deflection. They are

especially effective on lower-speed arterials and in environments where nighttime pedestrian activity is common.

- **Variable speed signs and dynamic messaging** provide real-time feedback to drivers based on their speed or the presence of pedestrians. Messages such as "Slow Down, Pedestrian Crossing Ahead" or "School Zone, Reduce Speed" help raise driver awareness and reinforce safe behavior in areas with limited visibility. When paired with speed enforcement or other calming measures, these signs can be a powerful deterrent against high-risk driving behaviors at night.

Overall, practitioners noted that a layered approach, combining operational strategies with physical and visual enhancements, is essential to improving pedestrian safety after dark. While some of these treatments are relatively simple to implement, their impact can be significant, particularly in high-risk areas where traditional signal timing alone may not provide sufficient protection for vulnerable users.

3.5 Emerging Technology-Related Signal Timing Strategies

This section highlights signal timing strategies that leverage advanced and emerging technologies to improve nighttime traffic safety and efficiency. It explores the application of video-based analytics and computer vision to monitor traffic conditions and detect pedestrians in real time. Additionally, it covers the use of AI-driven adaptive signal control systems that adjust timing based on live traffic patterns, as well as the integration of CV technologies that enable communication between vehicles and infrastructure.

3.5.1 Video-Based Analytics and Computer Vision Technologies

Video-based analytics are increasingly recognized as a valuable tool for enhancing signal timing and pedestrian safety, particularly through the collection and interpretation of near-miss incidents and user behavior data. Although real-time signal control using near-miss detection is still limited, current applications are highly effective for performance monitoring and identifying recurring conflict points before they escalate into crashes. These systems can detect and differentiate between all roadway users, including pedestrians, bicyclists, and vehicles, providing a rich dataset to support adaptive signal timing, CV applications, and pedestrian-oriented interventions.

Potential real-time functions include automatically extending pedestrian clearance intervals, activating warning beacons, or initiating all-red clearance phases when potential conflicts are detected. However, nighttime deployments present challenges, as low ambient lighting reduces the reliability of conventional video detection. To improve performance under these conditions, future systems may integrate thermal cameras,

radar, or LiDAR to ensure accurate pedestrian and vehicle detection regardless of lighting quality.

In the long term, video analytics offer a data-driven foundation for implementing advanced safety strategies such as dynamic speed management, extended crossing times, and context-sensitive lighting. While many real-time applications are still emerging, experts view these technologies as having strong potential to improve nighttime pedestrian safety by supporting evidence-based signal adjustments tailored to actual user behavior and conditions.

3.5.2 AI-Driven Adaptive Signal Control

AI-driven adaptive signal control shows strong promises for enhancing nighttime safety at signalized intersections by adjusting signal timing in real time based on observed traffic patterns, conflicts, and near-misses. Pilot deployments with vendors such as NoTraffic and Derq have demonstrated the technology's ability to detect crashes and near-conflict scenarios, providing detailed, actionable data for rapid intervention. For instance, one newly signalized location recorded multiple crashes within two weeks, prompting the swift addition of a protected left-turn phase, an example of how AI-based systems can facilitate evidence-based design improvements in near real-time.

Despite its potential, widespread adoption remains limited. Key barriers include high implementation and maintenance costs, outdated signal infrastructure, and the need for trained staff to monitor and manage the systems. In addition, detection quality is critical; without accurate and reliable inputs, the performance of AI-driven adaptive systems is significantly reduced. As a result, many agencies consider broad deployment feasible only in the next five or more years.

Experts also noted that adaptive signal control systems have historically prioritized mobility over safety. Today's AI-enhanced adaptive systems typically adjust the start and end of green phases and may extend green lights to protect vehicles in dilemma zones. However, their capacity to reduce crashes directly is still evolving.

Looking ahead, next-generation adaptive systems that integrate real-time traffic speeds, conflict data, and multimodal behavior could shift the focus toward safety-centered optimization. While current tools are more effective at improving efficiency, the combination of AI, advanced detection, and real-time analytics has strong potential to support proactive safety interventions, particularly in complex nighttime conditions.

3.5.3 CV Technology

CV technology provides real-time data on vehicle trajectories, behaviors, and interactions with roadway infrastructure, offering new opportunities to improve nighttime signal safety.

While current CV applications are largely observational, such as monitoring driver responses to yellow intervals, tracking frequent hard braking, or assessing arrival-on-green rates, the technology holds strong potential for proactive safety interventions.

For instance, CV systems could be used to warn drivers of upcoming red-light violations, pedestrian presence, or nearby cyclists, especially in low-visibility nighttime conditions. These warnings could be delivered via in-vehicle alerts, roadside units, or connected apps, and may be integrated with radar or video detection systems to enhance situational awareness. Blank-out signs or dynamic red extensions could also be triggered to prevent crashes when a hazard is detected.

Several pilot programs are exploring these applications. In Franklin, Tennessee, the city has deployed the TravelSafely app at 13 intersections using Applied Information's platform. This system pulls real-time data from signal controllers to alert both drivers and pedestrians of potential conflicts, such as an approaching red light or pedestrians in the crosswalk.

Despite these advances, widespread CV deployment remains limited, largely due to low penetration rates and infrastructure costs. Nonetheless, interviewees emphasized that CV technology can support gap judgment, speed management, and red-light extension strategies, and may become a powerful tool for improving nighttime safety as adoption grows. Continued research and pilot testing are essential to understand how CV data can be best leveraged for real-time signal adjustments, pedestrian protection, and automated enforcement enhancements.

3.5.4 Other Emerging Technologies

Emerging technologies are creating new opportunities to enhance nighttime signal operations by enabling more responsive and data-informed decision-making. Practitioners identified several key innovations, including advanced traffic signal controllers capable of generating high-resolution Automated Traffic Signal Performance Measures (ATSPMs), non-intrusive detection systems integrated directly with signal controllers, and centralized platforms that can aggregate and analyze corridor-level data in real time.

These technologies allow agencies to monitor signal performance more accurately, detect issues such as missed calls or inefficient phase utilization, and adjust timing plans dynamically, especially useful during low-volume nighttime hours. For example, real-time data can be used to fine-tune cycle lengths, detect speeding patterns, or extend pedestrian phases when necessary, helping to reduce crash risks and improve operational efficiency.

Implementation varies significantly across agencies, depending on available funding, infrastructure maturity, and staff expertise. While the potential benefits are clear, including improved safety for pedestrians, smoother traffic flow, and better detection of a typical behavior, broader adoption will depend on continued evaluation, cost reduction, and proof of effectiveness in real-world nighttime conditions.

Together, these emerging technologies represent a shift toward proactive, data-driven traffic signal management, with the capacity to significantly improve safety and performance on arterial roadways, particularly at night, when visibility and driver awareness are reduced.

3.6 Key Findings from Expert Interviews

Nighttime operations on arterial roadways remain an understudied area in traffic engineering, despite posing significant and unique safety challenges. Interviews with agency practitioners highlighted the need for dedicated research and targeted strategies to address issues such as excessive vehicle speeds, impaired driving, red-light running, limited visibility, and vulnerable road user safety after dark. These challenges are compounded by lower traffic volumes, inadequate lighting, glare, and limitations in detection and signal infrastructure.

3.6.1 Key Safety Challenges During Nighttime Operations

To effectively improve nighttime safety, it is important to understand the core challenges these conditions present. Interviewees identified several critical risk factors affecting nighttime arterial operations:

- Nighttime arterial safety is influenced by a convergence of risk factors: **higher travel speeds, driver fatigue or impairment, and limited visibility**.
- **Low traffic volumes** can lead to risky behaviors, including red-light running and aggressive acceleration to “catch” green lights.
- **Visibility issues**, including poor street lighting, obstructed signs, and glare from headlights, reduce driver reaction time and compromise pedestrian safety.
- **Vulnerable road users** such as pedestrians and cyclists are at increased risk due to driver inattention and limited conspicuity.

3.6.2 Signal Timing and Operational Strategies

Adjusting signal timing and operations to better suit nighttime conditions is a crucial step toward improving safety. Practitioners highlighted the following strategies and considerations:

- **Shortened signal cycles**, **minimum recalls**, and **half-cycle operations** can be used at night to reduce unnecessary delays and discourage speeding.
- However, **poorly calibrated detection systems** can lead to long waits on minor streets, undermining operational goals and increasing driver frustration.
- **Free or fully actuated signal operations** are typically preferred after 9:00 PM, but must be carefully managed to avoid unsafe vehicle behavior.
- **Removing coordination** (i.e., early free operation) during off-peak periods improves responsiveness and reduces delays but must be implemented based on real-time data.

3.6.3 Speed Management and Progression Strategies

Controlling vehicle speeds is fundamental to reducing nighttime crash severity and improving pedestrian safety. Key findings include:

- Signal progression at night must balance traffic flow with speed control. Strategies include:
  - **Shorter cycle lengths** to break up speeding patterns.
  - Intentional "bumpy" progression to discourage excessive speeds.
  - **Setting progression speeds 5 mph below posted limits** to encourage compliance without causing frustration.
- Tools such as **dilemma zone protection** and advanced vehicle detection help extend greens safely and reduce red-light running.

3.6.4 Enhancing Pedestrian Safety at Night

Pedestrian safety at night depends on improving visibility and responsiveness through both engineering and technology. Effective approaches shared by interviewees include:

- Visual treatments are essential:
  - **RRFBs and PHBs** increase pedestrian visibility and encourage driver yielding, particularly when combined with good lighting.
  - **Retroreflective signal backplates**, raised crosswalks, in-pavement lighting, and properly lit crosswalks improve nighttime detection of signals and people.
- **Automated pedestrian detection** technologies allow for dynamic signal adjustments, including extending walk times for slower pedestrians and activating signals without button presses.
- **LPIs** give pedestrians a head start before vehicles move, though their effectiveness at night is debated and may depend on traffic volumes and intersection characteristics.

3.6.5 Specialized Signal Strategies for Nighttime Use

Certain signal timing modifications can directly influence driver behavior to enhance nighttime safety beyond standard signal operations. Interviewees recommended:

- Rest-in-red holds mainline traffic on red until demand is detected, breaking up speeding waves and improving speed compliance.
  - Effective for low-volume intersections and hilly terrain but requires precise detection and cycle timing.
  - Advanced detection, such as radar, is critical to reliably differentiate between speeders and normal traffic.
- All-red clearance intervals provide a brief buffer between conflicting phases, enhancing pedestrian safety in poor visibility.

3.6.6 Technology and Innovation

New technologies are transforming the potential to monitor, analyze, and improve nighttime safety in real time. Practitioners discussed the following emerging tools:

Video-Based Analytics

- Emerging use of video analytics allows agencies to analyze near-misses and unsafe behaviors.
- While mostly used for performance monitoring, future integration with thermal, radar, or LiDAR could support real-time safety interventions like extended pedestrian phases or green extensions.

AI-Driven Adaptive Signal Control

- AI systems dynamically respond to real-time traffic conditions, potentially improving both efficiency and safety.
- Pilot projects show promise in identifying conflict patterns (e.g., multiple left-turn crashes) and enabling rapid adjustments.
- However, limitations remain due to high costs, infrastructure requirements, and current focus on mobility rather than safety.

CV Technology

- CV systems provide real-time data on vehicle trajectories, speeds, and behaviors.
- Applications include driver alerts for red-light running, warnings of pedestrian presence, and coordination with signals via mobile apps (e.g., Franklin, TN's TravelSafely).

- Despite potential, low penetration rates and integration challenges limit widespread adoption.

Emerging Detection and Centralized Monitoring

- New tools such as LiDAR-based pedestrian detection, automated left-turn conflict monitoring, and centralized signal performance dashboards offer promising safety gains.
- ATSPMs can be used to detect skipped phases, misaligned coordination, or late arrivals during nighttime hours.

4 Case Studies

This chapter presents four representative case studies that illustrate how nighttime arterial safety can be improved through targeted signal timing revisions, speed-management-oriented operations, lighting enhancements, and CV technologies. These case studies document practical implementation experiences, summarize measurable outcomes where available, and identify transferable insights for future nighttime signal timing and operational strategies.

The four selected cases represent different types of nighttime safety countermeasures. The Manatee County US 41 case focuses on corridor-level nighttime signal timing revisions and pedestrian safety enhancements. Portland's rest-in-red strategy demonstrates an intersection-level speed management approach during low-volume nighttime periods. The FDOT LED lighting retrofit program highlights the role of improved illumination in reducing nighttime crash risk. The CV case, based on THEA's CV Pilot and its relevance to the planned Pinellas County SR 60 West Coast Smart Signal Corridor, illustrates how real-time detection and safety messaging can support nighttime safety under low-visibility conditions.

Together, these cases provide a practical foundation for understanding how different strategies can be applied individually or in combination to address nighttime arterial safety challenges. They also support the development of implementation guidance and evaluation approaches in later chapters of this report.

4.1 Case Study Selection Approach

The case studies were selected to represent a range of nighttime safety strategies that are relevant to arterial corridors and signalized intersections. Each case was chosen because it addresses one or more nighttime-specific safety issues, such as excessive speeds during low-volume periods, reduced visibility, vulnerable road user exposure, limited driver expectancy, or the need for improved detection and warning systems.

The selection also considered the transferability of each strategy to Florida arterial environments. The US-41 case was included because it provides a Florida-based example of using nighttime signal timing as a speed management and pedestrian safety tool. Portland's rest-in-red strategy was selected as a national example of a low-cost, operationally focused treatment that changes default signal behavior to discourage high-speed nighttime entries. The FDOT LED lighting retrofit program was selected because it directly addresses nighttime visibility and provides statewide and District 7 evaluation results. The CV case was selected because it demonstrates how advanced detection,

vehicle-to-infrastructure communication, and real-time safety alerts can support future nighttime operations, particularly along smart corridors such as SR-60.

The four case studies therefore cover both proven and emerging approaches. They include operational strategies, infrastructure improvements, and technology-enabled applications. This combination allows for a comparison of different implementation pathways and identifies common lessons for agencies seeking to improve nighttime arterial safety.

4.2 Case Study 1: Manatee County US-41 Corridor Signal Timing Revisions

The first case study focuses on nighttime signal timing revisions along the US-41 corridor in Manatee County, from Tallevast Road to Orlando Avenue (Figure 4-1). This corridor had a documented history of severe crashes and was identified as one of the highest-risk corridors in FDOT District 1. Over a five-year period, the corridor recorded 31 fatal crashes and 264 serious injuries. The corridor also includes commercial areas and activity centers that generate pedestrian activity during evening and nighttime hours (Florida Department of Transportation, 2025b) (FDOT 2025b).

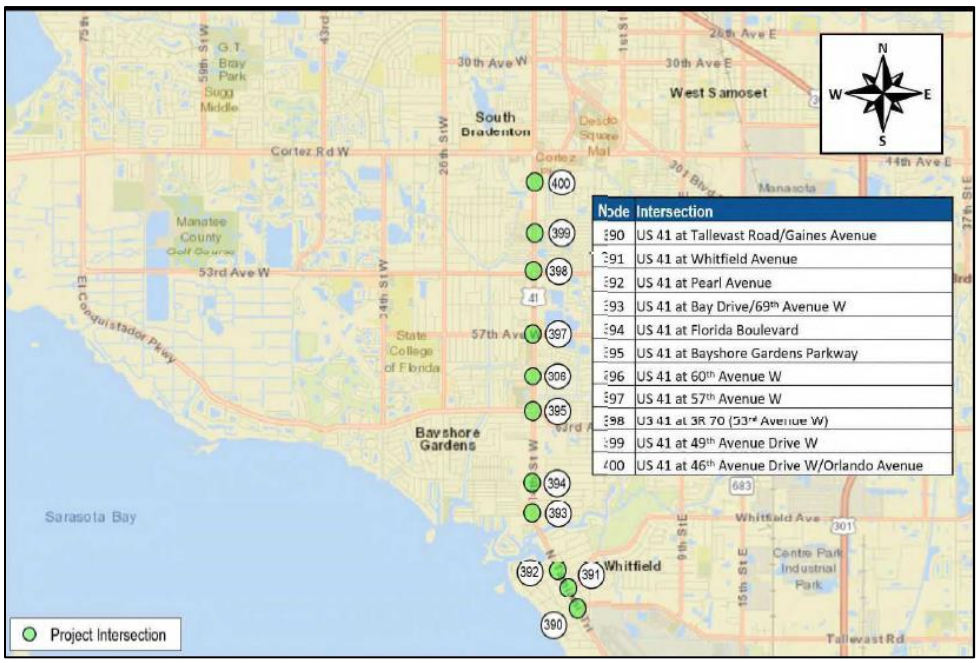


Figure 4-1. US-41 corridor speed management program and detector locations

Source: Florida Department of Transportation (2025b)

Before the timing revisions, the corridor operated with long daytime-style cycle lengths, including cycles as long as 160 to 200 seconds during some periods, and free operation

during overnight hours. These conditions created wide green bands and allowed drivers to travel through multiple intersections at relatively high speeds. The posted speed limit ranged from 45 to 50 mph, while observed 85th-percentile nighttime speeds reached approximately 55 to 60 mph. This mismatch between posted speeds, nighttime operating speeds, and pedestrian exposure contributed to elevated safety risk.

The nighttime signal timing strategy was designed to reduce operating speeds, improve pedestrian safety, and create a more predictable corridor operation during low-volume periods. FDOT District 1 and Manatee County updated the time-of-day signal timing plans along the corridor. A key change was the replacement of late-night free operation with a dedicated nighttime coordinated pattern using a short 60-second cycle length. This revised nighttime pattern reduced long green waves, narrowed effective green bands, and limited opportunities for continuous high-speed progression.

The revised timing plan also shortened cycle lengths during multiple time periods. For example, weekday overnight periods that previously operated in free mode were changed to Pattern 11 with a 60-second cycle. Other daytime and evening periods were also shortened, with some cycle lengths reduced from 160 or 200 seconds to 100, 120, or 160 seconds depending on the period. During the late evening and overnight hours, the shorter cycles were intended to better match reduced traffic demand and discourage speeding.

The nighttime minimal-cycle operation used short phase splits and a small offset to support lower-speed operations. Pattern 11 included a 60-second cycle length, phase splits generally ranging from approximately 14 to 29 seconds, and a 7-second offset at a representative intersection. This configuration shifted the corridor away from long coordinated progression and toward a more responsive low-volume nighttime operation. It provided stable service for the mainline while allowing side-street and turning movements to be accommodated without encouraging high-speed travel.

Pedestrian safety enhancements were also incorporated into the corridor timing revisions. All intersections were programmed with Leading Pedestrian Intervals, typically providing a 5-second head start before adjacent turning vehicles received a green indication. This improved pedestrian visibility and reduced conflicts with turning vehicles, which is particularly important during nighttime conditions. At locations with higher pedestrian activity, Rest-in-Walk operation was also implemented, allowing the pedestrian indication to remain in the WALK state during low vehicle demand. This treatment reduced pedestrian delay and promoted safer crossing behavior.

The evaluation showed that the timing revisions achieved the intended speed management effect with only modest operational trade-offs. Northbound average speeds during the evening period decreased from 41.0 mph before implementation to 35.0 mph after

implementation, representing a reduction of approximately 14.6%. Southbound average stops increased from 2.8 to 4.6, and southbound weekend travel time increased by approximately 37.8 seconds. These increases were expected because the strategy intentionally broke up long nighttime green-wave progression to reduce continuous high-speed travel.

Table 4-1 compares the full before-and-after signal timing plans and cycle lengths. The previous timing plan relied heavily on long daytime-style cycles and FREE mode during overnight hours, which allowed extended green bands and inconsistent nighttime operations. In contrast, the revised plan introduces shorter cycle lengths, standardized nighttime Pattern 11 control, and more defined transitions between daytime and nighttime periods. These changes form the operational foundation for reducing progression speeds and improving safety during low-volume nighttime conditions.

