Understanding Bicycle Signal Operations and Leading Bicycle Interval (LBI) Implementations

Final Report

PREPARED BY

Center for Urban Transportation Research
University of South Florida

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CUTR Internal Award Project

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SECTION 1 Introduction

Bikes are among the sustainable modes of transportation and bicycling can help decrease congestion, reduce emissions, and enhance health. Due to their numerous benefits, they are currently one of the promoted modes in the United States. Yet, bicyclists are vulnerable roadway users and are subject to safety concerns. The safety challenges faced by bicyclists are more evident when looking at serious crashes. Although only 1.9% of total crashes are bicycle related, bicycle crashes account for 5.6% of fatal crashes (Alluri et al., 2017).

For years, Florida has had the largest number of bicyclist fatalities in the nation. As a result, the reduction of bicyclist crashes, including fatalities and injuries, is among the top priorities of the Florida Department of Transportation (FDOT). For example, there were 15,716 bicycle crashes in Florida in 2018 and 2019. Of these crashes, 316 were bicyclist fatalities, 1,616 were bicyclist incapacitating injuries, and 10,754 were bicyclist other injuries (Signal4Analytics). Of the 857 bicyclist fatalities that occurred nationwide in 2018, 19% occurred in Florida (NHTSA). The numbers for the last two years show an increase in these crashes in the state with 18,349 bicycle crashes in 2022 and 2023, among which 441 were fatalities and 1639 were incapacitating injuries (Signal4Analytics).

A 2019 New York City Department of Transportation study concluded that 89% of bicyclist fatalities and serious injuries happen at intersections. A statewide analysis of bicycle crashes considering crashes and facility types and crash hot spots in Florida demonstrated that most bicycle crashes happen at signalized intersections and on urban roadways (Alluri et al., 2017). Many of those crashes also occurred during wrong-way bicycling or during motorist right turn maneuvers (right hook crashes), as shown in Figure 1-1.

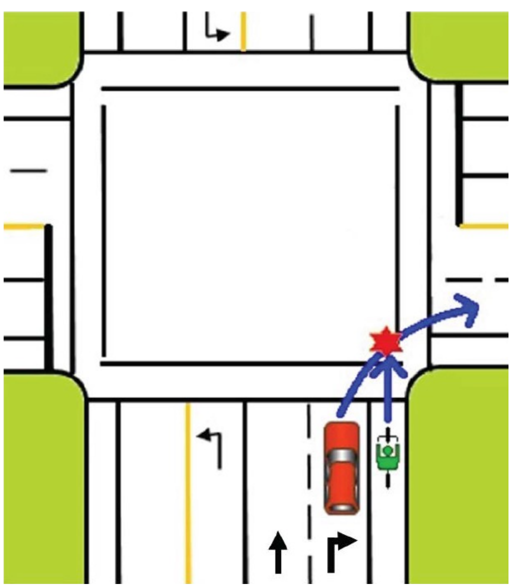


FIGURE 1-1

Right hook crash, common type of bicycle crashes at intersections

Source: Kothuri et al. (2018)

Addressing the safety challenges faced by bicyclists is increasingly important in Florida and in the nation due to the escalation of the number of bicycle users in the state and in the United States. Thus, it is important to consider bicycle facility improvements and innovative countermeasures to enhance the mobility and safety of vulnerable bicyclists. Based on previous studies, improving the safety of bicyclists at intersections and especially at signalized intersections will be among the most beneficial steps in reducing bicycle crashes. FDOT has already begun investing in innovative bicycle infrastructure and countermeasures. The first protected cycle track with bicycle signal heads at intersections in Downtown Tampa by FDOT District 7 is an example of groundbreaking efforts to ensure the safety and comfort of bicyclists throughout the state.

This research project aims to contribute to bicycle safety and treatment knowledge to help improve the experience of bicyclists in Florida and across the nation. It specifically focuses on signal timing control strategies or treatments at intersections that can help decrease the conflicts between bicycles and vehicles (especially turning vehicles). In addition to investigating bicycle signal operations in general, the study also focuses on leading bicycle interval (LBI), which could be useful where a bikeway on a through movement conflicts with turning traffic (NCHRP, 2020). The treatments either enable cyclists to clear the intersection or set their presence before priority is given to the rest of the traffic, which can prevent cyclist right turn collisions and in some cases left turn crashes as well. Findings from this study can be used and expanded in future work. Altogether, they can help improve bicycle safety in Florida and the United States and boost the attractiveness of that transportation mode.

1.1 Project Objectives

The objective of this research study was to evaluate bicycle signal operations across the nation and the world to identify national and international case studies. Another aim of the project was to explore LBI implementations. The results of this work can help practitioners understand bicycle signal operations and the safety benefits of using LBIs at locations, such as cycle tracks and intersections. The project can also help with widespread adoption of innovative and safe bicycle infrastructure across Florida in the future. The review and case studies can inform Florida’s future bicycle signal and LBI installations, and assist in reducing bicyclist crashes, fatalities, and injuries. Bicycle signal faces are now included in the 11th version of the Manual of Uniform Traffic Control Devices (MUTCD) published in December 2023; this research could assist with further details on how to implement bicycle signal treatments.