Table 4-1. Comparison of Before-and-After Signal Timing Plans and Cycle Lengths for US-41 Corridor

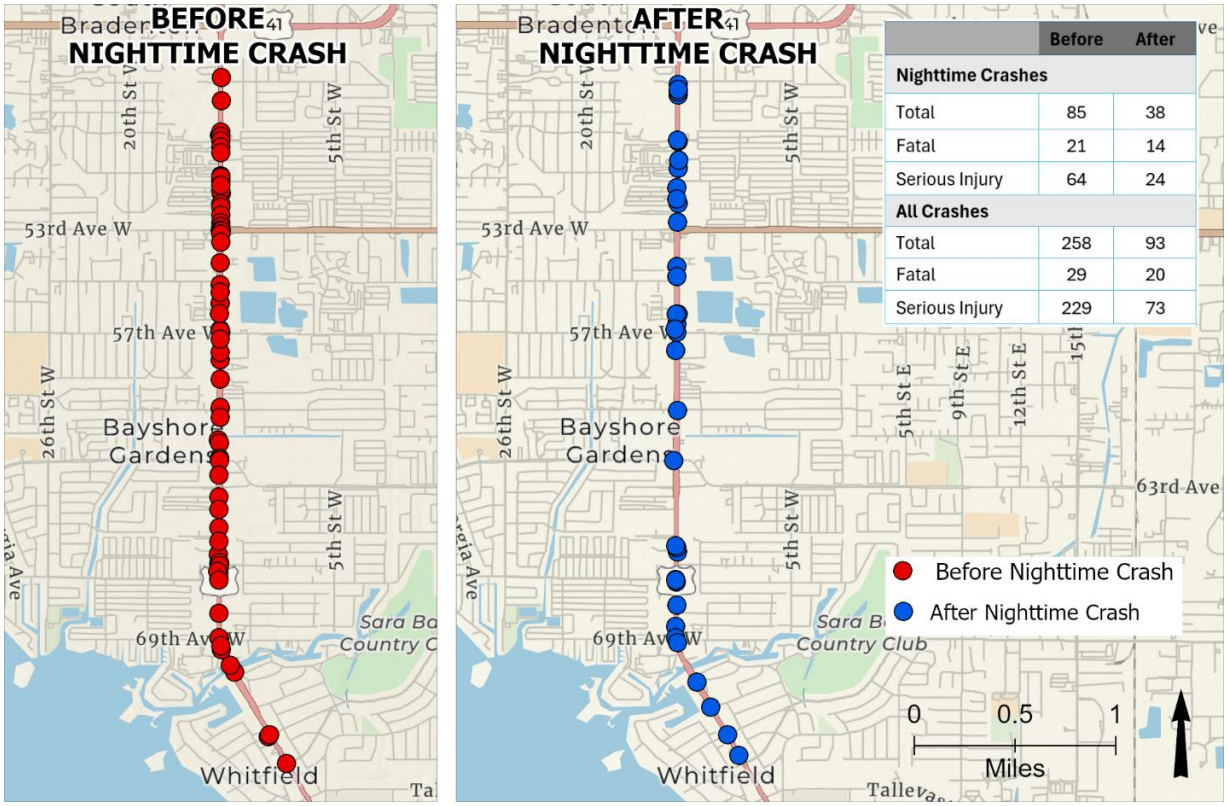
Day	Time Period	Before Pattern	Before Cycle Length	After Pattern	After Cycle Length
Monday–Friday	00:00–06:00	FREE	—	11	60 sec
	06:00–10:00	1	160 sec	1	120 sec
	10:00–14:00	2	200 sec	2	100 sec
	14:00–18:30	3	200 sec	3	160 sec
	18:30–22:00	4	140 sec	4	90 sec
	22:00–23:59	FREE	—	11	60 sec
Saturday	00:00–07:00	FREE	—	11	60 sec
	07:00–09:30	5	140 sec	5	90 sec
	09:30–18:00	6	160 sec	6	120 sec
	18:00–23:00	5	140 sec	5	90 sec
	23:00–23:59	FREE	—	11	60 sec
Sunday	00:00–07:00	FREE	—	11	60 sec
	07:00–09:30	7	140 sec	7	90 sec
	09:30–18:00	8	160 sec	8	120 sec
	18:00–21:00	7	140 sec	7	90 sec
	21:00–23:59	FREE	—	11	60 sec

Table 4-2 summarizes nighttime performance outcomes based on field observations collected during the evening and late-evening periods (18:00–23:00). These time windows immediately precede or overlap with the start of the overnight minimal-cycle operation (Pattern 11) and therefore provide reliable insight into nighttime operational performance.

Table 4-2. Nighttime Vehicle Performance Evaluation (Evening Period 18:00-23:00)

Measure	Period	Before	After	Difference	% Change
NB Average Speed (mph)	18:30–22:00	41.0	35.0	−6.0	−14.6%
SB Average Number of Stops	18:30–22:00	2.8	4.6	+1.8	+64%
SB Weekend Travel Time (min)	18:00–23:00	7.57	8.2	+37.8 (sec)	+8.3%

The safety outcomes were substantial. A before-and-after crash analysis found that corridor-wide improvements, including signal retiming, median modifications, and enhanced enforcement visibility, were associated with a 50% reduction in fatal and serious-injury crashes, with a 99% confidence level. Nighttime crashes declined from 85 in the before period to 38 in the after period, as shown in Figure 4-2. Fatal crashes decreased from 21 to 14, and serious-injury crashes decreased from 64 to 24. Fatal and serious bike/pedestrian crashes also decreased by approximately 34%, with an 80% confidence level.



	Before	After
Nighttime Crashes		
Total	85	38
Fatal	21	14
Serious Injury	64	24
All Crashes		
Total	258	93
Fatal	29	20
Serious Injury	229	73

Figure 4-2. Nighttime crash outcomes before and after corridor improvements on US-41 (2016–2020 vs. 2021–2025)

Source: Signal4 Lab (2025)

Overall, the US-41 case demonstrates that nighttime signal timing can be used as an active safety countermeasure. By replacing overnight free operation with short-cycle coordination, reducing progression speeds, narrowing green bands, and adding pedestrian priority treatments, the corridor achieved lower speeds and meaningful crash reductions. The case also shows that modest increases in stops or travel time may be acceptable when they occur during low-volume periods and are associated with improved nighttime safety.

4.3 Case Study 2: Portland Rest-in-Red Strategy

The second case study focuses on Portland's rest-in-red strategy. rest-in-red is a traffic signal operation in which the signal rests in an all-red state when no vehicles are present and only changes to green when an approaching vehicle is detected. This strategy is intended to reduce speeding, discourage red-light running, and improve safety during late-night and early-morning periods when traffic volumes are low but speeding risk may be high (Addison, 2012).

Portland has advanced rest-in-red as part of its Vision Zero program. The first Portland installation was located at NE 7th Avenue and NE Lloyd Boulevard (Figure 4-3), near the Congressman Earl Blumenauer Bicycle and Pedestrian Bridge. This location includes substantial pedestrian and bicycle activity, making it an appropriate setting for a strategy intended to reduce high-speed vehicle entries and improve multimodal safety.

Figure 4-3. Location and intersection layout of the rest-in-red installation at NE 7th Avenue and NE Lloyd Boulevard in Portland, Oregon

A second implementation was completed along SE Powell Boulevard between SE 21st Avenue and SE 33rd Avenue (Figure 4-4). This corridor is one of Portland's highest-crash streets and has a history of speed-related nighttime injuries and fatalities. PBOT and ODOT upgraded the signals along the corridor in 2024 and activated rest-in-red to manage late-night and early-morning speeds. Portland is also preparing to expand this type of operation along 82nd Avenue as part of a broader signal upgrade program.

Figure 4-4. Aerial View of the SE Powell Boulevard & SE 28th Avenue intersection with rest-in-red signal installations, Portland, Oregon

The primary safety rationale for rest-in-red is speed management. During low-volume nighttime periods, traditional signal operations may allow drivers to approach intersections at high speeds, especially when green indications remain active or when vehicles encounter little traffic. Rest-in-red interrupts this pattern by requiring drivers to slow or stop unless a valid detection is received and the signal transitions to green. This creates a more cautious approach environment and reduces the likelihood of high-speed entries into intersections.

Implementation depends on two key components: reliable detection and modern signal controllers. Portland primarily uses microwave detection mounted on mast arms or signal poles to detect approaching vehicles several hundred feet upstream of the intersection. This long-range detection allows the system to identify an approaching vehicle and transition out of the all-red state when appropriate. Microwave detection is especially useful because it can be installed without pavement cuts and can support nighttime low-volume operations. Microwave detection provides:

- Long-range vehicle detection suitable for nighttime low-volume conditions
- Direct indication of an approaching vehicle to transition out of rest-in-red
- Flexible installation without pavement cuts

This upstream detection allows the signal to remain red during low-volume periods until a vehicle is detected approaching the intersection.

Modern signal controllers are also essential because they allow the intersection to operate in different modes by time of day. During daytime or higher-volume periods, the controller can operate normal coordinated plans. During late-night and early-morning hours, the controller can shift into rest-in-red mode, using smart detection inputs to manage vehicle service. Newer controller platforms support:

- Multiple operational modes, including rest-in-red
- Integration with smart detection technologies
- More responsive and adaptive timing during low-volume periods

Portland's rest-in-red deployments (Figure 4-5) are still in the early stages of evaluation. PBOT is collaborating with Oregon State University on a multi-year study to assess operational performance, speed compliance, and safety outcomes. Preliminary performance findings are expected after sufficient before-and-after nighttime data have been collected and validated. At the time of this report, detailed quantitative results were not yet available.

Figure 4-5. Late-night road users will be seeing red when they approach SE 28th on Powell

Source: City of Portland (2025b)

Although formal evaluation results are pending, initial observations have been positive. PBOT reported qualitative feedback from agency staff and nearby residents indicating that the treatment appears to reduce nighttime speeding and high-speed entries. Community

feedback suggested that drivers were less likely to race through the treated intersections at night. While this feedback does not replace a formal statistical evaluation, it is consistent with the expected safety mechanism of rest-in-red.

The Portland case also highlights important implementation considerations. Detector configuration is critical. If upstream detection is too long or not properly calibrated, the signal may place a call too early and transition to green before the driver has meaningfully slowed. PBOT observed that some radar models created early calls and premature green indications, requiring adjustments to detection range and timing settings. These findings show that rest-in-red is not simply a programming change; it requires careful detector placement, calibration, and field validation.

The strategy is currently most appropriate for simpler approaches where detection is reliable, and lane association is clear. Multi-lane approaches can create challenges for accurate speed measurement and lane discrimination. Rest-in-red is also most appropriate for nighttime or low-volume conditions because it can increase delay if used during higher traffic demand. Therefore, agencies considering this strategy should select locations with documented nighttime speeding or crash issues, simple detection geometry, and sufficient controller and detection capabilities.

Overall, Portland's rest-in-red case demonstrates a promising operational approach for managing nighttime speed at isolated intersections or high-risk corridors. While quantitative safety results are still under development, the strategy provides a useful model for using signal indications to influence driver behavior during periods when traditional traffic volumes are too low to naturally calm speeds.

4.4 Case Study 3: FDOT LED Lighting Retrofit for Nighttime Safety

The third case study focuses on FDOT's statewide LED lighting retrofit program (Florida Department of Transportation, 2025a). Unlike the US-41 and Portland cases, which rely primarily on signal timing and operational logic, this case addresses nighttime safety through improved roadway illumination. The program was developed in response to the strong relationship between nighttime visibility and severe crash risk, particularly for pedestrians and other vulnerable road users. Figure 4-6 illustrates the geographic distribution of retrofit locations across Florida and presents representative examples of nighttime illumination improvements achieved through the program, highlighting its broad statewide coverage.

Figure 4-6. Statewide retrofit locations and representative nighttime illumination improvements

Source: Florida Department of Transportation (2025a)

Between 2017 and 2026, FDOT allocated approximately $100 million to retrofit or install lighting at more than 2,500 intersections across the State Highway System. The primary objective was to improve illumination uniformity, enhance pedestrian conspicuity, and provide better nighttime visibility for all roadway users. The program included both conversions from high-pressure sodium fixtures to LED technology and new lighting installations at locations that previously lacked lighting.

Figure 4-7 summarizes project completion status by FDOT district, indicating that the lighting retrofit initiative has been substantially implemented across most districts as of June 2025. Complementing these implementation outcomes, Figure 4-8 presents the annual distribution of program funds by project phase, demonstrating a clear progression from design-focused activities in the early years to construction-dominated investments as large-scale deployment advanced statewide.

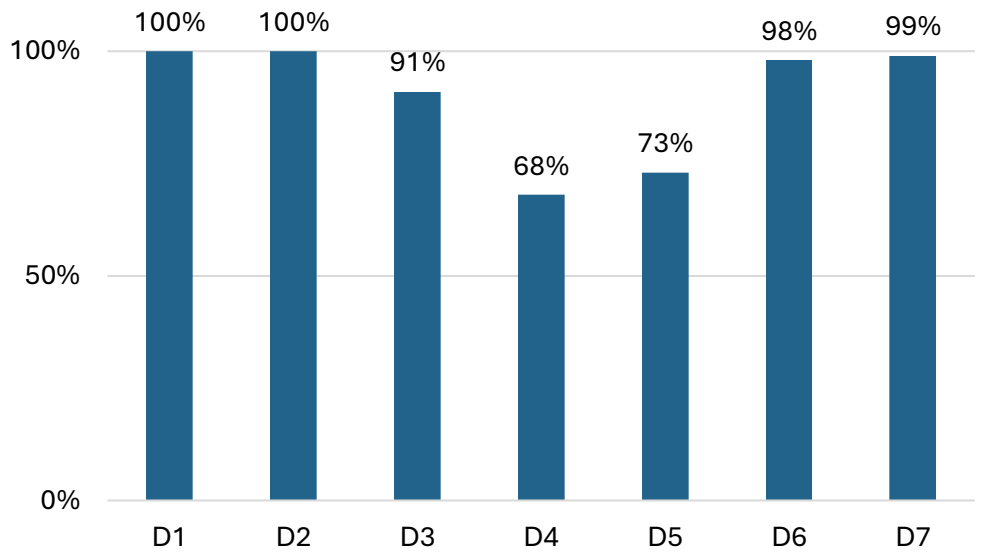


Figure 4-7. Project completion status by FDOT District (As of June 2025)

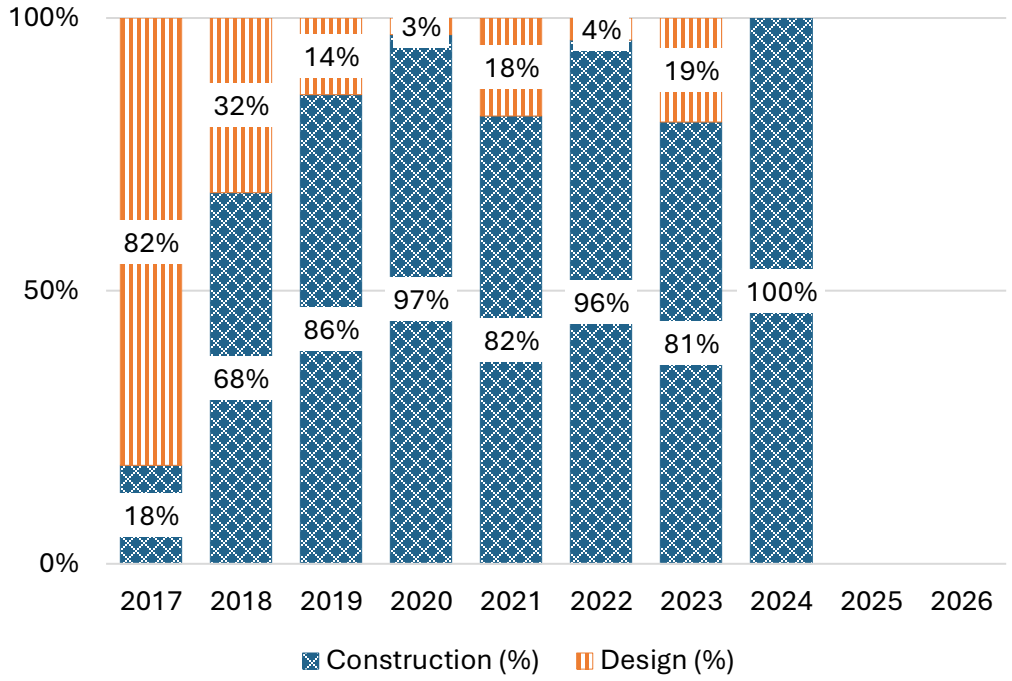


Figure 4-8. Annual distribution of program funds by phase (Design vs. Construction) (As of June 2025)

The statewide program was implemented across FDOT districts and was substantially completed in most districts by June 2025. Funding moved progressively from design activities in the early years toward construction as the program advanced. This phased

implementation allowed FDOT to identify lighting needs, complete design work, and deploy lighting upgrades across many intersections.

Within FDOT D7, the lighting retrofit initiative was implemented in partnership with the Center for Urban Transportation Research. More than 400 intersections in District 7 were retrofitted as part of the statewide effort. Locations were selected based on lighting conditions and nighttime crash history, with the goal of improving visibility at intersections that had historically poor illumination or elevated nighttime crash counts.

The design approach followed FDOT Roadway Design Memorandum 16-02, which required that existing and proposed fixtures within retrofit projects be converted to LED technology. The lighting design considered both horizontal and vertical illuminance. Horizontal illumination zones were defined using intersection areas such as sidewalk lines and stop bars, while vertical illumination was evaluated from the driver's perspective approaching the crosswalk. For signalized intersection retrofits, the criteria included average initial horizontal illumination levels of 1.5 foot-candles for interstates, expressways, freeways, and major arterials, and 1.0 foot-candles for other roadways. Uniformity and veiling luminance ratios were also considered to ensure consistent and effective illumination.

Implementation activities varied by location. Some sites required new poles, while others involved relocating existing poles or mounting LED fixtures on existing infrastructure. Electrical work included conduit installation, pull box placement, and power connections. The retrofit program focused specifically on lighting improvements and did not introduce non-lighting roadway modifications, allowing the safety effects of improved illumination to be more directly evaluated.

The statewide evaluation included 1,051 intersections using a standardized three-year before-and-after comparison. The results indicated that lighting retrofits were associated with reductions in nighttime crashes and nighttime crash severity. Total nighttime crashes decreased by 2.0%, corresponding to an absolute reduction of 538 nighttime crashes. Nighttime fatal and serious injury crashes declined by 19.3%, corresponding to an absolute reduction of 183 fatal and serious injury crashes, as shown in Figure 4-9.

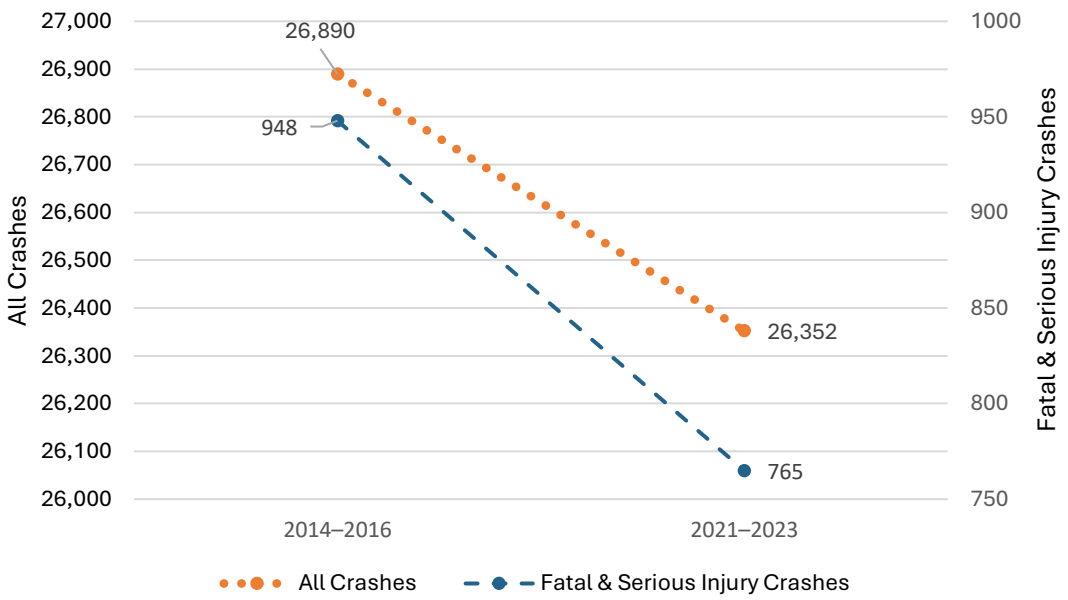


Figure 4-9. Statewide nighttime crash trends at lighting retrofit intersections (three-year before-and-after periods)

District 7 corridor-level analysis provided more detailed insight into local safety effects, shown in Figure 4-10. Six selected corridors were included: SR-600, SR-574, SR-45, US-41, SR-55, and SR-580. All six corridors experienced reductions in nighttime crashes between the before year of 2018 and the after year of 2020. SR-574 decreased from 41 nighttime crashes to 21. SR-45 decreased from 20 to 11. US-41 decreased from 20 to seven. SR-580 decreased from 10 to five. SR-600 and SR-55 also experienced reductions, though the magnitude varied by corridor.

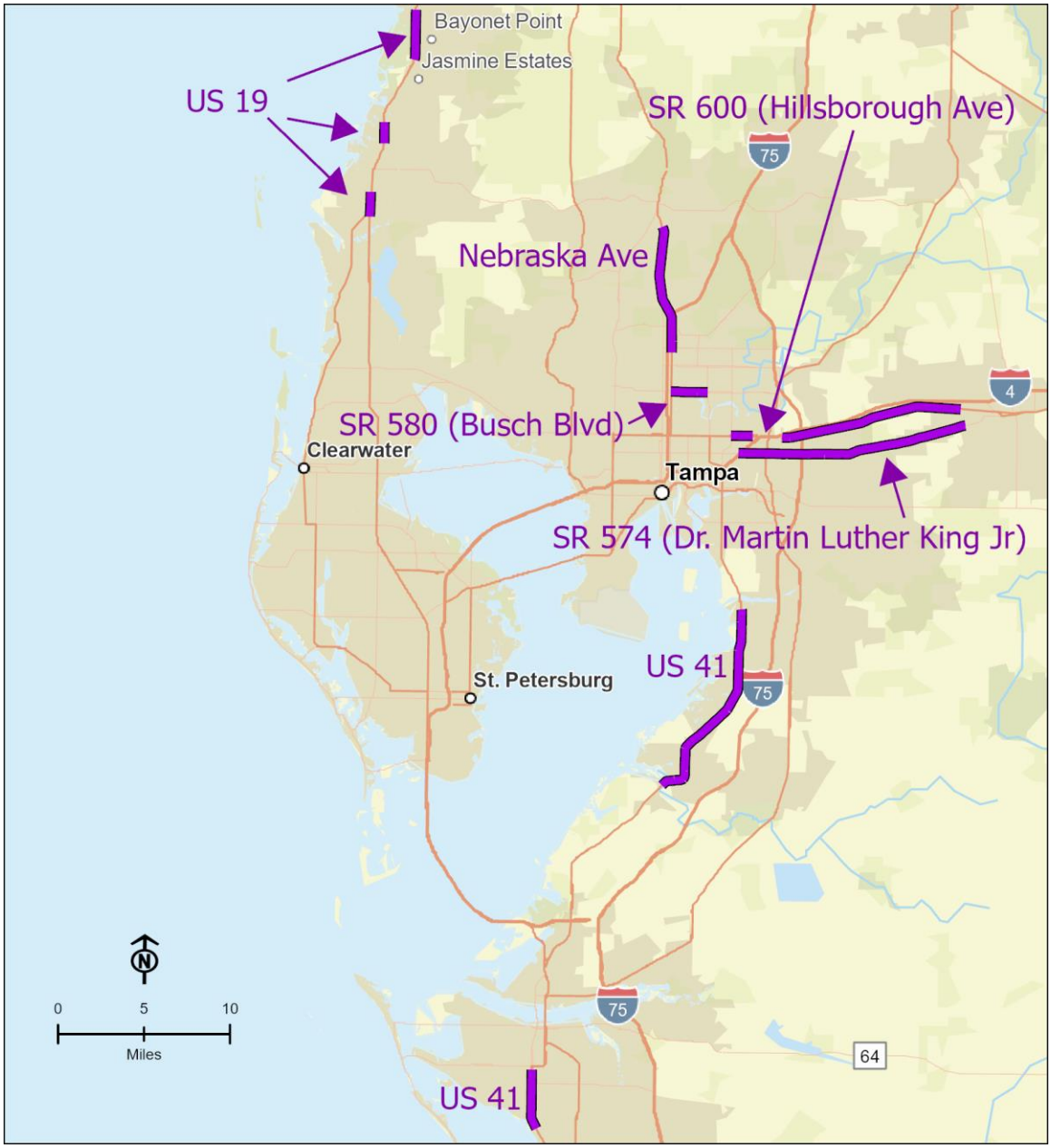


Figure 4-10. Geographic distribution of roadway corridors included in the LED lighting safety evaluation

Several intersection-level improvements were also noted. Along SR-600, the intersection at North 30th Street decreased from six crashes in 2018 to three crashes in 2020. Mango Road decreased from three to one, and North 22nd Street decreased from six to four. Along SR-574, multiple intersections showed substantial reductions, including locations at Falkenburg Road, the southbound I-75 ramp, Williams Road, Lakewood Drive, and Pine Street. Along US-41, nighttime crashes decreased at multiple intersections, and none of the evaluated intersections showed an increase after the retrofit, as shown in Figure 4-11.

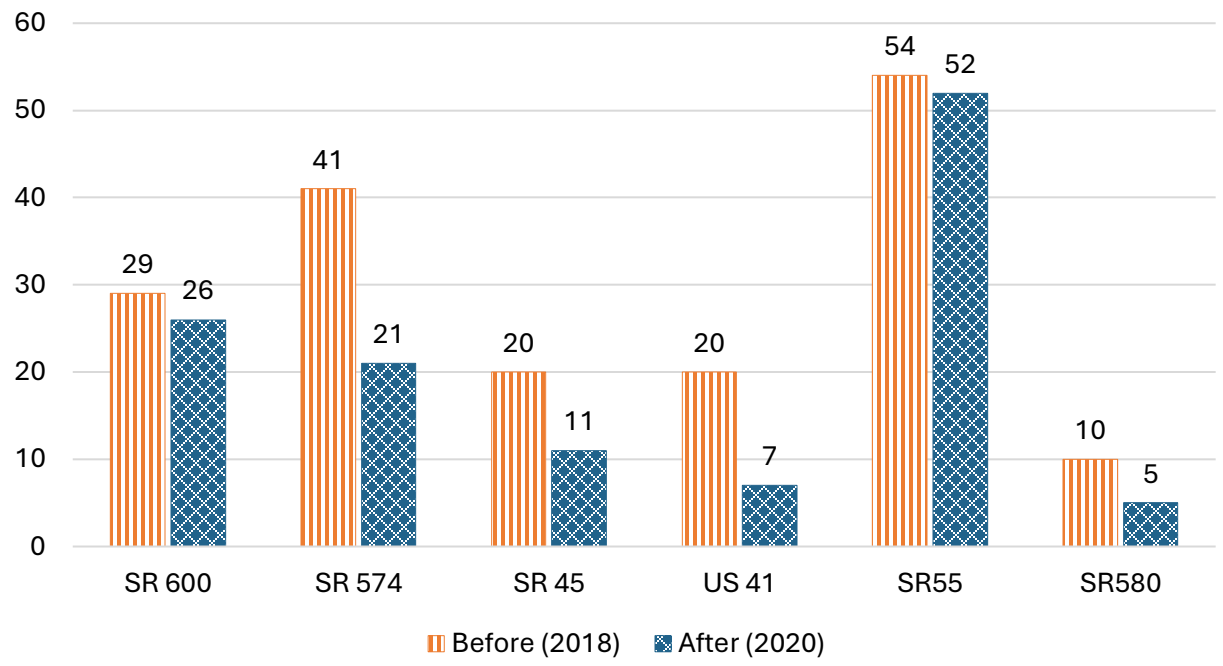


Figure 4-11. Nighttime crash frequencies before (2018) and after (2020) LED lighting retrofits at selected corridors

Overall, the FDOT LED lighting retrofit case demonstrates that improved illumination is a foundational nighttime safety strategy. LED lighting upgrades improved visibility, pedestrian conspicuity, and the ability of drivers to perceive vehicles, pedestrians, roadway geometry, and potential conflict points. The statewide and District 7 findings suggest that lighting improvements can reduce both total nighttime crashes and severe nighttime crashes. The case also shows that lighting enhancements can complement signal timing and detection strategies by creating a safer visual environment for all nighttime operations.

4.5 Case Study 4: THEA CV Pilot Program and Technologies

The fourth case study focuses on CV technologies and their relevance to nighttime safety on the planned Pinellas County SR-60 West Coast Smart Signal Corridor (Concas et al., 2022). Because the SR-60 corridor is a planned smart signal deployment, the case draws on lessons from the THEA CV Pilot Program, which provides regional experience with connected vehicle safety applications, real-time communication, pedestrian detection, and warning systems.

The THEA CV Pilot deployed vehicle-to-infrastructure and vehicle-to-vehicle applications along selected urban arterials, expressway ramps, pedestrian crossings, and transit corridors in the Tampa Bay region. The pilot emphasized real-time safety messaging,

conflict detection, and driver warning applications. These capabilities are highly relevant to nighttime conditions because reduced visibility increases the importance of reliable detection and timely warnings.

A key application was the Pedestrian Collision Warning system. This application was designed to detect pedestrians (Figure 4-12) near crossings and broadcast warning messages (Figure 4-13) to approaching CVs. During deployment, the system was initially equipped with LiDAR sensors. However, the project team later replaced LiDAR with thermal-imaging sensors because LiDAR performance was not sufficiently reliable at night. The thermal sensors provided more stable pedestrian detection in dark or glare-affected environments, making the system better suited for nighttime operations.

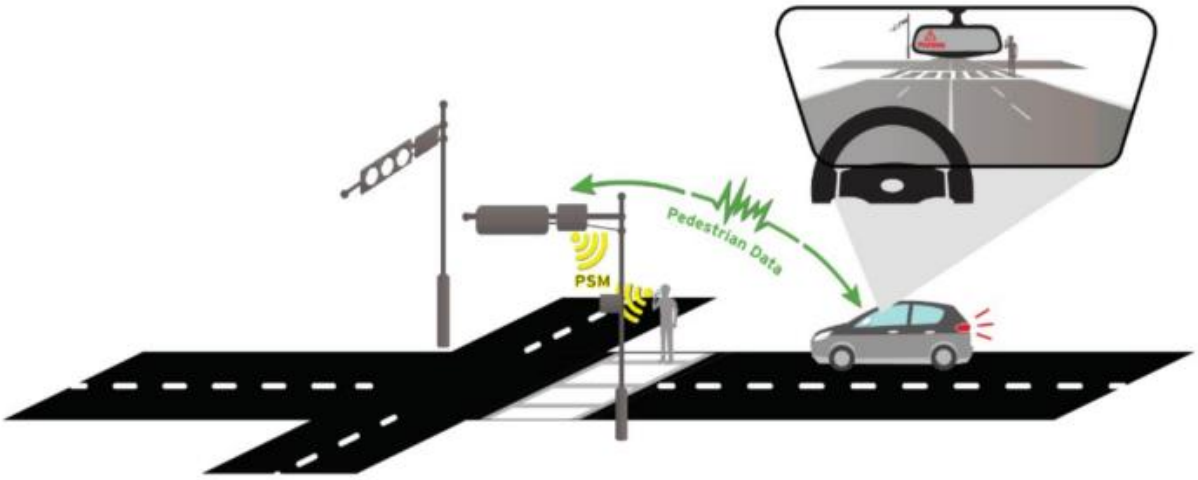


Figure 4-12. Pedestrian collision warning functional overview

Source: Concas et al. (2022)

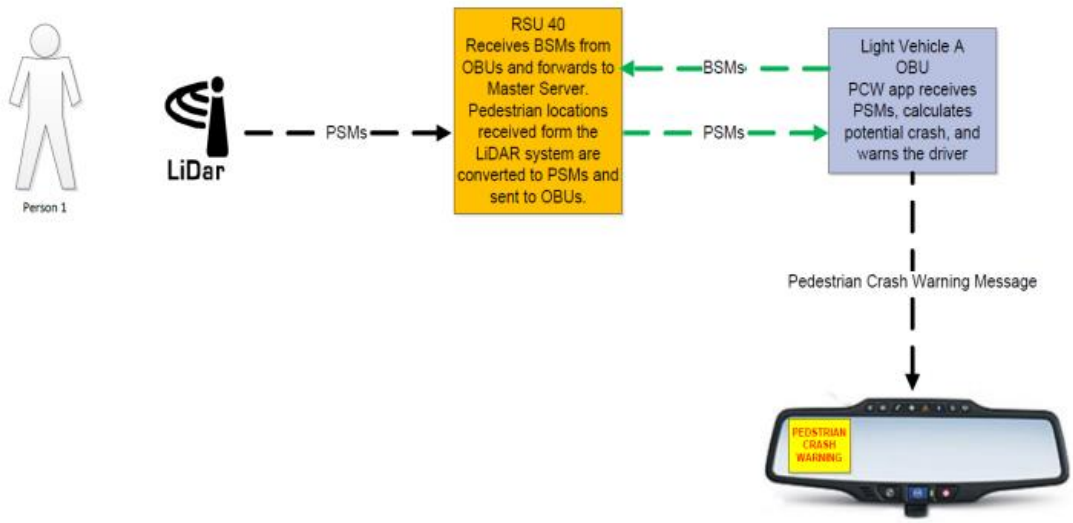


Figure 4-13. Pedestrian collision warning functional flows

Source: Concas et al. (2022)

The CV deployment was supported by a large-scale system architecture that included 49 roadside units and more than 1,000 participating vehicles equipped with aftermarket onboard units. This infrastructure enabled continuous exchange of Basic Safety Messages and supported real-time warning applications. The system was also designed for 24/7 monitoring, allowing performance indicators such as roadside unit uptime, message volumes, application activation frequency, and warning patterns to be tracked continuously.

The Pedestrian Collision Warning application illustrates how CV systems can function as a proactive safety layer. Sensor data were used to identify pedestrian locations, translate those detections into pedestrian safety messages, and transmit warnings to connected vehicles. Similar warning logic was used in other applications such as Forward Collision Warning and Emergency Electronic Brake Light, both of which rely on continuous message exchange to identify potential hazards and issue driver alerts.

The evaluation results most directly related to nighttime operations, were limited but useful. The Wrong-Way Entry application was evaluated during the PM peak period, defined as 3:00 PM to 12:00 AM, which includes nighttime conditions. Within this period, the system correctly identified 14 of 19 potential wrong-way entry events. This result indicates that CV applications can detect high-risk movements during evening and nighttime periods.

The Pedestrian Collision Warning application did not provide night-time-only quantitative safety outcomes. However, the documented transition from LiDAR to thermal imaging is an

important implementation finding. It demonstrates that sensor selection must account for low-light reliability and that nighttime safety applications may require different sensing technologies than daytime applications. Thermal detection improved the system's ability to operate under low illumination and helped address pedestrian visibility limitations at night.

The lessons from THEA's CV Pilot are directly relevant to the SR-60 West Coast Smart Signal Corridor. SR-60 is expected to integrate advanced traffic controllers, enhanced detection, roadside communication infrastructure, pedestrian warning systems, and CV applications. The THEA experience provides a technical foundation for designing this type of corridor, particularly with respect to real-time communication, 24/7 monitoring, sensor reliability, and multimodal safety warning logic.

Overall, this case demonstrates that CV and smart signal technologies can complement traditional signal timing, lighting, and pedestrian safety treatments. These technologies can support nighttime safety by improving detection reliability, generating real-time warnings, and helping drivers respond to hazards that may be difficult to see under low-visibility conditions. At the same time, the case shows that technology-based strategies require careful sensor selection, continuous monitoring, and system refinement to ensure reliable nighttime performance.

4.6 Cross-Case Synthesis

The four case studies demonstrate that nighttime arterial safety can be improved through several complementary strategies. Although each case used a different approach, the strategies can be grouped into four functional categories: nighttime-specific signal timing, enhanced detection and speed management, lighting improvements, and technology-enabled warning systems.

The US-41 and Portland cases show that nighttime safety can be enhanced by signal operations designed specifically for after-dark conditions. Traditional free operation or daytime-style coordination may not adequately address nighttime risks, including excessive speeds, long gaps, low driver expectancy, and pedestrian exposure. On US-41, short-cycle coordination, narrower progression bands, and pedestrian priority treatments reduced high nighttime operating speeds while preserving basic corridor function. In Portland, rest-in-red used an all-red default state to discourage high-speed entries at selected intersections. Both cases demonstrate that signal timing can influence nighttime driver behavior and should be treated as a safety tool rather than only a mobility tool.

Reliable nighttime detection was also a common requirement. US-41 relied on responsive timing and detection to support low-volume operations. Portland's rest-in-red strategy

depended on upstream vehicle detection to determine when to transition from red to green. The CV case demonstrated the importance of sensor reliability for nighttime pedestrian detection, particularly the shift from LiDAR to thermal imaging. These examples show that detection quality directly affects the ability of nighttime strategies to operate as intended.

Lighting improvements emerged as a foundational safety element. The FDOT LED retrofit program showed that improved illumination can reduce nighttime crash frequency and severity. Lighting also supports the effectiveness of other strategies by improving the visibility of pedestrians, vehicles, signal indications, and roadway geometry. Even advanced signal timing or CV systems benefit from adequate illumination because drivers still rely heavily on visual information when responding to roadway conditions.

Technology-enabled warning systems provide an additional layer of nighttime safety. The THEA CV Pilot showed that real-time communication, roadside units, onboard units, pedestrian warnings, and wrong-way entry detection can support safety under low-visibility conditions. These technologies do not replace signal timing, lighting, or roadway design, but they can enhance driver awareness and support faster responses to hazards.

Across all four cases, the strongest approach is not a single countermeasure but a layered strategy. Signal timing revisions can manage speed and improve driver expectancy. Lighting upgrades can improve visibility. Detection systems can make operations more responsive. CV applications can provide real-time alerts. When combined, these strategies address multiple dimensions of nighttime risk and create a more reliable safety environment for drivers, pedestrians, bicyclists, and other roadway users.

The case studies also reveal common implementation barriers. First, many agencies still rely on late-night free or flashing operations, which can sometimes limit the use and evaluation of proactive nighttime timing strategies. Second, legacy field hardware can reduce the effectiveness of nighttime operations because older detectors, cabinets, or lighting systems may produce missed detections, false calls, or unreliable performance. Third, nighttime-specific data are often limited, making it difficult to evaluate crash outcomes, pedestrian activity, speed patterns, and operational changes. Fourth, nighttime implementation and maintenance require staff availability outside normal work hours, which can limit calibration, inspection, and field validation.

Despite these barriers, the cases show that practical improvements are possible. Short-cycle nighttime coordination, Rest-in-red operations at appropriate locations, LED lighting retrofits, modern detection, and CV-ready infrastructure all provide feasible pathways for reducing nighttime crash risk. The key is to match the treatment to the specific nighttime problem at each corridor or intersection.

4.7 Key Findings from the Case Studies

The case studies provide several important findings for nighttime signal timing and arterial safety improvement. First, nighttime signal timing should be developed as a distinct operational strategy rather than a simplified version of daytime timing. The US-41 case showed that replacing free operation with short-cycle coordination can reduce nighttime speeds and improve safety. Portland's rest-in-red strategy demonstrated that nighttime signal displays can be intentionally designed to slow drivers and reduce high-speed intersection entries.

Second, short cycle lengths and narrow progression bands can be effective nighttime speed management tools. During low-volume conditions, long green bands may encourage drivers to travel at excessive speeds through multiple intersections. Shorter cycles and reduced progression opportunities can moderate speeds, increase driver expectancy, and reduce severe crash risk.

Third, pedestrian safety should be integrated into nighttime timing strategies. Leading Pedestrian Intervals, Rest-in-Walk where appropriate, pedestrian detection, and adequate clearance timing can improve pedestrian visibility and reduce conflicts with turning vehicles. These strategies are especially important along commercial corridors, midblock crossing areas, and locations where pedestrian activity continues after dark.

Fourth, lighting is a critical supporting condition for nighttime safety. FDOT's statewide and District 7 LED retrofit results demonstrate that improved illumination can reduce nighttime crashes and severe injuries. Lighting upgrades also support other countermeasures by improving driver perception and increasing the visibility of pedestrians, cyclists, roadway features, and signal indications.

Fifth, detection reliability is essential. Rest-in-red, adaptive nighttime timing, pedestrian warning systems, and CV applications all depend on accurate detection. Nighttime conditions can challenge some technologies, so agencies should carefully evaluate sensor type, placement, range, calibration, and maintenance needs.

Sixth, CV and smart signal technologies can provide additional safety benefits, particularly through real-time warnings and enhanced hazard detection. The THEA CV Pilot showed that wrong-way entry detection and pedestrian warning systems can operate during evening and nighttime conditions, but it also highlighted the need for low-light-optimized sensors such as thermal imaging.

Finally, the case studies suggest that the most effective nighttime safety approach is layered and context sensitive. Agencies should combine operational strategies, lighting

improvements, reliable detection, pedestrian-focused treatments, and emerging technologies based on corridor-specific crash patterns, traffic conditions, and user needs. This integrated approach provides the strongest foundation for improving nighttime arterial safety and supports the development of practical guidance for FDOT and local agencies.

5 Before-and-After and Field Evaluation Approaches and Results

This chapter presents the results of the field evaluations and before-and-after analyses conducted on two Florida corridors. The evaluation of nighttime coordinated traffic signal operations, including study site characteristics, driving behavior analysis, and subjective driver assessments, was conducted along the US-41 corridor. The evaluation of nighttime pedestrian signal strategies, including crash analysis and field study results, was conducted along the Fletcher Avenue corridor. The chapter concludes with a summary of the key findings.

5.1 Evaluation Framework

Two corridors in Florida were evaluated to assess the effectiveness of the implemented nighttime traffic signal retiming strategies. These sites were selected based on documented safety concerns, implementation of innovative treatments, and suitability for comparative analysis:

- US-41 – Implementation of nighttime signal retiming strategies, featuring shortened cycle lengths and coordinated signal progression to manage vehicle speeds and enhance safety.
- Fletcher Avenue – Pedestrian-related signal treatments, including RRFBs and a PS.

The evaluation consisted of the following key components:

- **Site Selection and Field Visits:** Researchers conducted site visits to the US-41 and Fletcher Avenue corridors to verify treatment conditions, identify comparable control sites, and finalize the data collection and analysis plan for evaluating nighttime traffic signal strategies.
- **Field Data Collection:** Safety-related performance measures, including speed and driver behavior indicators, were collected at the treatment and control sites along the US-41 corridor. For the Fletcher Avenue corridor, before-and-after crash and field data were analyzed to assess the safety and operational impacts of nighttime pedestrian signal improvements
- **Cross-Sectional Analysis for the US-41 Corridors:** Safety measures at treatment sites were compared with those at control sites without the treatment to assess the effectiveness of nighttime signal timing and operational strategies in reducing speeding and unsafe driving behavior.

- **Before-and-After Crash Analysis for the Fletcher Ave Corridor:** For Fletcher Avenue, historical pedestrian and bicycle crash data were analyzed for three years before implementation, three years immediately after implementation, and three recent years following installation of RRFBs and a PS. This allowed for assessment of short-term and sustained safety impacts.
- **Statistical Analyses:** Statistical analyses were conducted to assess the effectiveness of the implemented strategies in reducing nighttime crashes and speeding and to determine the statistical significance of the observed changes.
- **Key Findings Documentation:** Key findings, strategy effectiveness, implementation successes, and lessons learned were documented to inform and support future implementation of nighttime traffic signal timing strategies.

5.2 Evaluation of US 41 Coordinated Nighttime Signal Operations

This section presents an evaluation of the effectiveness of the nighttime signal retiming strategies implemented on US-41, including data collection and analysis, and key findings. The study corridor extends from US-41 at Tallevast Road/Gaines Avenue to US-41 at 46th Avenue Drive W/Orlando Avenue in Manatee County. The corridor is approximately 3.7 miles long and includes 11 signalized intersections (Table 5-1) within the study limits. US-41 functions as a multilane arterial corridor and was evaluated as a treatment site for nighttime traffic signal timing strategies. Figure 5-1 presents the location of the study corridor.