1.2 Organization of Report

The rest of this report is organized as follows: section 2 summarizes the literature review on bicycle signal operations and leading bicycle signal interval; section 3 elaborates on case studies; and section 4 provides conclusions.

SECTION 2 Literature Review

This section presents a summary of past work about bicycle signal operations and LBI. It encompasses criteria, requirements, considerations, conditions, evaluation results, and safety effectiveness of the treatments. Different types of bicycle signal operations (bicycle signals with exclusive and non-exclusive phases) are identified.

2.1 Bicycle Signal Operations

A bicycle signal is a signal that can show a green, yellow, or red indication with a bicycle-shaped symbol to give priority to different bicycle movements and to facilitate safe bicycle crossings (Figure 2-1 and Figure 2-2). The typical arrangements of bicycle signal faces included in the newly released MUTCD is shown in Figure 2-1. Bicycle signals enhance signal compliance and safety. They usually require leading or protected phases for bicycle movements during which conflicting vehicle movements are restricted (NACTO, 2011). Often, an extra phase is needed to the traffic signal cycle to accommodate bicycle signals. It is important to have bicycle signals at places with high bicyclist volume and turning vehicles or where bicyclists are dealing with a complex intersection (National Academies of Sciences & Medicine, 2020).

FIGURE 2-1

Typical arrangements of bicycle signal faces

Source: MUTCD (2023)

Various types of bicycle signals exist, including bicycle signal heads, active warning beacons, and hybrid signals for bike route crossing of major streets. This report focuses on the conventional bicycle signals at signalized intersections. Currently, there are also variations of bicycle signals at intersections. Some types of bicycle signals at signalized intersections include exclusive bicycle phases (protected bike signal and bike scramble) and non-exclusive bicycle phases (leading bicycle signal and split leading bicycle signals). Exclusive bicycle phases are explained next, and more information on non-exclusive bicycle phases is given later in the section on leading bicycle signal intervals.

FIGURE 2-2

Bicycle signal with exclusive bicycle phase

Source: National Academies of Sciences & Medicine (2020)

Protected Bike Signal

A protected bike signal involves a separate full signal phase for bikes and a full turning phase for vehicles. For the first phase (Phase A in Figure 2-3), bikes are given priority while right turning vehicles receive a red arrow. This is followed by the second phase (Phase B in Figure 2-3), where motor vehicles have their turn phase with a green arrow and a red signal for bikes. This treatment is most applicable for the locations under (or with) the following conditions (ITE, n.d.; NACTO, 2019):

- High turning vehicle volumes (if right turn volumes from the adjacent lane exceed 120 to 150 vehicles per hour or if conflicting left turn volumes (on two-way streets) across the bikeway exceed 60 to 90 vehicles per hour)
- Speeds at 30 mph or higher
- Low yielding behavior of drivers
- Multiple turn lanes exist across a bikeway

It is important to note that this treatment can lead to longer wait times and delays for motorists and sometimes for non-motorists. However, designing the signal progressions to bike-friendly speeds can decrease bicyclist delays caused by a separate turn movement (NACTO, 2019). Blank-out signs can be utilized during bicycle phases to prohibit right and left turns for vehicles.

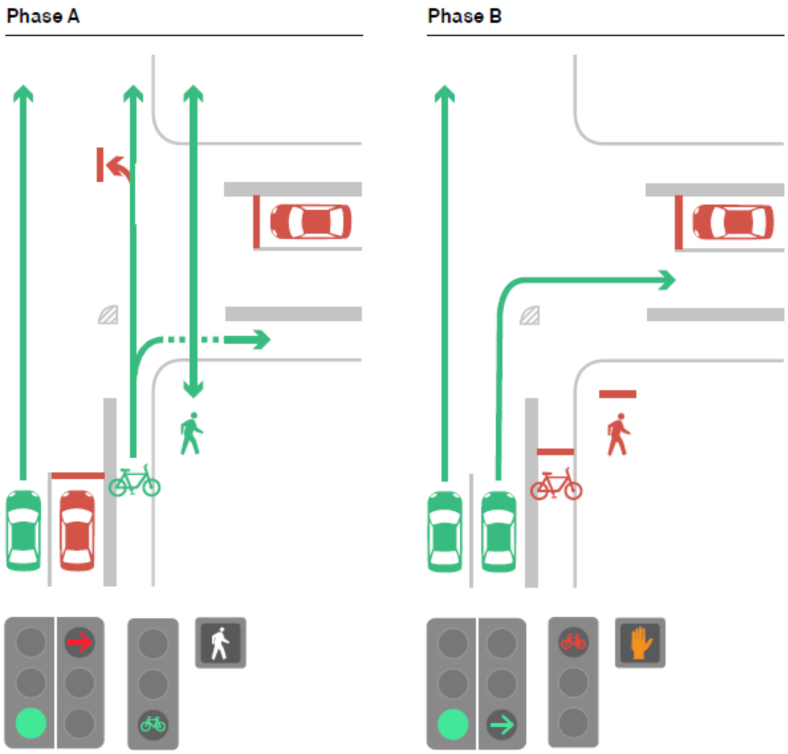


FIGURE 2-3
Protected bike signal

Source: NACTO (2019)

Another image demonstrating an example of a protected bike signal phase used for protected intersections for bicyclists is shown in Figure 2-4.