Table 5-1. Signalized Intersections along Study Corridor US-41

No.	Intersection	AADT	Speed Limit (mph)	Lanes per Direction
1	US-41 at Tallevast Road/Gaines Avenue	45000	45	3
2	US-41 at Whitfield Avenue	45000	45	3
3	US-41 at Pearl Avenue	45000	45	3
4	US-41 at Bay Drive/69th Avenue W	45000	45	3
5	US-41 at Florida Boulevard	45000	45	3
6	US-41 at Bayshore Gardens Parkway	45000	45	3
7	US-41 at 60th Avenue W	45500	45	3
8	US-41 at 57th Avenue W	45500	45	3
9	US-41 at SR-70 (53rd Avenue W)	45500	45	3
10	US-41 at 49th Avenue Drive W	46500	45	3
11	US-41 at 46th Avenue Drive W/Orlando Avenue	46500	45	3

The treatment evaluated along the US-41 corridor consisted of a nighttime signal retiming strategy based on coordinated signal operation across the study section. Consistent with

the project methodology, the strategy emphasized shortened cycle lengths and coordinated signal progression to better manage vehicle speeds and improve nighttime safety. The coordinated timing plans implemented by FDOT District 1 included revisions to cycle lengths, offsets, and splits at all 11 intersections. The time-of-day plans indicate that shorter cycle lengths were implemented during late-night periods compared to daytime operations. These timing characteristics are consistent with a corridor-level nighttime retiming strategy designed to improve traffic progression under lower nighttime traffic volumes while also helping to reduce the likelihood of speeding and other unsafe driving behaviors.

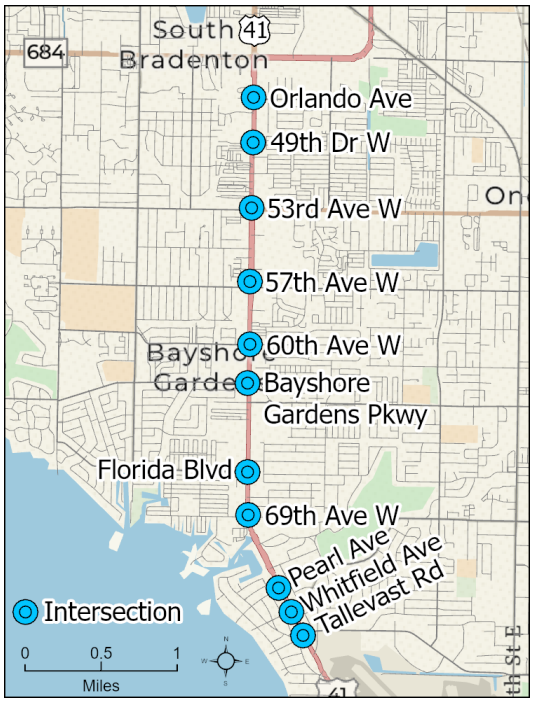


Figure 5-1. US-41 corridor (treated site)

5.2.1 Control Sites

A comparison corridor on US-41, shown in Figure 5-2 and detailed in Table 5-2, was chosen as a control site. This corridor includes nine signalized intersections, with geometry and traffic patterns similar to the study corridor. At night, signals operating under free operation may have varying cycle lengths. While this operation can be efficient, it may encourage traffic on the major street to speed up when drivers see green signals several signals ahead. At the same time, side-street traffic generally does not have to wait long for a green signal. However, when side-street traffic is detected and receives a green signal, vehicles traveling on the major street may be required to brake abruptly.

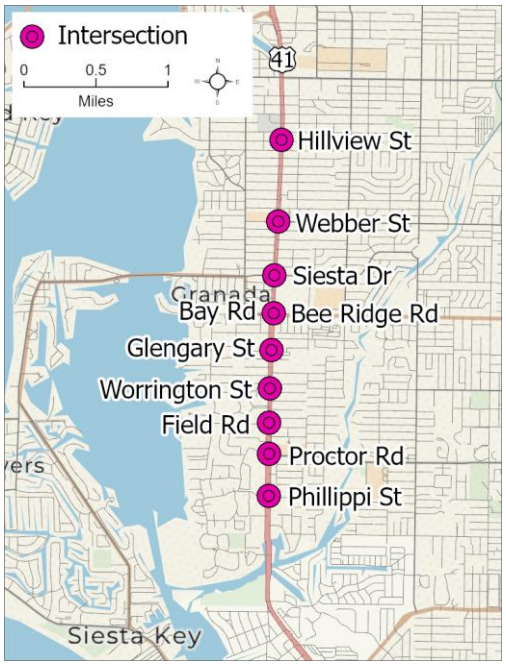


Figure 5-2. US-41 corridor (control site)

Table 5-2. Signalized Intersections along Study Corridor US-41 (Control Site)

No.	Intersection	AADT	Speed Limit (mph)	Lanes
1	US-41 at Hillview St	58500	45	3
2	US-41 at Webber St	52000	45	3
3	US-41 at Siesta Dr	52000	45	3
4	US-41 at Bay Rd/Bee Ridge Rd	51000	45	3
5	US-41 at Glengary St	51000	45	3
6	US-41 at Worrington St	51000	45	3
7	US-41 at Field Rd	51000	45	3
8	US-41 at Proctor Rd	49000	45	3
9	US-41 at Phillippi St	49000	45	3

5.2.2 Driving Behaviors at Intersections

Data Collection

Two types of data were collected for the US-41 corridor evaluation: (1) driver behavior data at intersections and (2) survey data from subjective evaluations of traffic signal progression with short cycle lengths as a nighttime speed management strategy. Since the before-and-after crash data had already been evaluated by FDOT District 1 and documented in Chapter 4, those results were not included in this chapter. For the intersection-level driver behavior analysis, two intersections along the US-41 corridor were selected as treated sites, and two additional intersections were selected as control sites for comparison. The treated intersections were US-41 at 60th Avenue and US-41 at 57th

Avenue, while the control intersections were SR-70 at 37th Street and US-41 at Webber Street. Field observations were conducted in person during a three-hour nighttime period from 9:00 PM to 12:00 AM. During the observation period, the following driver behavior events were recorded: passing on yellow, passing on red, hard braking, and stopping after the stop bar. These measures were selected to capture driver responses associated with potential conflicts and late decision-making at signalized intersections under nighttime conditions. Examples of observed behaviors are shown in Figure 5-3 and Figure 5-4.

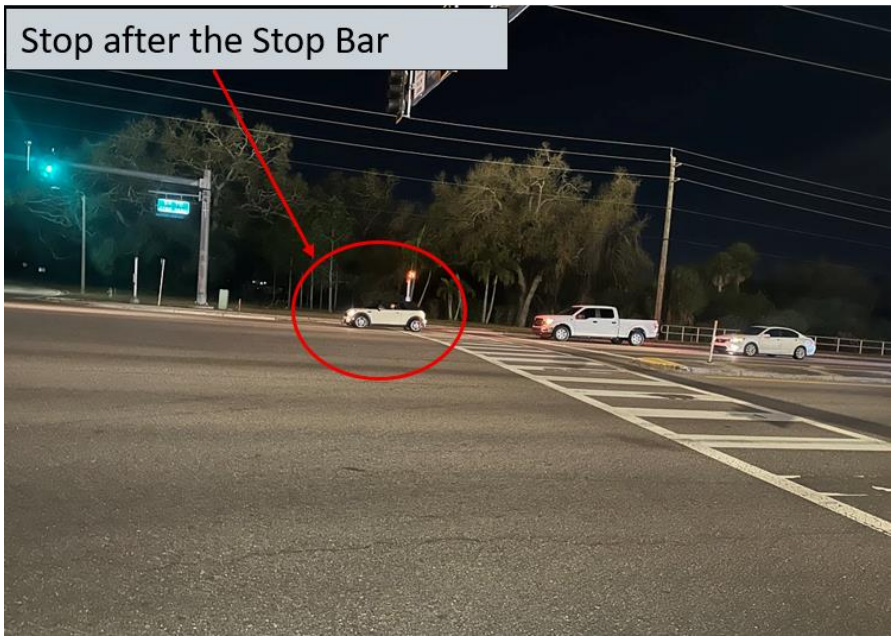


Figure 5-3. Example of a vehicle stopping after the stop bar

Figure 5-4. Example of a vehicle passing on a yellow light

Data Analysis

Table 5-3 summarizes the observed driver behavior at the treated and control intersections along the US-41 corridor.

Table 5-3. Comparison of Driver Behavior at Treated and Control Intersections

Sites	Intersection	Passing on Yellow	Passing on Red	Hard Braking	Stopping after Stop Bar
Group 1	SR-70 @ 37th St (Control)	5.0% (=39/777)	0.6% (=5/777)	0.1% (=1/777)	1.7% (=13/777)
	US-41 @ 60th Ave (Treated)	3.9% (=144/3657)	0.7% (=26/3657)	0.1% (=4/3657)	1.9% (=69/3657)
	Fisher's Exact p-value	0.17	1.00	1.00	0.77
	Statistically Significant at α = 0.10	No	No	No	No
Group 2	US-41 @ Webber St (Control)	4.2% (=16/386)	0.0% (=0/386)	1.3% (=5/386)	6.2% (=24/386)
	US-41 @ 57th Ave (Treated)	2.6% (=8/306)	0.0% (=0/306)	0.0% (=0/306)	2.0% (=6/306)
	Fisher's Exact p-value	0.30	1.00	0.07	0.01
	Statistically Significant at α = 0.10	No	No	Yes	Yes
Combined Treated and Control Sites	Control	4.7% (=55/1163)	0.4% (=5/1163)	0.5% (=6/1163)	3.2% (=37/1163)
	Treated	3.8% (=152/3963)	0.7% (=26/3963)	0.1% (=4/3963)	1.9% (=75/3963)
	Fisher's Exact p-value	0.18	0.52	0.01	0.01
	Statistically Significant at α = 0.10	No	No	Yes	Yes

Note: For each category, the rate was calculated as the number of observations of the specific behavior divided by the total number of vehicles passing through the intersection.

- For the comparison between US-41 at 60th Avenue and SR-70 at 37th Street, the treated site showed lower rates of passing on yellow (3.9% vs. 5.0%) and similar rates of hard braking (0.1% vs. 0.1%), but slightly higher rates of passing on red (0.7% vs. 0.6%) and stopping after the stop bar (1.9% vs. 1.7%).
- Fisher's exact tests indicated that none of the observed differences between US-41 at 60th Avenue and SR-70 at 37th Street were statistically significant at α = 0.10.

- For the comparison between US-41 at 57th Avenue and US-41 at Webber Street, the treated site showed lower rates of passing on yellow (2.6% vs. 4.2%), hard braking (0.0% vs. 1.3%), and stopping after the stop bar (2.0% vs. 6.2%), while both sites recorded 0.0% passing on red.
- Fisher's exact tests indicated that the differences in hard braking and stopping after the stop bar between US-41 at 57th Avenue and US-41 at Webber Street were statistically significant at α = 0.10, whereas the differences in passing on yellow and passing on red were not statistically significant.
- When the treated and control intersections were combined, the treated sites continued to exhibit lower rates of hard braking (0.1% vs. 0.5%) and stopping after the stop bar (1.9% vs. 3.2%), and both differences remained statistically significant at α = 0.10.
- Differences in passing on yellow and passing on red between the combined treated and control intersections were not statistically significant at α = 0.10.

Figure 5-5 illustrates that coordinated nighttime signals, compared to free operations, reduce the rates of hard-braking and stopping after the stop bar by 80% (=[5%-1%]/5%) and 41% (=[3.2%-1.9%]/3.2%), respectively. These behaviors indicate drivers' intention to stop at a red signal and are associated with higher collision risk. Coordinated signal timing on US-41 significantly lowers these risky actions.

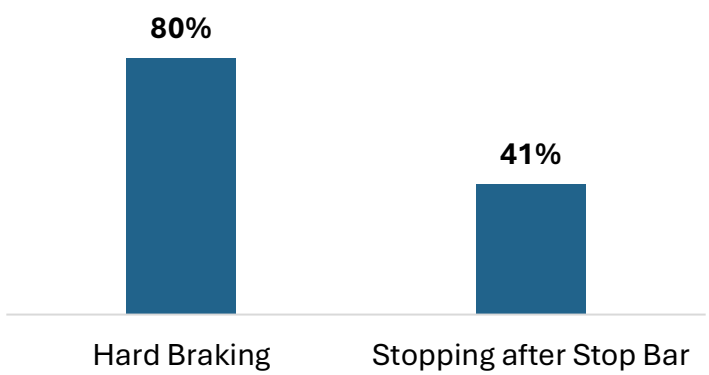


Figure 5-5. Reduction in hard-braking events and post-stop-bar stopping under coordinated nighttime signal operations relative to free operation

Conversely, passing through the intersection at the onset of a red or yellow signal reflects drivers' intent to proceed despite the signal change. The implementation of coordinated nighttime signals did not yield a statistically significant difference in these behaviors compared to uncoordinated operation.

5.2.3 Subjective Evaluation of Coordinated Signal Approaches at Night

Data Collection

In addition to conducting intersection-level driver behavior observations, a survey was administered to gather drivers' perspectives on speed management along the US-41 treatment corridor under nighttime signal timing conditions.

A camera was mounted on the windshield of a study vehicle, which was then driven multiple times along both the treatment and control corridors while maintaining the prevailing traffic speed. The collected footage was segmented into 8- to 10-minute clips to accurately identify the signal status encountered at each intersection.

The downstream signals can affect driving behavior. When drivers see a red signal ahead while traveling through an upstream intersection (Figure 5-6), they often slow down early and approach the next intersection at a reduced speed.

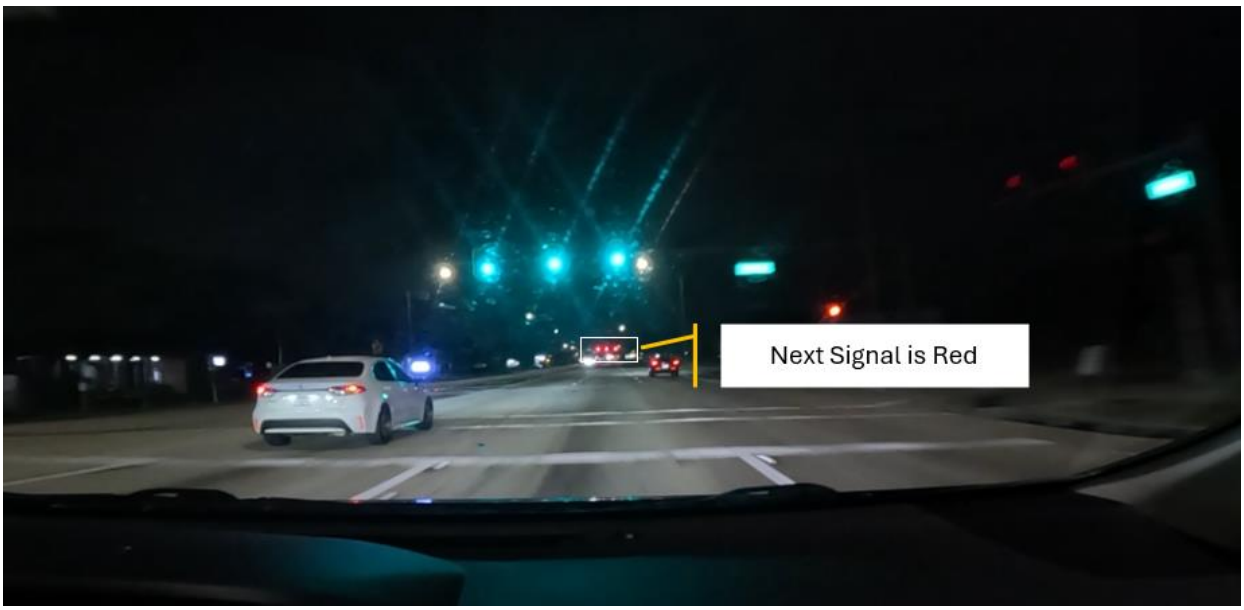


Figure 5-6. Example of a red signal at the downstream intersection

Conversely, when the downstream signal is observed as green (Figure 5-7), drivers tend to maintain a relatively high speed or accelerate to continue through the intersection without stopping. Similarly, if the next signal is not visible (Figure 5-8), drivers may be more likely to maintain relatively higher speeds due to the lack of visual cues indicating the need to slow down.

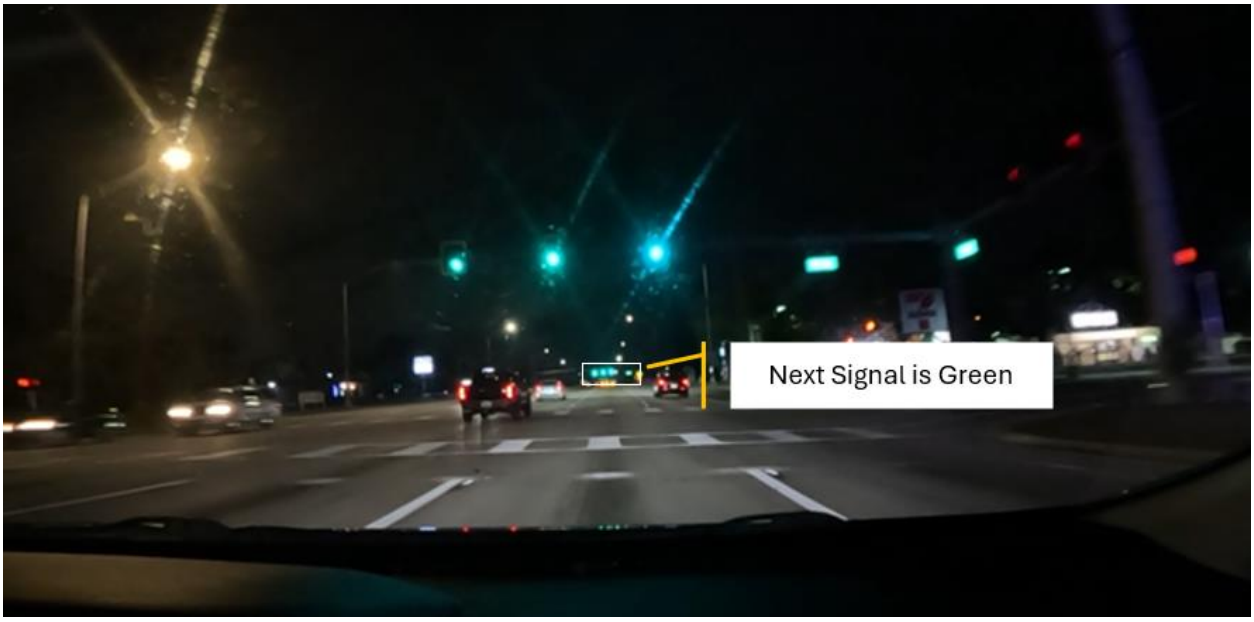


Figure 5-7. Example of a green signal at the downstream intersection

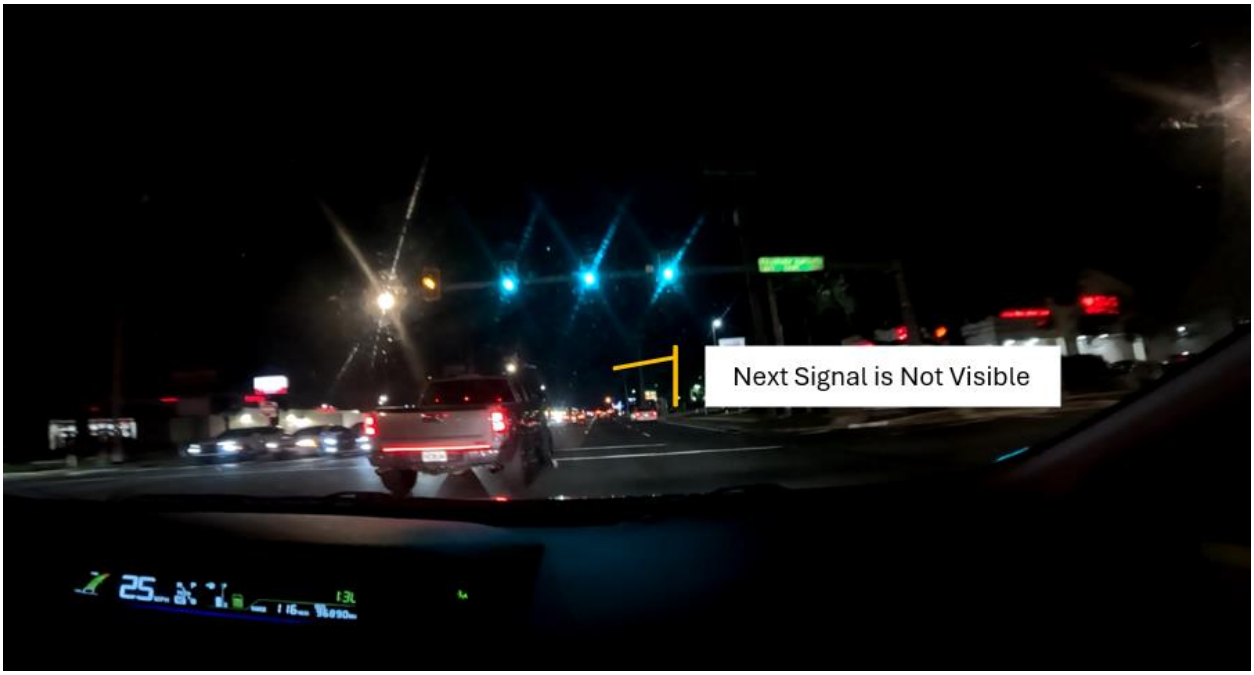


Figure 5-8. Example where the next signal is not visible

Data Analysis

Question 1

Question 1 was designed to examine drivers' responses to a downstream signal displaying red (Figure 5-6). Figure 5-9 compares the response distributions between the treated and control corridors. Participants in the treated corridor were substantially more likely to report that a downstream red signal would "often" discourage them from speeding up (61%) compared to participants in the control corridor (7%). In contrast, the majority of participants in the control corridor selected "rarely" (71%), whereas only 18% of participants in the treated corridor selected this response. Additionally, 21% of participants in the treated corridor reported "always," compared to 11% in the control corridor.