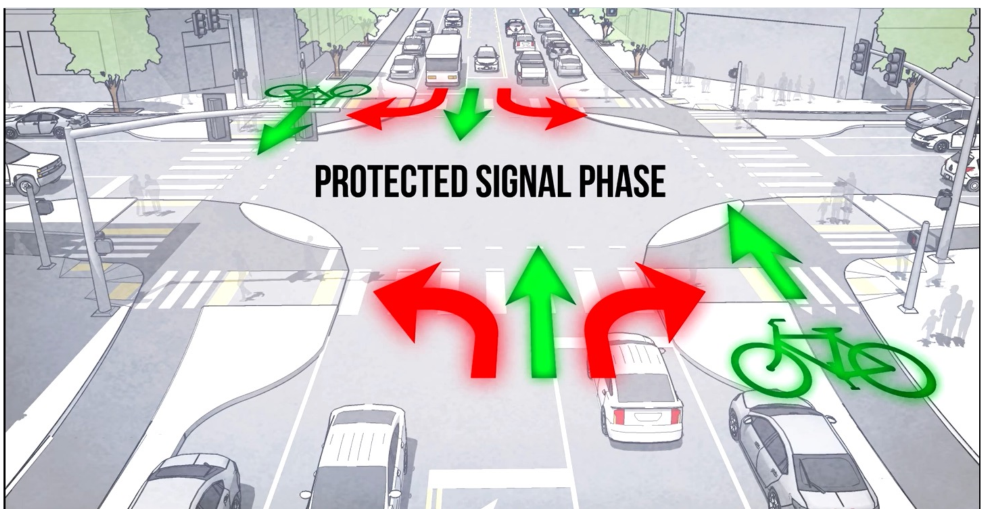


FIGURE 2-4
Protected bike signal phase used for protected intersections for bicyclists

Source: Falbo (2014)

Bike Scramble

In addition to the use of protected bike signal phasing at locations with high bike volumes, bicycle all-cross phasing, also known as bike scramble phasing, can be used (Figure 2-5). The bike scramble phasing provides additional time for cyclists to navigate through the intersection, particularly when there is significant demand for diagonal movements. The bike scramble is suitable for protected intersections; however, it is currently prohibited with the use of bicycle signal faces under MUTCD IA-16. The bike scramble has similar disadvantages as the protected bike signal phase, including the increase in delays at intersections for motorists and non-motorists.

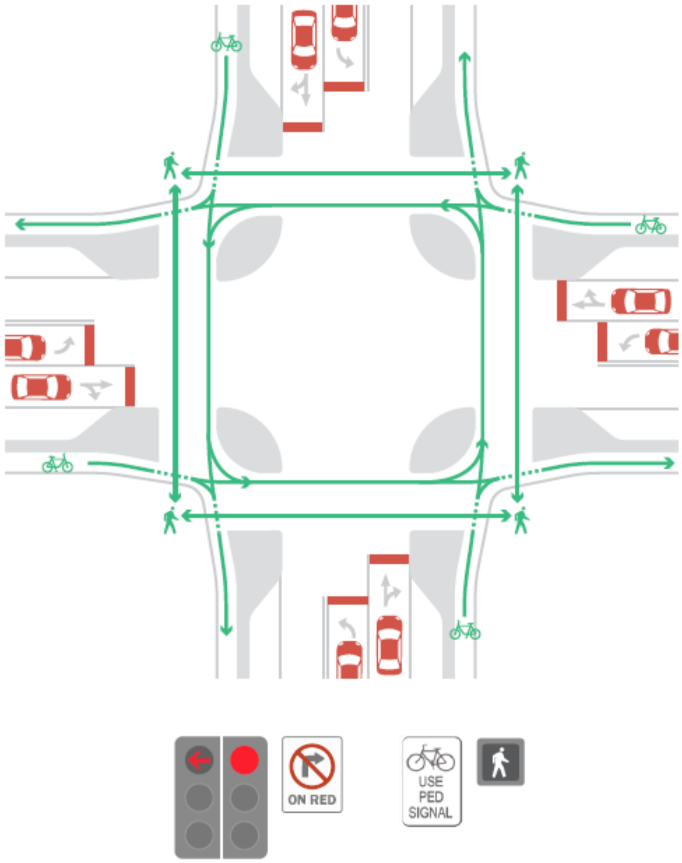


FIGURE 2-5

Bike scramble

Source: NACTO (2019)

2.1.1 Criteria and Requirements for Implementation

In general, bicycle signals should be installed at locations that meet the following criteria (National Academies of Sciences & Medicine, 2020):

- Signalized intersections with high bicycle volumes and high turning-vehicle volumes.
- Locations where a highly used bicycle route (including shared-use path) must cross a major, signalized intersection to connect users to the rest of the route (sometimes requiring bicyclists to cross diagonally).
- Intersections with contraflow bike lanes or separated bike lanes.
- Intersections where a bicycle facility transitions from a cycle track to a bicycle lane.
- Complex intersections that may otherwise be difficult for bicyclists to navigate.