These results suggest that the treatment (coordinated traffic signal and short cycle length at night) increased the opportunities and drivers' awareness of downstream traffic conditions and improved the likelihood that drivers would moderate their speed in response to a red signal ahead.

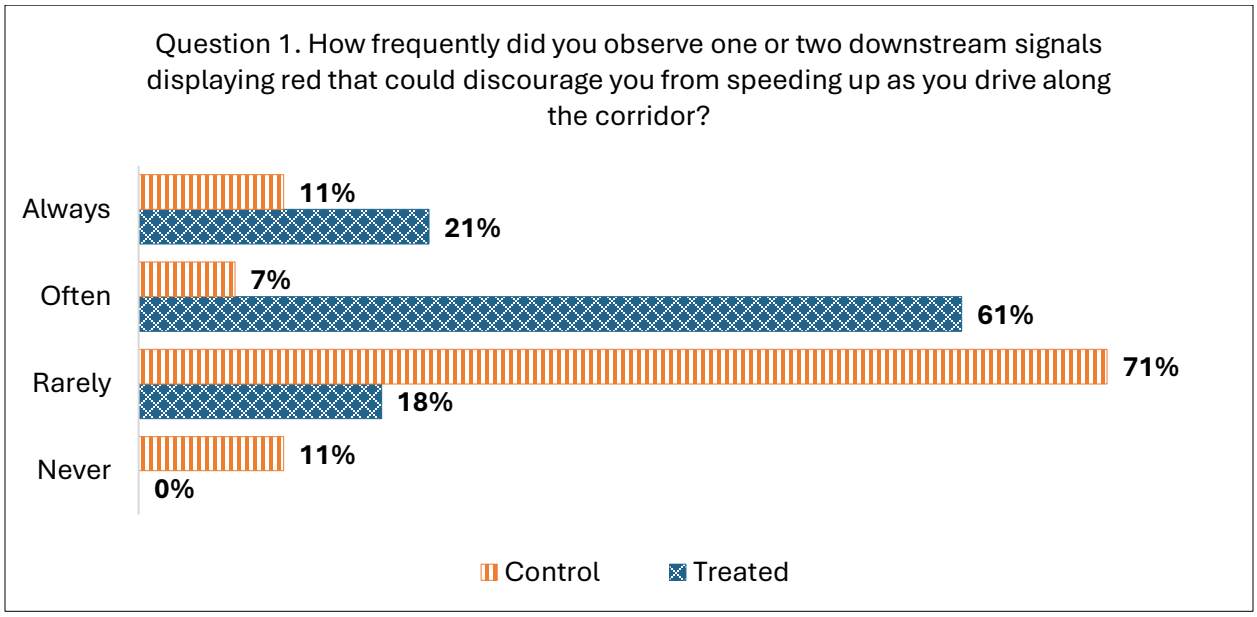


Figure 5-9. Participants' responses to Question 1

Question 2

Question 2 was designed to identify the factors that influenced participants' decisions not to speed up when they selected "Always" or "Often" in Question 1. Figure 5-10 compares the selected factors between the treated and control corridors. The most frequently

selected factor in both corridors was the expectation of stopping at upcoming signals when speeding up, reported by 87% of participants in the treated corridor and 80% in the control corridor.

A notable difference was observed for the belief that maintaining or lowering speed would result in better signal progression. Only 26% of participants in the treated corridor selected this factor, compared to 100% of participants in the control corridor. Participants in the control corridor were also more likely to report that vehicles ahead influenced their decision not to speed up (40%) compared to participants in the treated corridor (13%). No participants in either corridor selected difficulty changing lanes due to surrounding traffic. Additionally, "Other" factors were reported more frequently in the control corridor (20%) than in the treated corridor (4%).

Overall, the results suggest that drivers in the treated corridor were more consistently influenced by the expectation of encountering red signals ahead, whereas participants in the control corridor appeared to rely more on perceived signal progression benefits and surrounding traffic conditions when deciding not to speed up.

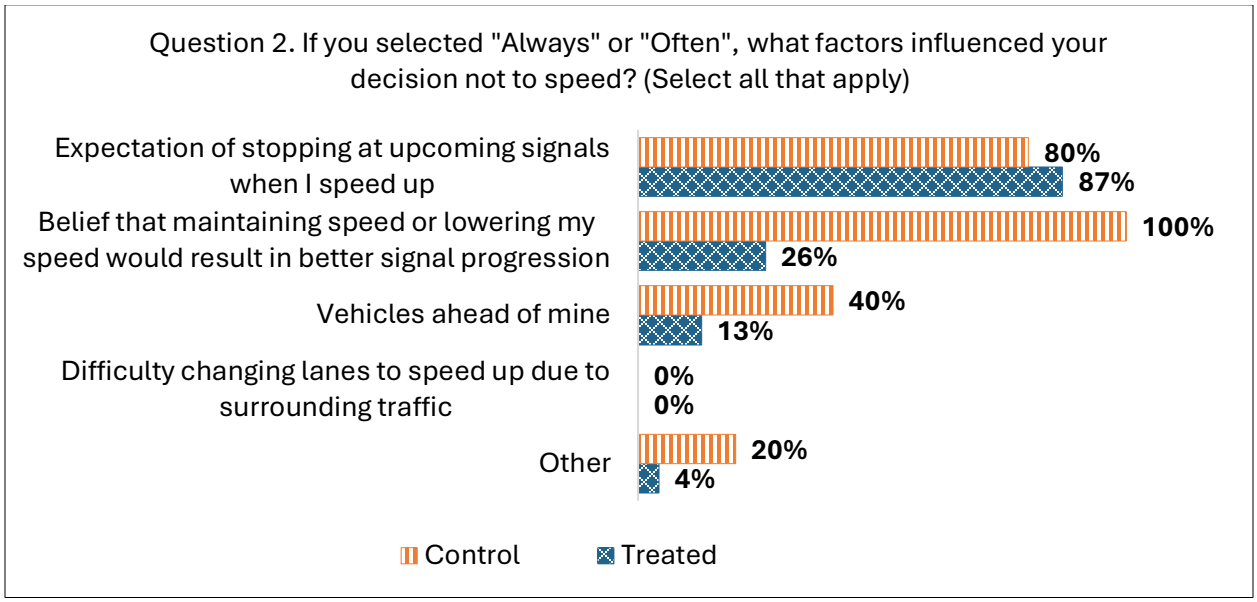


Figure 5-10. Participants' responses to Question 2

Question 3

Question 3 was designed to examine how participants responded when they frequently observed downstream green signals, specifically those who selected "Rarely" or "Never" in Question 1. Figure 5-11 compares the reported behavioral influences between the treated and control corridors.

The majority of participants in both corridors indicated that they were more likely to speed up to pass the next signal before it turned red, with 100% of participants in the control corridor and 80% in the treated corridor selecting this response. A substantial difference was observed regarding surrounding traffic conditions. All participants in the treated corridor (100%) reported that faster surrounding traffic enabled them to speed up, compared to only 30% of participants in the control corridor. Additionally, 20% of participants in the treated corridor indicated that they considered speeding up but were prevented by traffic conditions, whereas no participants in the control corridor selected this response.

No participants in either corridor selected "I was not influenced to speed up" or "Other." Overall, the results suggest that when downstream green signals were frequently visible, participants in both corridors were more inclined to accelerate in an attempt to clear the next intersection. However, drivers in the treated corridor appeared to be more influenced by surrounding traffic conditions and dynamics when making speeding decisions.

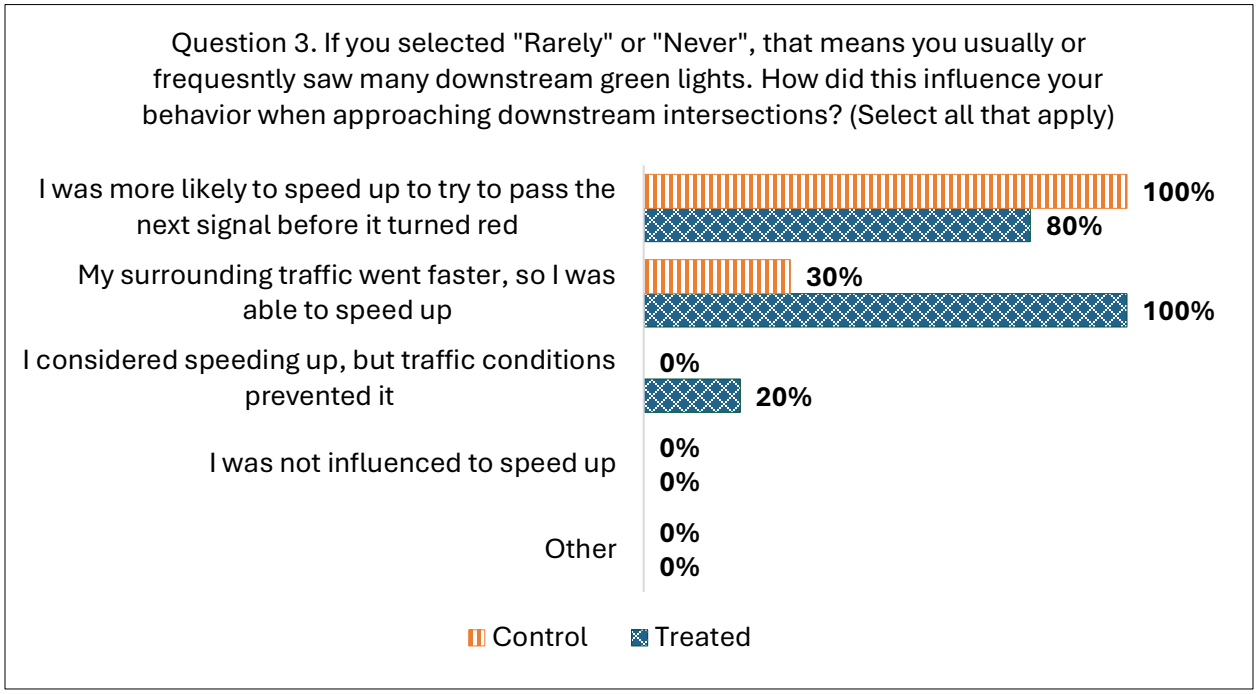


Figure 5-11. Participants' responses to Question 3

5.3 Evaluation of Fletcher Avenue Pedestrian Treatments

This section presents the evaluation of the effectiveness of nighttime pedestrian crossing treatments installed along arterial corridors. It includes crash data analysis, field observations, and key findings related to the effects of pedestrian signals on nighttime pedestrian safety.

5.3.1 Study Sites

In 2014, six pedestrian crossing treatments were installed along the Fletcher Avenue corridor, between Nebraska Avenue and Bruce B. Downs Boulevard. These treatments consisted of five Rectangular Rapid Flashing Beacons (RRFBs) and one Pedestrian Signal (PS) at midblock, as illustrated in Figure 5-12.

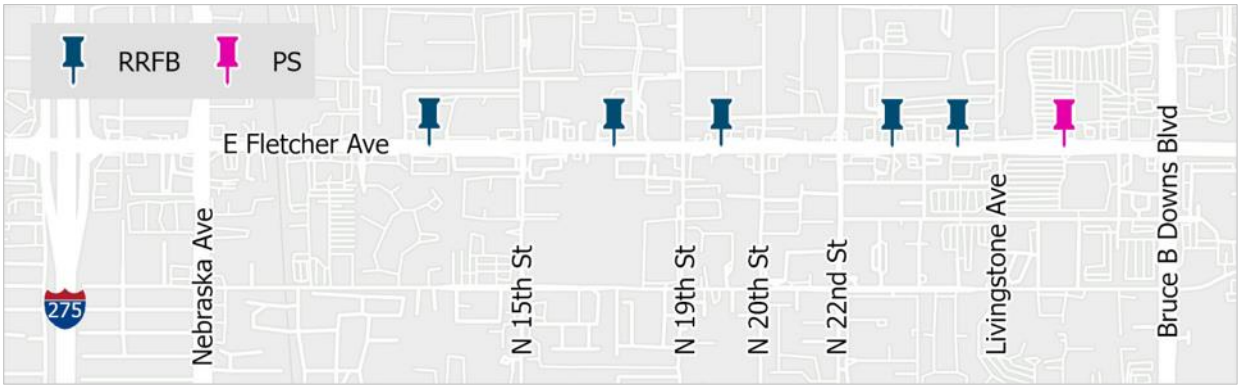


Figure 5-12. RRFB and PS at midblock locations on the Fletcher Ave corridor

This project task evaluated the nighttime effectiveness of the six pedestrian crossing treatments using both field observations and crash data analysis. The evaluation considered the safety of both pedestrians and bicyclists. Figure 5-13 presents images of the two types of pedestrian crossing signals installed along the Fletcher Avenue corridor. Photo 1 shows a Google Street View image of the PS at midblock located west of Interstate Bruce B Downs Blvd, facing west. Photo 2 shows a Google Street View image of an RRFB located west of N 15th Street, also facing west. The operations of the two treatments are given below:

- RRFB: RRFB is a pedestrian-activated warning device installed at uncontrolled crossings. When a pedestrian presses the push button, a pair of high-intensity amber LED beacons mounted on both sides of the crosswalk sign flash in a rapid, irregular pattern to alert approaching drivers. The beacons continue flashing while pedestrians are in the crosswalk, prompting drivers to yield. Unlike a full traffic signal, the RRFB does not display a red stop indication; it functions as a conspicuity enhancement that increases driver awareness and yielding behavior, particularly under low-light and nighttime conditions.
- PS: PS is a pedestrian-activated, full traffic control device installed at a mid-block crossing location. When a pedestrian presses the push button, the signal displays a red indication to approaching vehicles, requiring them to stop, while a WALK indication authorizes the pedestrian to cross. Unlike the RRFB, the PS legally

compels drivers to stop rather than merely encouraging yielding, providing a higher level of protection for crossing pedestrians.

Figure 5-13. Image of a PS at midblock in picture 1 and an RRFB in picture 2 on Fletcher Ave corridor

5.3.2 Crash Analysis

Crash data were collected using Signal Four Analytics. The analysis included a three-year period before the pedestrian signal installation (2011–2013) and two three-year periods after installation: 2015–2017 and 2023–2025. Table 5-4 summarizes pedestrian and bicycle crashes along the Fletcher Avenue corridor for the before period (2011–2013) and two after periods (2015–2017 and 2023–2025), with an emphasis on nighttime crash occurrences.

During the **Before Period**, a total of 18 pedestrian crashes were recorded, 12 of which occurred at night, representing 66.7% of all pedestrian crashes. Bicycle crashes totaled nine, with five occurring at night, accounting for 55.6%. These results indicate that a significant proportion of both pedestrian and bicycle crashes occurred during nighttime conditions prior to the installation of the pedestrian crossing treatments.

In **After Period 1** (2015–2017), the total number of pedestrian crashes remained at 18; however, nighttime pedestrian crashes decreased to nine, lowering the nighttime proportion to 50.0%. Bicycle crashes increased slightly to 12, but nighttime bicycle crashes dropped substantially to two, representing just 16.7%. These results suggest a significant reduction in nighttime bicycle crashes and a moderate decrease in the proportion of nighttime pedestrian crashes following the installation of the pedestrian crossing treatments.

In **After Period 2** (2023–2025), total pedestrian crashes decreased substantially to six, with three occurring at night, maintaining a nighttime proportion of 50.0%. Bicycle crashes declined further to three, with no nighttime bicycle crashes reported, indicating a complete elimination of nighttime bicycle crashes along the corridor.

Table 5-4. Nighttime Pedestrian and Bicycle Crashes Before and After Installation of RRFBs and PS at midblock on Fletcher Ave Corridor

Time	Pedestrian Crashes			Bicycle Crashes		
	All	Nighttime	Nighttime (%)	All	Nighttime	Nighttime (%)
2011 Before Period	2	1	50.0	2	2	100.0
2012 Before Period	9	7	77.8	4	2	50.0
2013Before Period	7	4	57.1	3	1	33.3
Total	**18**	**12**	**66.7**	**9**	**5**	**55.6**
2015 After Period 1	5	2	40.0	5	1	20.0
2016 After Period 1	8	4	50.0	5	1	20.0
2017 After Period 1	5	3	60.0	2	0	0
Total	**18**	**9**	**50.0**	**12**	**2**	**16.7**
2023 After Period 2	0	0	N/A	1	0	0
2024 After Period 2	3	2	66.7	0	0	N/A
2025 After Period 2	3	1	33.3	2	0	0
Total	**6**	**3**	**50.0**	**3**	**0**	**0**

The spatial distribution of nighttime pedestrian and bicycle crashes is shown in Figure 5-14. During the before period, pedestrian crashes were frequent and widely distributed, with nighttime crashes occurring throughout much of the corridor. Following the 2014 installation of RRFBs and the PS, both the number and spatial density of nighttime crashes decreased. Only a few nighttime crashes were observed in After Period 2, concentrated in limited sections of the corridor.

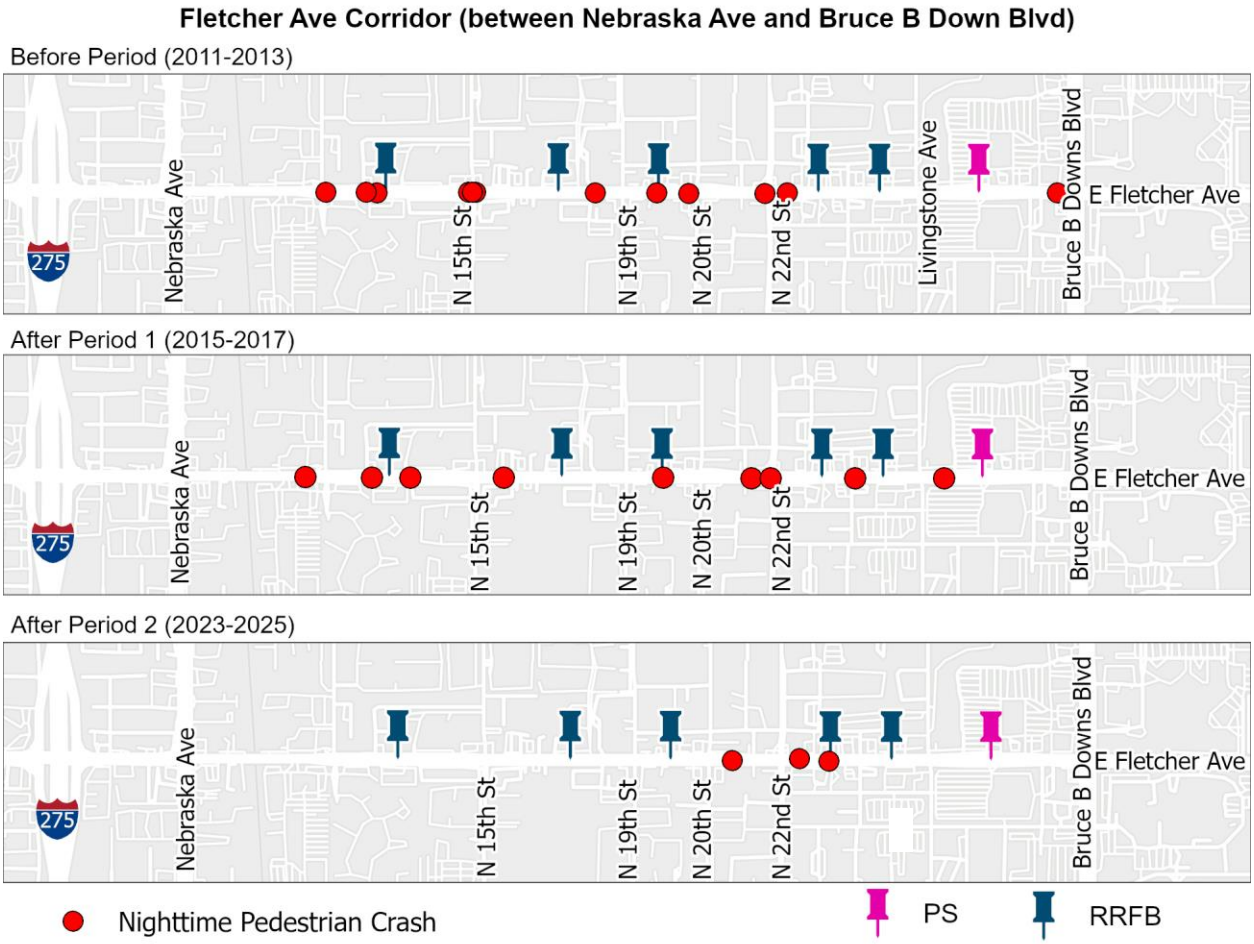


Figure 5-14. Spatial distribution of nighttime crashes before and after installation of RRFBs and PS at midblock on Fletcher Avenue corridor

The severity analysis of nighttime pedestrian and bicycle crashes is presented in Figure 5-15 and Table 5-5. For all pedestrian crashes (daytime and nighttime) during the before period, 11 were non-severe crashes (61%), and seven were severe crashes (39%). The same distribution was observed in After Period 1, with 11 non-severe crashes (61%) and seven severe crashes (39%). During After Period 2, total pedestrian crashes decreased to six, comprising four non-severe crashes (67%) and two severe crashes (33%), indicating an overall reduction in both the number and severity of crashes in After Period 2.