The standards for bicycle signals in the newly released 2023 MUTCD state:

- A bicycle signal face may be used to provide a protected bicycle signal phase or a leading or lagging bicycle interval.
- If used, a bicycle signal face shall only be used to control bicyclist movements from a designated bicycle lane or from a separate facility, such as a shared-use path.
- If used, a bicycle signal face shall only be used to control bicyclist movements where bicyclists moving on a GREEN BICYCLE or YELLOW BICYCLE signal indication are not in conflict with any simultaneous motor vehicle movement at the signalized location, including right (or left) turns on red.
- Bicycle signal faces shall not be used to control conflicting bicyclist movements from perpendicular or nearly perpendicular directions.
- Bicycle signal faces shall not be used for controlling any bicyclist movement that is sharing an approach lane with motor vehicle traffic.
- Bicycle signal faces shall not be used in any manner with respect to the design and operation of a hybrid beacon.
- Bicycle signal (R10-40, R10-40a, R10-41, R10-41a, or R10-41b) sign shall be installed immediately adjacent to (including above or below) every bicycle signal face.

Further requirements for installing bicycle signals are explained in Table 2-1.

TABLE 2-1 *Bicycle Signal Requirements*

REQUIRED	
	The bicycle signal head shall be placed in a location clearly visible to oncoming bicycles
	If the bicycle phase is not set to recall each cycle, bicycle signal heads shall be installed with appropriate detection and actuation.
	An adequate clearance interval (i.e., the movement's combined time for the yellow and all-red phases) shall be provided to ensure that bicyclists entering the intersection during the green phase have sufficient time to safely clear the intersection before conflicting movements receive a green indication. "*In Davis, the current signal phasing provides for a minimum bicycle green time of 12 seconds and a maximum green time of 25 seconds. Additionally, a two-second all red interval is provided at the end of this phase as opposed to only one second at the end of other phases.* Metropolitan Transportation Commission. Safety Toolbox: Engineering. Bicycle Signals.
	If the bicycle signal is used to separate through bicycle movements from right turning vehicles, then right turn on red shall be prohibited if it is normally allowed. This can be accomplished with the provision of a traffic signal with red, yellow, and green arrow displays. An active display to help emphasize this restriction is recommended.

Source: NACTO (2011)

The estimated cost of bicycle signals is around $2,500 to $49,999 and rises with the number of signal heads and the type of bicycle detection used. For example, the price of loop detection is approximately $5,000 and a button for active detection also costs around $5,000. Additional conditions that can influence the price of bicycle signals include the availability of traffic signal conduit at the intersection and the age of the equipment (National Academies of Sciences & Medicine, 2020).

2.1.2 Considerations and Conditions for Implementation

In general, the type of bicycle signal that can be used at an intersection may depend on numerous factors, including speed limits, average daily traffic (ADT), anticipated bicycle crossing traffic, and the configuration of planned or existing bicycle facilities (NACTO, 2011). Bicycle signals can be of two types: active and passive (NACTO, 2011). For active bicycle signals or active detection, bicyclists need to push a button, which should be at an accessible location that does not require bicyclists to leave the road. Passive bicycle detection (Figure 2-6) is desirable as it automatically detects the presence of the user. Loop detectors, video, and microwave detection could be used to detect bicyclists (NACTO, 2011; National Academies of Sciences & Medicine, 2020), call a phase, or to extend a phase to enable bicyclists to clear an intersection. This may be useful for locations with minimum green times dedicated to car users that are unable to serve bicyclists (National Academies of Sciences & Medicine, 2020).

Bicyclists should be considered at signalized intersections that detect users. Well-designed detection can prevent dangerous behaviors, such as ignoring red signal indications, and can reduce delay at signalized intersections. Bicycle detection and signals can make travel convenient for bicyclists. Pavement markings and/or signs can help inform bicyclists of bicycle detection location. Combining passive and active bicycle detection could increase compliance and confirm to bicyclists that they have been detected. That may be useful until passive bicycle signal detection becomes more frequent, common, and reliable (National Academies of Sciences & Medicine, 2020).

FIGURE 2-6

Passive bicycle detection pavement markings

Source: National Academies of Sciences & Medicine (2020)

For example, the Street Transportation Department in Phoenix installed detection devices in the pavement at signalized intersections to sense stopped bicycles waiting to move through the intersections (Figure 2-7). The detection devices help to activate a green light for bicyclists, which enhances efficiency, reduces delay for bicyclists, and decreases red light running that is bicycle related. This was done without causing excessive delays to motorists (City of Phoenix).

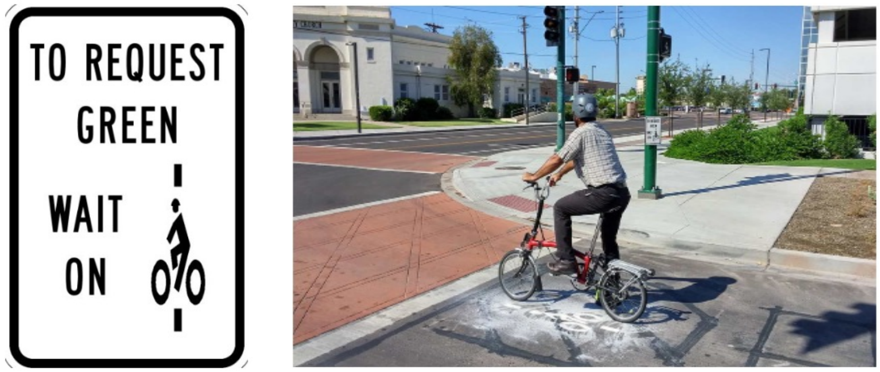


FIGURE 2-7
Bicycle detection in Phoenix

Source: City of Phoenix

When installing bicycle signals, a few important considerations are listed below (National Academies of Sciences & Medicine, 2020) are illustrated further in Table 2-2 to Table 2-5:

- Bicycle signals should be clearly visible to approaching bicyclists.
- Bicyclists' movements should be considered when selecting minimum green times and clearance intervals due to slower speeds and start-up times.
- Intersection crossing markings should be considered where the bicycle travel path through the intersection is unusual.
- Visual variations between vehicular signal heads and bicycle signal heads should be considered (e.g., size, backplate color).
- The signal should be installed with actuation and appropriate detection for bicyclists.
- Supplemental, near-side signals with smaller lenses and lower mounting height should be considered to provide additional clarity for bicyclists.
- The addition of separated or exclusive bicycle signal phases can increase delays for all users at the intersection, which may decrease compliance. As such, each intersection should be studied carefully to balance the safety and operational needs of pedestrians, bicyclists, and motorists.

TABLE 2-2 ***Bicycle Signal Recommendations***

RECOMMENDED	
	A supplemental "Bicycle Signal" sign plaque should be added below the bicycle signal head to increase comprehension.
	Signal timing with bicycle-only indications should consider having the signal recall with each cycle prior to implementation with detection. This will increase awareness of the interval for motorists and bicyclists. In a close network of signals, the timing should consider how often a bicyclist will be stopped in the system to insure that undue delay is not a result of the bicycle-only signal.
	Intersection crossing markings should be used where the bicycle travel path through the intersection is unusual (e.g., diagonal crossing) or needed to separate conflicts.
	Passive actuation of bicycle signals through loops or another detection method is preferred to the use of push-buttons for actuation where practical. Passive actuation is more convenient for bicyclists. If push buttons are used, they should be mounted such that bicyclists do not have to dismount to actuate the signal.

Source: NACTO (2011)

TABLE 2-3 *Bicycle Signal Recommendations (Continued)*

RECOMMENDED (CONTINUED)

There are currently no national standards for determining the appropriate clearance intervals for bicycle signals. However, the primary factors in choosing an appropriate clearance interval are bicyclist travel speed and intersection width. The following provides general guidance for selecting clearance intervals. This guidance should be tailored to local conditions using engineering judgment.

- At a minimum, the bicycle clearance interval should be sufficient to accommodate the 15th percentile biking speed (i.e., it should accommodate 85 percent of bicyclists at their normal travel speed). This is consistent with MUTCD guidance on pedestrian clearance intervals.
- Ideally, typical bicyclist speeds (V) should be measured in the field to determine a clearance interval appropriate for local conditions. However, at intersections with level approaches, 14 feet per second (9.5 miles per hour) may be used as a default speed in the absence of local data.

> *A research study collecting cyclist speeds on 15 trails throughout the United States found that the 15th percentile cycling speed is approximately 9.4 miles per hour.*
>
> Federal Highway Administration. (2006). Shared Use Path Level of Service Calculator. Publication: FHWA-HRT-05-138.

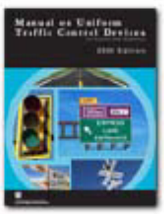
- Intersection width (W) should be calculated from the intersection entry (i.e., stop-line or crosswalk in the absence of a stop-line) to half-way across the last lane carrying through traffic.
- Calculate the total clearance interval (Ci) based on the following equation:

$$C_i = 3 + \frac{W}{V}$$

- Yellow intervals for automobiles will typically be shorter than those needed for bicycles, because of slower bicycle travel speeds. The intersection clearance time needed for bicyclists can be met partly through the automobile yellow interval, as well as through the all-red phase.
- The above guidance should be supplemented with engineering judgment as some wider intersections could be left with extremely long all-red signal phases.