For nighttime pedestrian crashes, the before period included six non-severe (50%) and six severe crashes (50%). During After Period 1, nighttime crashes decreased to four non-severe crashes (44%) and five severe crashes (56%). Nighttime crashes were further reduced to one non-severe crash (50%) and one severe crash (50%) in After Period 2, reflecting a substantial decline in the frequency of nighttime pedestrian crashes.

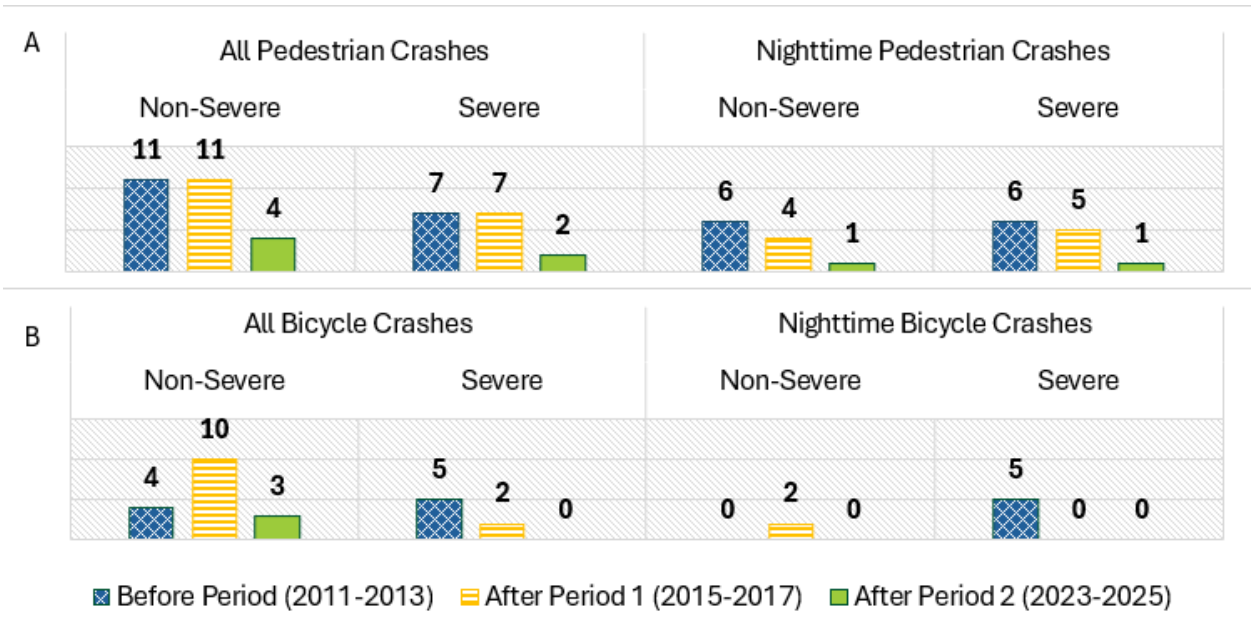


Figure 5-15. Severity of pedestrian (A) and bicycle (B) crashes before and after installation of RRFBs and PS at midblock on Fletcher Ave corridor

For all bicycle crashes (daytime and nighttime), there were four non-severe crashes (44%) and five severe crashes (56%) recorded during the before period. During After Period 1, crash severity shifted toward lower levels, with 10 non-severe crashes (83%) and two severe crashes (17%). During After Period 2, all three bicycle crashes were non-severe crashes (100%), with no severe crashes reported.

Focusing specifically on nighttime bicycle crashes, all five crashes in the before period were severe crashes (100%). During After Period 1, two nighttime crashes occurred, both recorded as non-severe crashes (100%). During After Period 2, no nighttime bicycle crashes were reported, indicating a complete elimination of severe nighttime bicycle crashes along the corridor (Figure 5-15 B).

Table 5-5. Severity of Nighttime Pedestrian and Bicycle Crashes Before and After Installation of RRFBs and PS at midblock on Fletcher Ave Corridor

Crash Type	Crashes	Time	Before Period		After Period 1		After Period 2	
Pedestrian Crashes	All	Non-severe	11	61%	11	61%	4	67%
		Severe	7	39%	7	39%	2	33%
	Nighttime	Non-severe	6	50%	4	44%	1	50%
		Severe	6	50%	5	56%	1	50%
Bicycle Crashes	All	Non-severe	4	44%	10	83%	3	100%
		Severe	5	56%	2	17%	0	0%
	Nighttime	Non-severe	0	0%	2	100%	0	0%
		Severe	5	100%	0	0%	0	0%

The before-and-after analysis indicates a reduction in nighttime pedestrian crashes and a notable decrease in nighttime bicycle crashes, particularly during After Period 2. These findings suggest that the implemented pedestrian crossing treatments, including RRFBs and PS, contributed to improved nighttime safety for vulnerable road users along the Fletcher Avenue corridor.

Overall, both nighttime pedestrian and bicycle crashes decreased across the study periods, with clear reductions in crash frequency and severity. Nighttime pedestrian crashes declined from 12 in the before period to nine in After Period 1 and two in After Period 2. Nighttime bicycle crashes decreased from five in the before period, all of which were severe, to two in After Period 1, both non-severe, and to zero in After Period 2. These results indicate reductions in both the number and severity of nighttime crashes, with severe bicycle crashes eliminated in the after periods.

In addition to the installation of five RRFBs and one PS, several other countermeasures were implemented during the same period, including:

- Raised pedestrian refuge islands and traffic separators
- LED lighting at crossings
- New and repaired sidewalks with ADA-compliant ramp upgrades
- Addition of bike lanes on both sides, creating a 3-mile corridor
- Reduction of the speed limit from 45 mph to 35 mph
- Public education campaigns and high-visibility enforcement

While the RRFBs and PS at midblock likely played a key role in improving pedestrian safety, the observed reductions in crashes may also be influenced by these additional countermeasures. Periods 1 and 2 included all implemented countermeasures.

5.3.3 Field Study

The field study was conducted to evaluate pedestrian crossing behavior and pedestrian-vehicle interactions at nighttime pedestrian signal installations along the Fletcher Avenue corridor in Tampa, Florida. The study evaluated two treated crossing locations: one equipped with a PS ad midblock and one equipped with a RRFB.

Field Data Collection

Field data collection was conducted along the Fletcher Avenue corridor to evaluate pedestrian crossing behavior and driver yielding behavior under nighttime conditions. The study included two treated locations on Fletcher Avenue. Field data collection was conducted during the evening period from 6:30 PM to 8:30 PM. At the treated sites,

observations included crosswalk use, push-button activation, signal compliance, driver yielding behavior, and near misses.

Table 5-6 presents the observed safety behaviors in the field study of pedestrian signals at night. Examples of field data collection are shown in Figure 5-16 to Figure 5-18.

Table 5-6. Observed Safety Behaviors in Fletcher Ave Field Study

Subjective	Safety Behavior	Description
Pedestrian	Crosswalk use	Pedestrians should cross within the marked crosswalk boundaries.
	Push button	Pedestrians press the push button to activate the pedestrian signal before crossing the roadway. If anyone in a pedestrian group presses the push button, the pedestrian group will be counted as having activated the push button.
	Signal compliance	Pedestrians wait for and obey the pedestrian signal indication before crossing the roadway. Crossing is permitted only when the WALK symbol or flashing countdown display is shown.
Pedestrian-vehicle	Yield to pedestrian	Vehicles yield to pedestrians who are crossing or preparing to cross the roadway. Only observations with the presence of both a pedestrian and a conflicting vehicle are counted.
	Near miss	A situation in which a pedestrian and a vehicle come into close conflict, requiring an evasive action to avoid a collision.

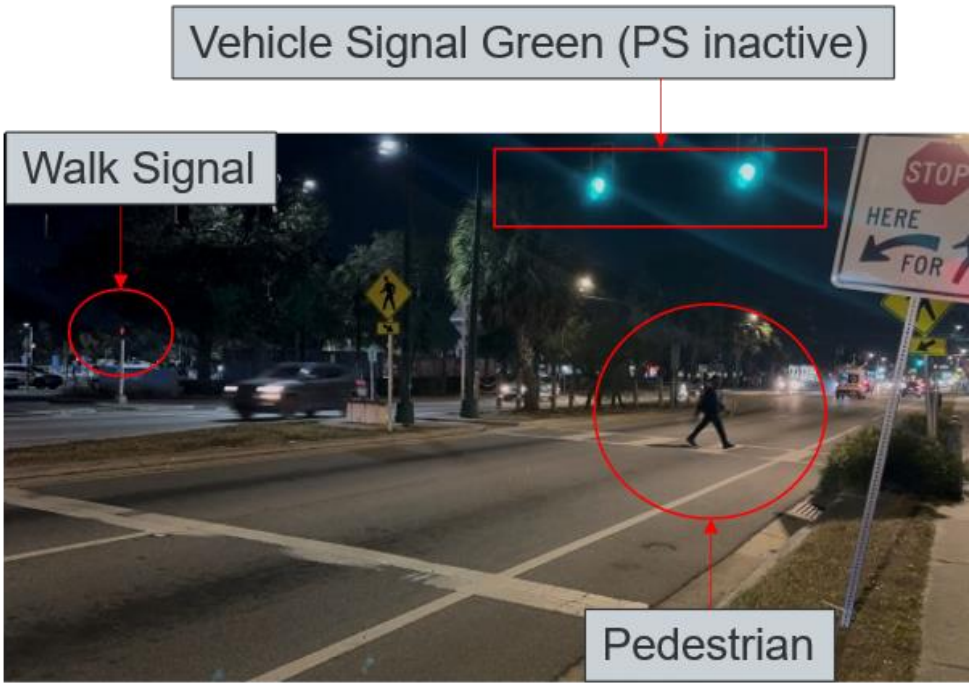


Figure 5-16. Example of a noncompliant pedestrian crossing at the Fletcher Avenue PS at midblock site

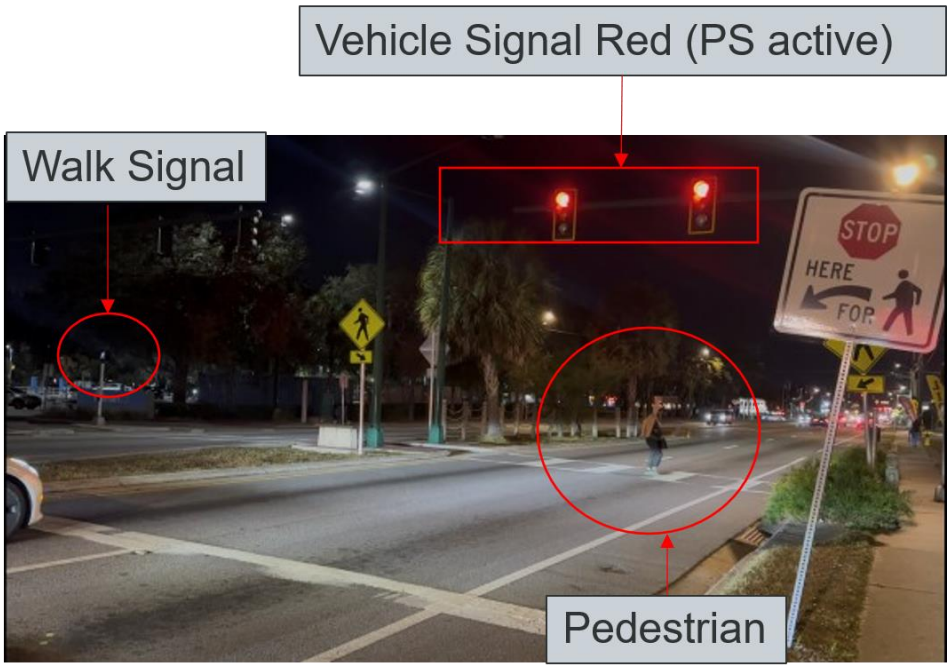


Figure 5-17. Example of a compliant pedestrian crossing with a PS at midblock on Fletcher Ave

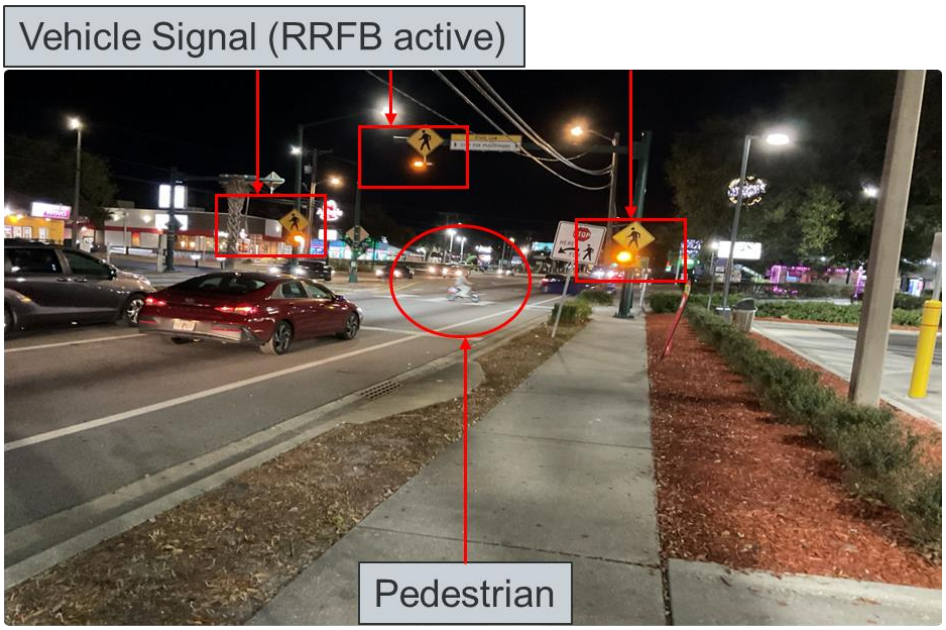


Figure 5-18. Example of a pedestrian crossing with RRFB on Fletcher Ave

5.3.4 Analysis Results

A total of 68 crossing events were observed during the field study, including 18 events at the PS site and 38 events at the RRFB site (Table 5-7).

Table 5-7. Field Data Collection for PS at midblock at Night

Corridor	No. of Observations	Push Button	Within Crosswalk	No vehicles	Compliance	Yield	Near Miss
PS	18	15	18	13	7	5	0
RRFB	38	18	25	2	18	22	4

Note: No Vehicle means no conflicting vehicles were present during the observation. Yielding behavior and near-miss rates were calculated using only those observations in which a conflicting vehicle was present. Push-button use indicates the observations in which the pedestrian activated the push button before crossing. Within crosswalk refers to observations in which pedestrians crossed within the marked crosswalk.

Pedestrian compliance was defined according to the operating characteristics of each treatment.

- **PS:** At the PS site, compliance required pedestrians to activate the push button, wait for the pedestrian walk indication, and cross within the marked crosswalk. For this study, the pedestrian walk indication was defined as the interval during which either the steady WALK symbol or the flashing countdown display was shown.
- **RRFB:** At the RRFB site, compliance referred to activating the beacon prior to crossing and crossing within the marked crosswalk.

Table 5-8 presents the comparison of pedestrian behaviors between PS and RRFB. The analysis results are summarized as follows:

Table 5-8. Comparison of Pedestrian Behavior Measures at PS at midblock and RRFB Sites on Fletcher Ave Corridor

Behavior	PS	RRFB	Statistical Test	Significant at 95%
Push Button	**83.3%** (=15/18)	**47.4%** (=18/38)	$\chi^2 = 6.53$ $p = 0.01$	**Yes**
Within Crosswalk	**100.0%** (=18/18)	**65.8%** (=25/38)	$\chi^2 = 8.02$ $p = 0.01$	**Yes**
Compliance	**38.9%** (=7/18)	**47.4%** (=18/38)	$\chi^2 = 0.36$ $p = 0.55$	No

- Push-button use was observed more frequently at the PS site (83.3%) than at the RRFB site (47.4%), and a chi-square test indicated that this difference was statistically significant ($\chi^2 = 6.53$, $p = 0.01$).
- Crossing within the marked crosswalk was also observed more frequently at the PS site (100.0%) than at the RRFB site (65.8%), and this difference was statistically

significant based on the chi-square test ($\chi^2 = 8.02$, $p = 0.01$). Proper crosswalk use was defined as crossing entirely within the marked crosswalk boundaries, while improper use included crossing outside the designated markings, at an angle, or entering the roadway at a point other than the designated crossing location.

- Compliance was lower at the PS site (38.9%) than at the RRFB site (47.4%); however, the chi-square test indicated that this difference was not statistically significant ($\chi^2 = 0.36$, $p = 0.55$).

Table 5-9 presents the comparison of vehicle-yielding-to-pedestrian behaviors at the PS site and the RRFB site. The results are given as follows:

Table 5-9. Comparison of Driver Yielding Behavior at PS at midblock Site and RRFB Site

Item	Yield	Non-Yield
PS	**100%** (=5/5)	**0%** (=0/5)
RRFB	**61.1%** (=22/36)	**38.9%** (=14/36)
Comparison	***p*-value**	**Significant at α = 0.05**
PS vs RRFB	0.1465	No

Vehicle yielding was observed more frequently at the PS site (100.0%) than at the RRFB site (61.1%); Fisher's exact test indicated that this difference was not statistically significant ($p = 0.1465$).

Table 5-10 presents the comparison of near-miss events at PS at midblock and RRFB sites. Near-miss (conflict) events were identified based on either vehicle hard braking to avoid potential collision or a close interaction between a moving pedestrian and a vehicle. The results are given as follows:

Table 5-10. Comparison of Near-Miss Events at PS at midblock Site and RRFB Site

Site	Near Miss	No Near Miss
PS	**0%** (=0/5)	**100%** (=5/5)
RRFB	**11.1%** (=4/36)	**88.9%** (=32/36)
Comparison	**p-value**	**Significant at α = 0.05**
PS vs RRFB	1.000	No

While no near-miss events were observed at the PS site compared with 11.1% at the RRFB site, Fisher's exact test indicated that this difference was not statistically significant ($p = 1.000$).

5.4 Key Findings from Field Evaluations and Before-and-After Studies

This project evaluated the effectiveness of innovative nighttime traffic signal timing and operational strategies implemented along two Florida arterial corridors to improve nighttime safety. The study examined coordinated nighttime signal retiming strategies with short cycle lengths on the US-41 corridor and pedestrian crossing treatments, including RRFBs and a PS, along the Fletcher Avenue corridor. The evaluation incorporated field observations, driver behavior analysis, subjective driver surveys, and before-and-after crash analyses for the Fletcher Avenue segment. Results showed that coordinated nighttime signal operations with short cycle length reduced risky driving behaviors, such as hard braking and stopping beyond the stop bar, while improving driver awareness of downstream signal conditions and discouraging speeding. The pedestrian crossing treatments contributed to reductions in nighttime pedestrian and bicycle crashes, improved driver yielding behavior, and enhanced pedestrian crossing compliance.

5.4.1 Key Findings

Overall, the findings from this study suggest that coordinated nighttime signal timing strategies with short cycle lengths and pedestrian crossing treatments with RRFBs and PSs can improve nighttime arterial safety by reducing risky driving behaviors, improving driver expectancy, enhancing pedestrian crossing compliance, and increasing driver yielding behavior. These treatments demonstrated potential to improve nighttime operational safety while maintaining efficient traffic progression under lower nighttime traffic volumes.

US-41 Corridor: Coordinated Nighttime Signals

The US-41 study evaluated a nighttime signal retiming strategy that used **shortened cycle lengths and coordinated signal progression** to manage vehicle speeds under low-traffic conditions.

- **Reduction in Risky Driving Behaviors**: Field observations showed that the coordinated signal timing significantly lowered the occurrence of dangerous late-decision driving behaviors. Compared to uncoordinated control intersections, the treated sites saw an 80% reduction in hard braking (0.1% vs. 0.5%) and a 41% reduction in vehicles stopping past the stop bar (1.9% vs. 3.2%). Differences in drivers passing on red or yellow lights were not statistically significant.
- **Discouragement of Speeding**: A subjective evaluation utilizing driver surveys revealed that coordinated traffic signal operation with short cycle lengths increased drivers' awareness of downstream red signals rather than of all or most green lights when they operate in a free operation mode. In the treated corridor, 61% of drivers

reported that seeing a downstream red signal would "often" discourage them from speeding, compared to only 7% of drivers in the control corridor.

- **Shift in Driver Decision-Making**: Drivers in the treated corridor were highly influenced not to speed by the expectation that they would just have to stop at upcoming red signals (87%). In contrast, drivers in the free-operating control corridor primarily relied on the belief that maintaining their speed would result in better signal progression (100%).

Fletcher Avenue Corridor: Pedestrian Signals (PS at midblock and RRFBs)

The Fletcher Avenue study evaluated the nighttime effectiveness of one Pedestrian Signal (PS) and five Rectangular Rapid Flashing Beacons (RRFBs).