Source: NACTO (2011)

TABLE 2-4 *Bicycle Signal Recommendations (Continued)*

RECOMMENDED (CONTINUED)	
	Bicyclists typically need longer minimum green times than motor vehicles due to slower acceleration speeds. This time is usually more critical for bicyclists on minor-road approaches, since minor-road crossing distance is typically greater than major-road crossing distance and minor-road crossings are often subject to short green intervals. Bicycle minimum green time is determined using the bicycle crossing time for standing bicycles. Some controllers have built-in features to specify and program a bicycle minimum green based on bicycle detection. However, if this is not available, and bicycle minimum green time is greater than what would ordinarily be used, the green time should be increased.
	Design and operation of bicycle signal heads should consider general MUTCD guidance on standards for traffic signals where applicable (e.g., positions of signal indications; visibility, aiming, and shielding of signal faces). Many of the MUTCD considerations for traffic signals will not apply to bicycle signals. Existing experience with bicycle signal installations in some cities has resulted in post mounted signals being utilized adjacent to the bikeway with a lower overall height. Such an installation functions more like a pedestrian signal than a vehicle signal. Some existing designs use shields and louvers to limit the driver's visibility of the bicycle signal to avoid any potential confusion. Engineering judgment should be used to ensure that the positioning of bicycle signal heads is optimal for each installation. It is recommended that bicycle signal heads be separated from motor vehicle signal heads by at least two feet to increase comprehension.

Source: NACTO (2011)

TABLE 2-5 ***Bicycle Signal Options***

OPTIONAL	
	For improved visibility, near-sided bicycle signals may be used to supplement far-side signals.
	Visual variation in signal head housing for the bicycle signal when compared to adjacent traffic signals may increase contrast and awareness.
	Near-side bicycle signals may incorporate a 'countdown to green' display to provide information about when a green bicycle indication will be provided. This treatment has proved popular in Europe, but there are currently no known installations in the United States.

Source: NACTO (2011)

The signal timings for intersections with bicycle signals should consider the following (ITE, n.d.):

- A minimum of 3 seconds and a maximum of 6 seconds for the yellow change interval.
- Cycle lengths of 60–90 seconds for quicker serviceability on bike-heavy approaches.
- Minimum greens could vary; 12 seconds is used by the city of Davis, California, and 8 seconds on major city bikeways in Portland, Oregon.
- Greater time for red clearance for bicyclists.
- Bicycle progression speed of 12–15 mph (19–24 kph).
- Recall and extension can be used for bicycle signals.

Bicycle signals are applied at specific locations or due to specific reasons, such as (NACTO, 2011):

- Where a stand-alone bike path or multi-use path crosses a street, especially where the needed bicycle clearance time differs substantially from the needed pedestrian clearance time.
- To split signal phases at intersections where a predominant bicycle movement conflicts with a main motor vehicle movement during the same green phase.
- At intersections where a bicycle facility transitions from a cycle track to a bicycle lane, if turning movements are significant.
- At intersections with contraflow bicycle movements that otherwise would have no signal indication and where a normal traffic signal head may encourage wrong-way driving by motorists.
- To give bicyclists an advanced green (like a leading pedestrian interval) or to indicate an "all-bike" phase where bicyclist turning movements are high.
- To make it legal for bicyclists to enter an intersection during an all-pedestrian phase (may not be appropriate in some cities).
- At complex intersections that may otherwise be difficult for bicyclists to navigate.
- At intersections with high numbers of bicycle and motor vehicle crashes.
- At intersections near schools (primary, secondary, and university).

2.1.3 Evaluation Results, Effectiveness, and Safety Benefits

This section covers evaluation results from different studies, effectiveness, and safety benefits of bicycle signals. For example, Oh & Kwigizile (2018) conducted a comprehensive analysis of bicycle signal systems implemented in various cities. The study examined the impacts of these systems on cyclist safety, intersection efficiency, and the overall experience of multimodal travelers. The authors collected data through field observations, surveys, and analysis of crash statistics. They conducted a two-pronged approach: before-after bicyclist surveys and VISSIM simulations. The findings of the study indicate that bicycle signal systems have a positive effect on improving safety for cyclists at urban intersections. The presence of dedicated signals for bicycles reduced conflicts between cyclists and motor vehicles, leading to fewer crashes and injuries. The study also highlighted that bicycle signals can enhance multimodal mobility by promoting the integration of cycling with other modes of transportation. The work emphasizes the importance of implementing appropriate bicycle signal systems based on the specific characteristics and needs of each intersection. The authors suggest that cities should consider factors such as traffic volume, intersection geometry, and cyclist behavior when designing and implementing bicycle signal systems.

Another study evaluated the effectiveness of two specific infrastructure treatments—bike boxes and protected intersections with bicycle signal treatments—in enhancing safety and multimodal mobility at urban signalized intersections. The author focuses on the challenges faced by cyclists when navigating through intersections and seeks to identify solutions that improve their safety and overall mobility. The author collects data from real-world scenarios, including observations, surveys, and analysis of relevant traffic and crash statistics. The findings of the study indicate that both bike boxes and protected intersections with bicycle signal treatments contribute positively to improving safety and multimodal mobility at urban signalized intersections. Protected intersections, which incorporate physical barriers and bicycle-specific signal treatments, enhance safety by separating cyclists from motor vehicle traffic and providing clear guidance for all users (Oh & Kwigizile, 2018).

Past work also investigated the understanding and recognition of bicycle signal faces by road users. It aimed to assess how well different user groups understand and interpret these specific signal faces designed for bicyclists. To conduct the study, Monsere et al. (2019) employed a combination of methods, including surveys, observations, and field tests. The authors examined the effectiveness of bicycle signal faces in conveying information to various road users, such as bicyclists, pedestrians, and motor vehicle drivers. The findings of the study shed light on road users' understanding of bicycle signal faces. The results showed variations across different user groups and pointed to factors causing those disparities.

The feasibility and efficiency of bicycle multi-phase crossing strategies at intersections was also investigated by Du, Wu, Qi, & Jia (2015). Using simulation models, the authors analyzed different multi-phase crossing designs specifically tailored for bicycle traffic at intersections. They evaluated the performance of these designs in terms of bicycle delay, throughput, and level of service. The study considers various factors such as intersection geometry, signal timing, and cyclist behavior to provide a comprehensive assessment. The findings of the study suggest that implementing bicycle multi-phase crossing strategies can effectively improve the efficiency of bicycle traffic at intersections. By separating bicycle movements into different signal phases, the authors observed reduced delays for cyclists and increased intersection capacity. The study also highlights the importance of considering the interaction between bicycles and other modes of transportation to optimize the overall performance of the intersection.

Another study conducted a comprehensive review of existing practices and regulations related to bicycle signals in the United States. Monsere, Figliozzi, Thompson, & Paulsen (2012) analyzed case studies, observed field installations, and examined the relevant literature on bicycle signal design and operation. Their work addresses various aspects, such as signal placement, detection technologies, signal timing, phasing options, and user behavior considerations. The authors provide insights into optimizing bicycle signal operations to enhance cyclist safety, improve traffic flow, and accommodate different intersection configurations.

Bicycle signals may decrease stress and delays for bicyclists and can discourage illegal and unsafe crossings (NACTO, 2011). Evidently, bicycle signals can improve bicycle safety at or near signalized intersections, as shown in Table 2-6. On the other hand, it should be noted that bicycle signals may increase delays for all other modes. Specific benefits of bicycle signal heads comprise the following (NACTO, 2011):

- Separate bicycle movements from conflicting motor vehicle, streetcar, light rail, or pedestrian movements.
- Priority to bicycle movements at an intersection (e.g., a leading bicycle interval).
- Accommodation of bicycle-only movements within signalized intersections (e.g., providing a phase for a contraflow bike lane that otherwise would not have a phase), though bicycle signals may also occur simultaneously with auto movement if combined with right-turn-on-red restrictions.
- Protection of bicyclists in the intersection, which may improve real and perceived safety in high-conflict areas.
- Improvement of operation and availability of appropriate information for bicyclists (as compared to pedestrian signals).
- Simple bicycle movements through complex intersections, which potentially improve operations or reduce conflicts for all modes.

TABLE 2-6 *Potential Effects of Bicycle Signals on Travel Modes*

Mode	Effect
Motorists	• May reduce crashes with bicyclists (Thompson et al. 2013) • May increase delay, depending on phasing
Bicyclists	• May increase safety
Pedestrians	• May reduce conflicts with bicyclists • May increase delay, depending on phasing
Large Trucks	• May reduce crashes with bicyclists • May increase delay, depending on phasing

Source: National Academies of Sciences & Medicine (2020)

The effectiveness of bicycle signals varies based on context. For example, Table 2-7 and Table 2-8 illustrate that bicycle signal operations can be highly effective if bicycle traffic is separated from other traffic. Bicycle signals are still moderately effective in other circumstances.