- **Significant Reduction in Nighttime Crashes**: The installation of the pedestrian signals contributed to a notable decline in crash frequency and severity over time.
  - **Pedestrian Crashes**: Nighttime pedestrian crashes dropped from 12 in the three-year "before" period down to just 3 in the most recent "after" period (2023–2025).
  - **Bicycle Crashes**: Nighttime bicycle crashes dropped from 5 in the before period (all of which were severe) to zero in the most recent after period, indicating a complete elimination of severe nighttime bicycle crashes. (Note: The report acknowledges that other countermeasures implemented simultaneously, such as LED lighting, lowered speed limits, and raised refuge islands, likely also contributed to these crash reductions.)
- **Improvement in Driver Yielding**: Drivers yielded to pedestrians 100% of the time at the PS at midblock site and 61.1% of the time at the RRFB site.
- **Differences in Pedestrian Compliance**: The PS at midblock treatment encouraged better pedestrian behavior than the RRFB treatments. At the PS at midblock site, 83.3% of pedestrians used the push button, and 100% crossed within the marked crosswalk. In contrast, at the RRFB sites, only 47.4% used the push button, and 65.8% stayed within the crosswalk.
- **Fewer Near Misses**: While not statistically significant, near-miss events observed between pedestrians and vehicles were 0% at the PS at midblock site compared to 11.1% at the RRFB sites.

6 Guidance Materials for Implementing Nighttime Signal Timing Strategies

Building upon the findings from the literature review, stakeholder interviews, case studies, field evaluations, and crash analyses, this chapter provides practical guidance materials for implementing effective nighttime traffic signal timing strategies and actionable recommendations for transportation agencies.

6.1 Summary of Overall Findings on Signal Timing-Related Countermeasures

Previous chapters provided a range of proven and promising strategies for signal timing, signal operations, and signal-related technologies that can help transportation agencies improve nighttime safety along arterial corridors. Some strategies were identified through the literature review, others emerged from stakeholder interviews, and several were discussed across multiple chapters. These strategies vary in complexity and cost, ranging from relatively simple, low-cost measures to solutions that require more substantial investment. A summary of these strategies, along with brief descriptions, is presented below.

- **Signal Operations with Short Cycle Length**: Reduces the overall signal cycle time.
- **Early Start of Signal Free Operations**: Transitions from coordinated operation to actuated control or free operations earlier in the evening to better respond to declining traffic volumes.
- **Speed Management via Signal Progression**: Uses signal coordination to encourage desired operating speeds and discourage speeding.
- **Rest-in-Red Operations**: Holds signals in red during low-demand periods until speed compliant vehicles are detected, suitable at isolated intersections on minor or collector roads.
- **Adaptive Signal Timing**: Dynamically adjusts signal timing based on real-time traffic conditions.
- **Dilemma Zone protection**: Extends the green interval so the vehicle can safely proceed through the intersection.
- **Increased Clearance Intervals**: Provides additional time for vehicles and pedestrians to clear intersections safely.

- **Pedestrian Signal Treatments (RRFBs, PHBs, MPSs, PSs, LPIs, and pedestrian countdown signals)**: Provides additional time for pedestrians to cross and improve pedestrians' visibility.
- **Rest-in-Walk Operations**: A pedestrian-oriented signal control strategy in which the pedestrian signal defaults to the WALK indication on major streets when there is no conflicting vehicular demand.
- **Automated Pedestrian Detection**: Detects pedestrians automatically and adjusts signal operations accordingly.
- **AI-Powered Video Analytics**: Uses artificial intelligence and camera technologies to monitor traffic operations and safety performance.
- **CV Technologies**: Enables communication between vehicles, infrastructure, and road users.
- **Retroreflective Signal Backplates**: Traffic signal backplates equipped with a retroreflective border (typically a yellow reflective strip) attached around the perimeter of the signal housing.
- **12-inch Signal Heads**: Traffic signal displays with 12-inch lenses that provide enhanced visibility for motorists, especially on higher-speed and higher-volume roadways.
- **Blankout Signs**: Illuminated traffic signs that display messages only when activated to provide dynamic, situation-specific information to drivers.

6.2 Framework for Nighttime Safety Strategy Selection and Implementation

Nighttime traffic conditions differ significantly from daytime operations, requiring agencies to move beyond traditional time-of-day signal plans. Given the elevated crash risks associated with nighttime driving, traffic signal timing strategies should prioritize safety rather than mobility. The proposed framework for selecting nighttime traffic operations strategies is presented in Figure 6-1. The project team proposes a five-step process to guide the selection procedure, as described in the following sections.

Figure 6-1. Framework for nighttime signal timing strategy selection

6.2.1 Step 1: Evaluation of Nighttime Crash Patterns, Severity, and Near-Miss Events

The countermeasure selection process begins with assessing nighttime arterial safety conditions by analyzing crash patterns, crash severities, and near-miss events. This step establishes a data-driven understanding of safety issues, helping agencies identify where and when problems occur. It serves as the foundation for all subsequent decisions. This includes analyzing:

- Crash frequency and severity

- Types of crashes (e.g., rear-end, angle, pedestrian-involved)
- Near-miss or conflict events

6.2.2 Step 2: Identification of Underlying Causes of Nighttime Crashes or Near-Miss Events

Following step 1, the framework emphasizes identifying the root causes and contributing factors behind nighttime crashes and near-miss events. Key issues include:

- Excessive vehicle speeds, often due to low traffic volumes
- Impaired driving and reduced alertness, common during nighttime hours
- Increased risk-taking behavior, frequently linked to long delays or detection failures
- Reduced visibility and expectancy of vulnerable road users, such as pedestrians and cyclists
- Reduced visibility of roadway features, including signs, markings, and intersection geometry

This step shifts the focus from symptoms (crashes) to causal mechanisms, enabling more targeted and effective interventions.

6.2.3 Step 3: Key Considerations for Countermeasure Selection

Once the contributing causes are identified, agencies can evaluate the contextual, operational, institutional, and financial factors that influence the feasibility, effectiveness, and long-term sustainability of potential countermeasures. Countermeasure selection can vary greatly between agencies depending on corridor conditions, operational objectives, available funding, staffing resources, technical capabilities, maintenance requirements, and agency priorities. As a result, the selection and implementation of nighttime arterial safety strategies should be tailored to the specific operational environment and agency constraints.

Key considerations include:

- **Traffic volume and demand variability** are critical considerations when selecting nighttime arterial safety countermeasures because traffic conditions can change considerably during late-night periods. Low-volume conditions may increase excessive speeding, red-light running, and risky driver behavior, while highly variable demand may require adaptive or responsive signal operations. Countermeasure selection should consider whether traffic patterns are stable, transitional, or highly fluctuating throughout the night to ensure efficient and safe operations.

- **Pedestrian and bicycle activity** influences the need for visibility enhancements, crossing treatments, and pedestrian-focused signal operations. Corridors with nighttime pedestrian activity, transit access, entertainment districts, schools, or midblock crossing demand may require treatments that improve conspicuity, driver yielding behavior, and pedestrian protection under low-light conditions.
- **Roadway characteristics**, such as intersection spacing, lighting conditions, and number of lanes, affect the suitability of nighttime countermeasures. Key considerations include intersection spacing, roadway classification, lane configuration, operating speeds, curves, grades, sight distance limitations, and corridor progression needs. Closely spaced intersections may benefit from coordinated signal timing, while high-speed or isolated intersections may require enhanced warning and visibility treatments.
- **Detection availability** is essential for adaptive timing, rest-in-red operation, dilemma zone protection, pedestrian activation, and other responsive control strategies. Detection availability and performance under nighttime and adverse weather conditions should also be considered.
- **Advanced signal controllers** support adaptive timing, real-time detection inputs, communication systems, and dynamic signal operations. Agencies need to evaluate whether existing signal controllers can support advanced operational strategies such as adaptive traffic control, CV applications, or LiDAR-based detection systems.
- **Funding availability** influences the feasibility, scale, and complexity of nighttime safety improvements. Conventional treatments, such as timing modifications, may require limited investment, while advanced technologies, such as adaptive signal systems, CV infrastructure, AI-powered analytics, or smart detection systems, may require some capital, maintenance, and operational resources.

6.2.4 Step 4: Countermeasure Selection and Implementation

Step 4 focuses on the selection and implementation of appropriate nighttime arterial safety countermeasures based on the identified crash causes, operational deficiencies, and site-specific conditions identified in the previous three steps. Several traffic signal–related countermeasures are available to address factors that contribute to nighttime crashes, including excessive vehicle speeds, impaired driving and reduced driver alertness, increased risk-taking behavior, reduced visibility of vulnerable road users, and reduced visibility of roadway features. While each countermeasure may target one or more of these factors, they differ in their expected ability to mitigate the underlying causes of crashes and near-misses. To support the selection and prioritization of appropriate

strategies, the countermeasures have been grouped into three categories based on their anticipated effectiveness in addressing specific contributing factors and enhancing nighttime safety. The categories are defined as follows:

- **Primary countermeasures** are considered the most effective and are expected to provide the greatest safety benefits for addressing the identified issue.
- **Secondary countermeasures** can provide meaningful safety improvements but are generally less impactful than primary treatments or may be more dependent on site-specific conditions.
- **Supporting countermeasures** are complementary treatments that may enhance the effectiveness of primary and secondary measures but, when implemented alone, are expected to provide comparatively smaller safety benefits.

The process also considers traffic demand, pedestrian and bicycle activity, roadway characteristics, technology availability, and funding constraints. Agencies can then select the most appropriate nighttime arterial safety countermeasures based on corridor conditions, while considering implementation complexity, infrastructure needs, operational feasibility, and cost. Some treatments can be implemented using existing signal infrastructure, whereas others require advanced detection, adaptive controllers, communication systems, or emerging technologies.

For example, basic operational strategies such as **Signal Operations with Short Cycle Lengths, Early Start of Signal Free Operation, and Speed Management via Signal Progression** are generally appropriate where traffic volumes, intersection spacing, and available detection systems support efficient signal coordination. Increased **Clearance Intervals, Dilemma Zone Protection, and All-red Clearance Intervals** are typically recommended for wider intersections, higher-speed approaches, or locations where additional clearance time is needed to improve safety. **Rest-in-Red Operations** are more suitable for low-volume or isolated roadways where traffic demand is limited.

Advanced technology-based countermeasures, including **Adaptive Signal Timing, AI-powered Video Analytics and Real-time Detection Systems, and CV Technology**, require functioning detection systems, advanced signal controllers, and adequate funding. Treatments such as **RRFBs, PHBs, MPS, Automatic Pedestrian Detection Systems, LPIs, and Rest-in-Walk** are generally recommended where pedestrian activity is high, crossings are complex or multilane, and funding and detection technologies are available.

Table 6-1 presents specific traffic signal-related countermeasures that can be implemented to mitigate contributing factors associated with nighttime arterial crashes or near-misses. The checkmarks indicate which countermeasures may help mitigate specific

safety issues, including excessive vehicle speeds, impaired driving, risk-taking behavior, reduced pedestrian visibility, and reduced roadway feature visibility. The matrix is intended to help transportation professionals quickly identify and select appropriate operational strategies to improve nighttime arterial safety. The summary is as follows:

- **Excessive vehicle speeds**: Agencies can prioritize speed management through signal progression. Secondary strategies include short cycle lengths, rest-in-red at isolated intersections on minor or collector roads, adaptive signal timing, dilemma zone protection, and CV technologies. Supporting measures include early start of free operation, increased yellow and all-red clearance intervals, and AI-powered video analytics.
- **Impaired driving and reduced alertness**: Agencies can prioritize increased yellow and all-red clearance intervals. Secondary strategies include signal progression for speed management, dilemma zone protection, CV technologies, and 12-inch signal heads. Supporting measures include short cycle lengths, early start of free operation, rest-in-red, adaptive signal timing, pedestrian treatments, and AI-powered video analytics.
- **Risk-taking due to side-street delays or detection failures**: Agencies can prioritize short cycle lengths, early start of free operation, adaptive signal timing, and AI-powered video analytics. Secondary strategies include rest-in-red and CV technologies. Supporting measures include signal progression for speed management and increased yellow and all-red clearance intervals.
- **Reduced pedestrian visibility and driver expectancy**: Agencies can prioritize RRFBs, PHBs, PSs), MPSs, LPIs, countdown signals, pedestrian dynamic flashing arrows, automated pedestrian detection, and rest-in-walk operation. Secondary strategies include short cycle lengths, signal progression for speed management, increased yellow and all-red clearance intervals, CV technologies, AI-powered video analytics, and 12-inch signal heads. Supporting measures include rest-in-red and adaptive signal timing.
- **Reduced roadway feature visibility**: Agencies can prioritize 12-inch signal heads and retroreflective signal backplates. Secondary strategies include RRFBs, PHBs, PSs, MPSs, LPIs, pedestrian dynamic flashing arrows, automated pedestrian detection, and CV technologies. Supporting measures include rest-in-walk operation and AI-powered video analytics.

Table 6-1. Nighttime Signal Timing Countermeasure Selection Guide

Underlying Causes of Crash Countermeasures: Primary *** Secondary ** Supporting *	Excessive Vehicle Speeds	Impaired Driving and Reduced Alertness	Increased Risk-Taking due to Extended Side-Street Delays or Detection Failures	Reduced Pedestrian Visibility and Diminished Driver Expectancy	Reduced Roadway Feature Visibility
Signal Operations with Short Cycle Lengths	**	*	***	**	
Early Start of Signal Free Operation	*	*	***		
Speed Management via Signal Progression	***	**	*	**	
Rest-in-Red Operations	**	*	**	*	
Adaptive Signal Timing	**	*	***	*	
Dilemma Zone Protection	**	**			
Increased Clearance Intervals	*	***	*	**	
RRFBs, PHBs, PSs, MPSs, LPIs, Pedestrian Dynamic Flashing Arrow		*		***	**
Automated Pedestrian Detection		*		***	**
Rest-in-Walk				***	*
Connected Vehicles	**	**	**	**	**
All-red Clearance Intervals	*	***	*	**	
AI-powered Video Analytics	*	*	***	**	*
12" signal heads and retroreflective signal backplates		**		**	***

This research also identified important supporting countermeasures that are non-signal-related yet can complement and enhance the effectiveness of traffic signal-related strategies aimed at improving nighttime arterial safety. The supporting non-signal countermeasures are presented in Table 6-2.

Table 6-2. Nighttime Non-Signal Countermeasures for Arterial Roads

Underlying Causes of Crashes or Near-misses	Countermeasure
Excessive Vehicle Speeds	Speed feedback signs
	Advanced warning signage
	Automated speed enforcement cameras*
Impaired Driving and Reduced Alertness	Adaptive signal lighting
	Rumble strips
	Enhanced lighting
	Variable message signs (warning of fatigue)
	Targeted DUI enforcement
Increased Risk-taking due to Extended Side-street Delays or Detection Failures	Variable message signs
	Advance warning signage
Reduced Pedestrian Visibility and Diminished Driver Expectancy	Enhanced lighting
	Adaptive signal lighting
	Pedestrian refuge islands
	High-visibility crosswalk markings
Reduced Roadway Feature Visibility	Roadway lighting (especially at curves and decision points)
	Remove visual clutter, trim vegetation
	Reflective lane delineators and raised pavement markers
	Reflective signage
	High-retroreflectivity pavement markings
All causes of nighttime crashes	Lighting, education, and enforcement

**Not permitted in Florida at the time the report was prepared.*

Figure 6-2 provides a structured screening and decision-support framework that agencies can use to diagnose contributing factors associated with nighttime crashes and identify the most appropriate primary countermeasures.

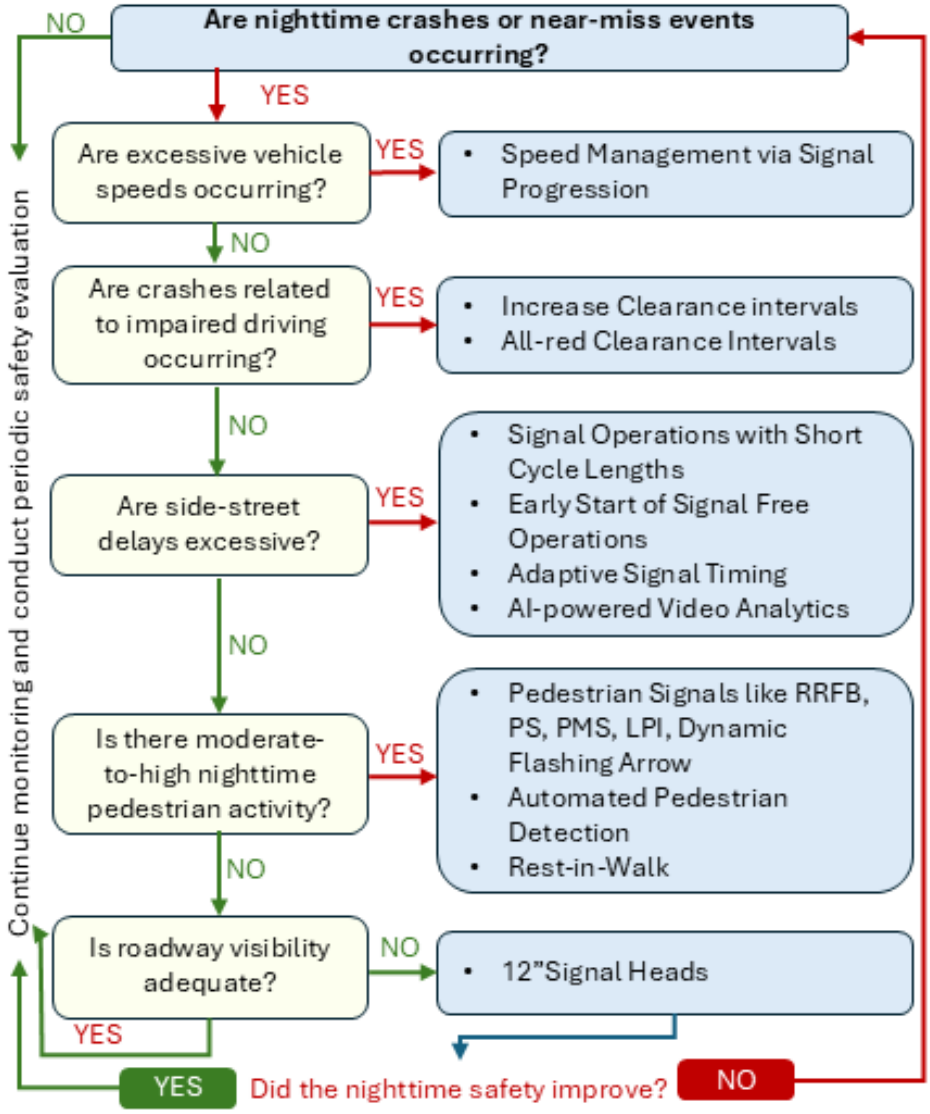


Figure 6-2. Nighttime safety issues and countermeasure selection decision flowchart

The matrix presented in Table 6-3 categorizes nighttime arterial safety countermeasures by the primary safety issue addressed and the relative complexity of implementation. The relative level of complexity might differ from agency to agency, depending on the current technological advancement in signal timing and available funds. The matrix categorizes strategies into easier/lower-cost treatments, moderate complexity operational strategies, and advanced or emerging technologies that typically require greater infrastructure investment, detection capability, communication systems, and controller integration.

Table 6-3. Matrix of Nighttime Arterial Safety Countermeasures by Safety Issue and Relative Implementation

Nighttime Safety Issue	Less Complex Strategies	Moderate Complexity Strategies	Advanced / Emerging Strategies
 Excessive Vehicle Speeds	*** Speed management via signal progression **Signal operations with short cycle lengths ** Dilemma zone protection * Increased clearance intervals * All-red clearance intervals * Early start of signal free operations	** Rest-in-red Operations	** Connected vehicle technology ** Adaptive Signal Timing * AI-powered video analytics and real-time detection systems
 Impaired Driving and Reduced Alertness	*** Increased clearance intervals ** Dilemma zone protection *** All-red clearance intervals ** 12" signal head * Signal operations with short cycle * Early start of signal free operations ** Speed management via signal progression	* Rest-in-red Operations * Pedestrian Hybrid Beacon * Midblock Pedestrian Signals * Pedestrian Signals * Pedestrian Dynamic Flashing Yellow Arrow * Rectangular Rapid Flashing Beacon	* Adaptive Signal Timing ** Connected vehicle technology * AI-powered video analytics and detection systems * Automated Pedestrian Detection System
 Increased Risk-taking due to Extended Side-street Delays or Detection Failures	*** Signal operations with short cycle lengths ** Early start of free operation * Speed management via signal progression * Increased clearance intervals ** Dilemma zone protection * All-red clearance intervals	** Rest-in-red Operations	*** Adaptive Signal Timing ** Connected vehicle technology *** AI-powered video analytics and real-time detection systems

*** Primary countermeasure
** Secondary countermeasure
* Supporting countermeasure

Table 6-3. Matrix of Nighttime Arterial Safety Countermeasures by Safety Issue and Relative Implementation Complexity (cont.)

Nighttime Safety Issue	Less Complex Strategies	Moderate Complexity Strategies	Advanced / Emerging Strategies
Reduced Pedestrian Visibility and Diminished Driver Expectancy	***Rest-in-walk ***Leading pedestrian interval **All-red clearance intervals *Increased clearance intervals	***Pedestrian Hybrid ***Beacon ***Midblock Pedestrian Signals ***Pedestrian Signals ***Pedestrian Dynamic ***Flashing Yellow Arrow ***Rectangular Rapid Flashing Beacon	***Automatic pedestrian detection systems **Connected vehicle technology **AI-powered video analytics and real-time detection systems **12" signal head
Reduced Roadway Feature Visibility	***12" signal head and retroreflective signal backplates *Rest-in-walk	**Pedestrian Hybrid Beacon **Midblock Pedestrian Signals **Pedestrian Signals **Pedestrian Dynamic **Flashing Yellow Arrow **Rectangular Rapid Flashing Beacon	**Connected vehicle technology *AI-powered video analytics and real-time detection systems **Automatic pedestrian detection systems

*** Primary countermeasure
** Secondary countermeasure
* Supporting countermeasure

6.2.5 Step 5: Countermeasure Performance and Monitoring

Step 5 focuses on monitoring and evaluating the performance of implemented nighttime arterial safety countermeasures to determine their effectiveness in improving safety and operations. This step includes the collection and analysis of crash data, near-miss events, driver and pedestrian behavior observations, operational performance measures, and user compliance. The evaluation process helps identify whether the implemented strategies successfully reduced nighttime safety risks and improved driver expectancy, pedestrian visibility, and traffic operations. If performance objectives are not achieved, the framework supports reevaluation and adjustment of the implemented countermeasures by starting the process over at Step 1.

6.3 Recommended Signal Timing Strategies

Signal timing is the most immediate and cost-effective tool for improving nighttime safety, especially on arterial corridors in urban and suburban areas. Based on the project findings, several key practices are recommended.

6.3.1 Signal Operations with Short Cycle Lengths

Agencies could consider using shorter cycle lengths during nighttime hours either for signal progression or free operations. Compared to traditional off-peak operations, shorter cycles help regulate vehicle speeds and improve service frequency. Some of the benefits include:

- Reduced excessive green time on major streets that encourages speeding
- Improved progression consistency at lower speeds
- More frequent service to side streets

6.3.2 Early Start of Signal Free Operations

During late evening or very low-demand periods, signals may transition from coordinated timing to free or fully actuated operation. This improves responsiveness while maintaining operational efficiency. The benefits of this strategy may include:

- Improved responsiveness to real-time demand
- Reduced unnecessary delay for minor movements
- Reduced speeding due to traffic signal progression in a longer cycle length
- Reduced driver frustration and risky behavior on minor streets

6.3.3 Speed Management via Signal Progression with Short Cycle Lengths

Signal progression could be intentionally designed to manage speeds rather than maximize throughput. Under nighttime conditions, lower traffic volumes allow greater flexibility to influence driver behavior through timing design.

- Set progression speeds equal to or below posted speed limits
- Introduce slight disruption (e.g., small intentional variations in signal progression) to discourage aggressive driving by reducing the incentive for high-speed travel between signals
- Avoid long uninterrupted green bands on major streets at night

This approach aligns with corridor-level findings where speed reductions contributed to improved safety outcomes.

6.3.4 Rest-in-Red Operations

Rest-in-Red is an effective nighttime traffic control strategy for managing speeding at low-volume, isolated intersections on minor or collector roads. Holding the signal red until a vehicle is detected requires drivers to decelerate to the posted speed (or lower) before entering the intersection, interrupting continuous high-speed flow on the road.

- Requires approaching drivers to decelerate to the posted speed (or lower) prior to entering the intersection
- Eliminates continuous green indications that can encourage excessive speeds
- Particularly effective at isolated intersections where high-speed approach behavior is common

Successful implementation depends on reliable vehicle detection upstream of the intersection and a clear public understanding of the operating logic to avoid driver confusion.

6.3.5 Pedestrian-focused Traffic Signal Strategies

To address the elevated risks faced by pedestrians at night, signal timing could incorporate treatments that enhance visibility and reduce conflicts, including RRFB, PHB, MPS, PS, LPI, pedestrian countdown signals, and dynamic flashing yellow arrow. These treatments provide:

- Enhanced crossing opportunities
- Improved driver’s yielding behavior
- Increased pedestrian conspicuity under low-light conditions
- Reduced conflicts with turning vehicles

These treatments help improve pedestrian safety and driver expectancy at intersections and crossing locations during nighttime operations.

6.4 Detection and Technology Considerations

Reliable detection is a critical foundation for all nighttime signal timing strategies. Poor detection performance can significantly reduce the effectiveness of even well-designed timing plans, particularly under low-light conditions where visibility constraints already challenge both drivers and infrastructure systems. As such, ensuring accurate and consistent detection could be considered a prerequisite for implementing any nighttime operational strategy.

6.4.1 Detection Reliability and Advanced Capabilities

Traditional detection methods, such as video-based systems, may experience reduced performance at night due to insufficient lighting, headlight glare, and environmental factors such as rain or fog. To address these limitations, agencies could consider deploying alternative detection technologies that are less sensitive to lighting conditions. Radar-based systems provide stable performance by directly measuring object movement and speed, while thermal and infrared sensors enhance the detection of pedestrians and cyclists in low-visibility environments. LiDAR-based systems can provide high-resolution spatial information without relying on ambient visible light; however, their field performance depends on sensor configuration, placement, occlusion, and object-detection and tracking algorithms. In some applications, thermal sensing may provide more reliable pedestrian identification and tracking, as demonstrated in the THEA case study discussed earlier.

Beyond improving basic detection reliability, advanced detection technologies enable a transition from passive signal operations to proactive safety management. Real-time pedestrian detection can support automatic phase activation or extension, reducing reliance on push-button inputs and improving crossing safety. Similarly, detection systems capable of identifying vehicle speed and trajectory can support strategies such as rest-in-red operations or adaptive timing adjustments. These capabilities allow signal systems to respond dynamically to real-time conditions rather than relying solely on pre-defined timing plans.

6.4.2 Integration with Smart and Emerging Technologies

The integration of detection systems with advanced signal control technologies, which can require advanced signal controllers, further enhances nighttime operations. Adaptive signal timing can use real-time detection data to continuously adjust cycle lengths, phase splits, and offsets, improving both safety and operational efficiency under highly variable

nighttime demand conditions. In addition, centralized performance monitoring tools, such as **ATSPMs**, enable agencies to evaluate detection accuracy and signal performance, supporting data-driven decision-making and ongoing system optimization.

Emerging CV technologies provide an additional layer of safety by extending detection beyond the physical limits of roadside infrastructure. Through vehicle-to-infrastructure communication, signal systems can transmit real-time information, such as signal phase and timing, pedestrian presence, and potential conflicts, directly to approaching vehicles. This capability is particularly valuable under nighttime conditions, when limited visibility can delay hazard recognition and response.

Despite these benefits, the implementation of advanced detection and technology systems requires careful consideration of cost, maintenance, and system integration. Agencies could prioritize scalable and context-appropriate solutions and ensure that detection systems remain reliable over time through regular calibration, maintenance, and performance monitoring.

6.5 Supporting Infrastructure Improvements

While signal timing and detection technologies play a critical role in improving nighttime safety, their effectiveness is highly dependent on the quality of supporting infrastructure. Inadequate lighting, poor visibility of traffic control devices, and insufficient pedestrian facilities can significantly limit the impact of operational strategies. Therefore, infrastructure improvements could be implemented in conjunction with signal timing strategies to create a comprehensive and reliable nighttime safety system.

6.5.1 Lighting Enhancements

Improving roadway lighting is one of the most effective and foundational strategies for enhancing nighttime safety. Adequate illumination directly addresses one of the primary limitations of nighttime driving, reduced visibility, and significantly improves the ability of drivers to detect pedestrians, cyclists, and roadway features. Upgrading to LED lighting at intersections and along arterial corridors provides more uniform and higher-quality illumination compared to traditional lighting systems. In addition, targeted lighting at pedestrian crossings and conflict-prone areas can further enhance visibility where it is most needed (Federal Highway Administration, 2013).

Findings from statewide lighting improvement initiatives demonstrate that enhanced illumination can lead to substantial reductions in nighttime crashes, particularly those involving severe injuries and vulnerable road users. These results highlight that lighting improvements are not only supportive measures but also serve as a critical prerequisite for the success of other operational and technological strategies.

6.5.2 Signal and Roadway Visibility Improvements

In addition to general lighting, improving the visibility of traffic control devices is essential for effective nighttime operations. Drivers rely heavily on visual cues to interpret signal indications, roadway geometry, and potential conflicts, all of which are more difficult to perceive under low-light conditions.

Agencies could prioritize the installation of retroreflective signal backplates to enhance signal conspicuity, particularly at intersections with complex movements or high approach speeds. Regular maintenance of signal lenses, signage, and pavement markings is also necessary to ensure visibility is not degraded over time. High-visibility pavement markings and reflective materials can further enhance lane recognition and driver guidance, reducing driver uncertainty and improving compliance with traffic control measures.

6.5.3 Pedestrian Infrastructure and System Maintenance

Given the elevated risk faced by pedestrians at night, infrastructure improvements could also prioritize pedestrian visibility and protection. High-visibility crosswalk markings and median refuges can significantly improve crossing safety, particularly along high-speed arterial corridors. In locations with frequent pedestrian activity, enhanced treatments such as raised crosswalks or focused lighting can further increase driver awareness and reduce conflicts.

In addition to physical improvements, ongoing system maintenance and monitoring are essential to ensure long-term effectiveness. Detection systems, lighting infrastructure, and signal equipment (i.e., signal controllers) must be regularly inspected and calibrated to maintain performance under nighttime conditions. Agencies could also conduct periodic nighttime-specific operational reviews to evaluate system performance, identify deficiencies, and guide adjustments. The use of performance monitoring tools, such as ATSPMs, can support data-driven decision-making and continuous improvement.

7 Conclusions and Recommendations

7.1 Conclusions

This research demonstrates that improving nighttime safety on arterial roadways requires a fundamental shift from conventional daytime-oriented traffic operations toward strategies specifically designed for nighttime conditions. The analysis confirms that nighttime crashes are not only more frequent relative to exposure but also significantly more severe due to a combination of high speeds, reduced visibility, and increased prevalence of impaired or distracted driving. These conditions create a high-risk environment, particularly for vulnerable road users such as pedestrians and bicyclists. As such, nighttime traffic operations must be treated as a distinct operational scenario requiring dedicated design, analysis, and management.

One of the most important conclusions of this study is the critical role of signal timing strategies in influencing driver behavior at night. Strategies such as short cycle lengths, speed management through signal progression, and early transition to actuated or free operation have been shown to reduce excessive speeds, minimize aggressive driving, and improve overall driver expectancy. These approaches directly address key contributing factors to nighttime crashes by limiting long, uninterrupted green phases that encourage speeding and by providing more frequent service to minor roadways. The findings consistently indicate that when signal timing is aligned with nighttime traffic conditions, both safety and operational performance can be significantly improved. On the US-41 corridor, coordinated short-cycle signal timing reduced risky driving behaviors by 80% for hard braking and 41% for stopping beyond the stop bar, while 61% of drivers reported that visible downstream red signals discouraged speeding and 87% adjusted their behavior due to expected stops.

The study also confirms the importance of rest-in-red operations as a targeted strategy for specific contexts, particularly at isolated or low-volume intersections. By requiring drivers to decelerate or stop before proceeding, this strategy effectively disrupts high-speed approaches and enhances driver awareness. However, its effectiveness depends heavily on reliable detection systems and careful implementation to avoid driver confusion. While not universally applicable, rest-in-red can serve as a valuable tool when deployed under appropriate conditions.

Another key conclusion is that pedestrian safety must be prioritized within nighttime operations. The research shows that treatments such as LPIs, RRFBs, PHBs, PS, and MPS significantly improve driver yielding behavior, pedestrian visibility, and compliance. Field evaluations confirm that these treatments reduce conflicts and crashes when

implemented in conjunction with improved lighting and supporting infrastructure. Given that a large proportion of pedestrian fatalities occur at night, these targeted interventions are essential components of any comprehensive nighttime safety strategy. On Fletcher Avenue, pedestrian-focused treatments led to substantial safety gains, with nighttime pedestrian crashes decreasing from 12 to three and bicycle crashes from five to zero, alongside improved driver yielding rates (100% at the Pedestrian Signal and 61.1% at RRFBs) and higher pedestrian compliance (83.3% push-button use and 100% crosswalk adherence at the PS at midblock site).

The findings further highlight that visibility improvements and lighting enhancements are foundational to nighttime safety. Adequate illumination directly improves drivers' ability to detect pedestrians, cyclists, and roadway features, thereby increasing reaction time and reducing crash likelihood. Statewide LED lighting initiatives have demonstrated substantial reductions in nighttime crashes, reinforcing the importance of investing in visibility improvements as a prerequisite for effective signal timing and operational strategies.

Emerging technologies, including adaptive signal control, AI-based video analytics, and CV systems, represent a promising pathway toward more proactive and data-driven nighttime traffic management. These technologies enable real-time monitoring and dynamic adjustments to signal operations, enhancing both safety and efficiency. However, the research also indicates that widespread implementation is currently limited by cost, infrastructure requirements, and the need for further validation of safety benefits. As such, these technologies should be viewed as complementary to, rather than replacements for, proven operational and infrastructure-based strategies.

A central conclusion of this study is that no single countermeasure is sufficient to effectively address nighttime safety challenges. Instead, the most successful outcomes are achieved through a layered and integrated approach that combines signal timing strategies, pedestrian treatments, visibility enhancements, and technology-based solutions. This holistic framework allows agencies to address multiple risk factors simultaneously and create a more predictable, forgiving, and safe roadway environment during nighttime conditions.

7.2 Recommendations

Based on the findings of this research, several key recommendations are provided to guide transportation agencies in improving nighttime arterial safety.

1. **Develop Nighttime-Specific Signal Timing Plans**

Agencies should move beyond traditional time-of-day signal plans and develop operational strategies specifically tailored to nighttime conditions. This includes implementing shorter cycle lengths, adjusting progression speeds to manage driving behavior, and transitioning to actuated or free operations during low-demand periods. Nighttime timing plans should prioritize safety over throughput and explicitly address risk factors such as speeding and unpredictable driver behavior.

2. Prioritize Speed Management Through Signal Operations

Given that excessive speed is a primary contributor to nighttime crash severity, agencies should incorporate speed management into signal timing design. Strategies such as signal progression with reduced progression speeds, intentional disruption of long green bands, and coordinated short-cycle timing should be applied to encourage compliance with desired operating speeds. These approaches can significantly reduce high-risk driving behavior and improve safety outcomes.

3. Expand Implementation of Pedestrian-Focused Treatments

Agencies should systematically deploy pedestrian safety treatments at high-risk locations, particularly along arterial corridors with nighttime pedestrian activity. Recommended treatments include LPIs, RRFBs, PHBs, and pedestrian signals, supplemented by high-visibility crosswalk markings, refuge islands, and ADA-compliant infrastructure. These measures are critical for improving pedestrian conspicuity and reducing conflicts with vehicles.

4. Invest in Lighting and Visibility Enhancements

Improving nighttime visibility should be considered a top priority. Agencies should expand LED lighting installations at intersections, crossings, and along corridors with high crash rates. Additional measures, such as retroreflective signal backplates, improved pavement markings, and reflective signage, should be implemented to enhance driver awareness and roadway comprehension. These improvements provide immediate and substantial safety benefits.

5. Ensure Reliable Detection Systems

Reliable detection is essential for the success of many nighttime strategies, including actuated control, rest-in-red operations, and adaptive signal timing. Agencies should evaluate the performance of existing detection systems and consider upgrading to radar, thermal, or LiDAR-based technologies that perform effectively under low-light conditions. Regular maintenance and calibration should also be prioritized to ensure continued reliability.

6. Adopt a Layered, Corridor-Level Approach

Rather than implementing isolated treatments, agencies should adopt a corridor-level strategy that integrates multiple safety measures. Combining signal timing adjustments with pedestrian treatments, lighting improvements, speed management strategies, and enforcement can produce synergistic effects and yield greater safety benefits than any single intervention alone.

7. Integrate Emerging Technologies Strategically

While advanced technologies offer significant potential, agencies should adopt a phased and strategic approach to implementation. Pilot projects should be used to evaluate the effectiveness of adaptive signal control, AI-based analytics, and CV applications. These technologies should complement existing strategies and be prioritized in locations with high crash risk or complex operational conditions.

8. Implement Data-Driven Monitoring and Continuous Improvement

Agencies should establish processes for ongoing performance monitoring and evaluation of nighttime operations. This includes analyzing crash data, near-miss events, traffic behavior, and system performance metrics. Tools such as ATSPMs can support data-driven decision-making and enable continuous refinement of implemented strategies.

9. Conduct Regular Nighttime Operational Reviews

Nighttime field reviews should become a standard practice to assess real-world performance under low-light conditions. These reviews can help identify issues related to visibility, detection, signal timing, and driver behavior that may not be apparent from daytime observations or data analysis alone.

10. Support Public Education and Enforcement

Finally, agencies should complement engineering strategies with education and enforcement efforts. Public awareness campaigns can help drivers understand new operational strategies, such as rest-in-red, while targeted enforcement can address nighttime behaviors such as speeding and impaired driving. A coordinated approach across engineering, education, and enforcement is essential for long-term success.

In summary, this research highlights that improving nighttime arterial safety requires a proactive, integrated, and context-sensitive approach. By implementing targeted signal timing strategies, enhancing visibility, prioritizing pedestrian safety, and leveraging emerging technologies, transportation agencies can create safer and more reliable

nighttime roadway environments. The adoption of these recommendations will not only reduce crashes and fatalities but also contribute to a more efficient and resilient transportation system for all users.

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Appendix A: Interview Questionnaire on Signal Timing Design and Operation Strategies to Improve Nighttime Arterial Safety

This interview is part of USF-CUTR's research for the Florida Department of Transportation (FDOT) focused on improving nighttime safety on urban and suburban roadways using traffic controls and signal timing strategies. The study seeks to identify challenges, strategies, best practices, success, and lessons learned in implementing the traffic signal controls and strategies to enhance safety after dark. The discussion will cover common safety concerns, driver behaviors, and nighttime-specific factors such as reduced visibility, speeding, vehicle speed judgment, distraction, and driver fatigue. Topics include strategies like flashing signals, actuated and pretimed modes, and "rest on red," using traffic signal progression to manage vehicle speed, as well as pedestrian-focused treatments. The interview will also examine the role of advanced technologies—such as video analytics, AI, automated detection, and connected vehicle applications—in supporting safer and more efficient nighttime operations.

1. What are the most common safety challenges related to traffic signals and signal timing during nighttime hours on urban and suburban roadways?
2. In your experience, which nighttime traffic signal operation strategy is better overall, and which is better for pedestrian safety, and why: (1) flashing yellow signals on main streets or flashing red signals on side streets, (2) signal operations on an actuated mode, signal progression in a short cycle in a pretimed mode, or rest on red during light traffic? How do these operation strategies affect driver behavior at night?
3. How do traffic signal timing strategies you know address nighttime driving behavior, particularly with regard to reduced visibility, speeding, available gaps for vehicle turning or vehicle speed judgment? Are they working?
4. Can you describe the practices for incorporating "signal rest on red" strategy at signalized intersections to improve nighttime safety when traffic volumes are low?
5. What is the effectiveness of using leading pedestrian intervals (LPI) and other pedestrian-focused signal strategies (e.g., rectangular rapid flashing beacon (RRFB), pedestrian hybrid beacon (PHB) to enhance pedestrian safety at night, especially on arterials with high traffic volumes?
6. What role does traffic signal progression play in managing vehicle speeds on arterials at night, especially in areas with pedestrian activities?

7. Video-based analytics and computer vision technologies are increasingly used for near-miss detection at intersections. How can these technologies be integrated with traffic signal operations to improve safety during nighttime hours?
8. What are the benefits and limitations of using AI-driven adaptive signal control to improve nighttime safety for pedestrians, cyclists, and motorists?
9. How can connected vehicle (CV) technology be integrated into signal timing systems to enhance nighttime safety for all road users, and what benefits or challenges have you observed in real-world applications?
10. Could automated pedestrian detection be used to improve signal timing during the night to better accommodate pedestrians? How can this technology be used to detect pedestrians earlier to provide safer crossing opportunities?
11. How do human factors, such as driver distraction, inattention, and fatigue during nighttime, affect nighttime signal timing design? What signal timing strategies can be implemented to mitigate these risks and enhance nighttime driving safety?

With the growing emphasis on smart city infrastructure, what emerging technologies do you foresee having the most potential for improving nighttime safety on urban and suburban roadways, particularly in terms of signal timing, vehicle and pedestrian interactions, and overall traffic management?

Appendix B: Survey Questions Regarding Driver's Perceptions of Speed Management

1. How frequently did you observe one or two downstream signals displaying red that could discourage you from speeding up as you drive along this corridor?

- *Always*
- *Often*
- *Rarely*
- *Never*

2. If you selected "Always" or "Often", what factors influenced your decision not to speed? *(Select all that apply)*

- *Expectation of stopping at upcoming signals when I speed up*
- *Belief that maintaining speed or lowering my speed would result in better signal progression*
- *Difficulty changing lanes to speed up due to surrounding traffic*
- *Vehicles ahead of mine*
- *Other (please specify): _____*
- *Not applicable*

3. If you selected "Rarely" or "Never", that means you usually or frequently saw many downstream green lights. How did this influence your behavior when approaching downstream intersections? *(Select all that apply)*

- *I was more likely to speed up to try to pass the next signal before it turned red*
- *My surrounding traffic went faster, so I was able to speed up*
- *I considered speeding up, but traffic conditions prevented it*
- *I was not influenced to speed up*
- *Other (please specify): _____*
- *Not applicable*