TABLE 2-7 *Recommended Countermeasures for Bicyclist Ride Through Signalized Intersection*

Effectiveness	Tier 1: Supports motorist yielding	Tier 2: Requires intervention to induce motorist yielding	Tier 3: Separate modes or require motorists to stop
High			Bicycle signals*
	Continuous raised median Crossing islands Lighting Parking restrictions/daylighting Passive bicycle signal detection* Protected intersections Road diet/rechannelization Roundabout Signal timing*	Continuous raised median Crossing islands Lighting Parking restrictions/daylighting Passive bicycle signal detection* Protected intersections Raised crossings Road diet/rechannelization Roundabout Signal timing*	Continuous raised median Crossing islands Grade-separated crossing Lighting Parking restrictions/daylighting Passive bicycle signal detection* Protected intersections Raised crossings Road diet/rechannelization Roundabout Signal timing*
Moderate	Bicycle signals*	Bicycle signals*	
	Curb extensions Mini-traffic signals Pedestrian countdown signals* Raised crossings Traffic signal	Curb extensions Grade-separated crossing Mini-traffic signals Pedestrian countdown signals* Traffic signal	Curb extensions Mini-traffic signals Pedestrian countdown signals* Traffic signal

*Countermeasures only appropriate for a signalized location.

Source: National Academies of Sciences & Medicine (2020)

TABLE 2-8 *Applicable Countermeasures to Various Issues*

Countermeasure	Effectiveness			Public Process	Motorist Traveling Straight							Motorist Turning			
	Tier 1: Supports motorist yielding	Tier 2: Requires intervention to induce motorist yielding	Tier 3: Separate modes or require motorists to stop	1 to 5 scale: 1 = no public process and 5 = extensive public process	Motorist failed to yield to pedestrian	Pedestrian failed to yield	Pedestrian dash	Bike crossing paths with uncontrolled motorist	Bike rides through/out – STOP sign	Motorist drives out into bike – STOP controlled	Bike rides through/out – signalized intersection	Motorist left turning into pedestrian parallel path	Motorist right turning into pedestrian parallel path	Motorist right turning into bike – same direction	Motorist left turning into bike – opposite direction
Active Warning Beacons	M	M	L	1	●	●	●	●	●			●	●	●	●
Advance Stop/Yield Lines	H	M	L	1	●	●	●	●	●						
All-Walk Phase	M	H	H	3	●	●	●					●	●		
Bicycle Lane Extension through Intersections	M	L	L	1				●		●				●	●
Bicycle Signals	M	M	H	1							●			●	●
Bike Boxes	M	M	M	1										●	
Continuous Raised Medians	H	H	H	4	●	●	●	●	●		●	●			●
Hardened Centerlines	H	H	H	1								●			●
Crossing Barriers	L	M	H	5	●	●	●	●							

Note: H = High, M = Medium, L = Low

Source: National Academies of Sciences & Medicine (2020)

As mentioned previously, bicycle signals have positive safety benefits and very positive user comfort benefits (Table 2-9). They do not require public process and have small spatial impact. Their relative cost is between $2,500 and $49,999.

TABLE 2-9 *Design Trade-offs of Safety Countermeasures*

	Spatial Impact	Estimated Cost	Maintenance Cost	Public Process	Motorists			Pedestrians			Bicyclists		
					Operations	User Comfort	Safety	Operations	User Comfort	Safety	Operations	User Comfort	Safety
Active Warning Beacons	Small	$$	$$	1	+ / -	+ / -	+ / -	+ / -	+	+	+ / -	+	+
Advance Stop/ Yield Lines	Small	$	$	1	+ / -	+ / -	+	+ / -	++	++	+ / -	++	++
All-Walk Phase	Small	$	$	3	- -	++	++	- -	++	++	- -	++	++
Bicycle Lane Extension through Intersections	Moderate	$	$	1	+ / -	+	+ / -	+ / -	+ / -	+ / -	+ / -	+	+
Bicycle Signals	Small	$$	$$	1	+ / -	+ / -	+ / -	+ / -	+ / -	+ / -	+ / -	++	+
Bike Boxes	Moderate	$$	$$	1	-	+	+ / -	+ / -	++	+	+	++	+
Continuous Raised Medians	Moderate	$$	$$	4	+ / -	+ / -	+	-	+	++	-	+	++
Hardened Centerlines	Small	$	$	1	+ / -	+ / -	+	-	+	++	-	+	++
Crossing Barriers	Moderate	$$	$$	5	++	++	++	- -	- -	++	- -	- -	++
Crossing Islands	Moderate	$$	$$	3	+ / -	+ / -	+	++	++	++	++	++	++
Curb Extensions	Moderate	$$	$$	1	+ / -	++	+ / -	++	++	+	++	++	+
Curb Radius Reduction	Moderate	$$	$$	1	- -	-	+	++	++	++	++	++	++
Gateway Treatments (R1-6 Signs)	Small	$	$	1	+ / -	-	+ / -	+	+	++	+	+	++
Grade-Separated Crossings	Large	$$$$	$$$$	5	+ / -	++	++	- -	- -	++	- -	- -	++

KEY

++ very positive benefit
+ positive benefit
+ / - neutral
- disbenefit
- - strong disbenefit

Relative Cost
$ = <2,500
$$ = 2,500–49,999
$$$ = 50,000–150,000
$$$$ = >150,000

Public Process
1. No public process, engineering decision
2. Public notice, engineering decision
3. Minimal public process, engineering decision
4. Moderate public process needed to build partner agency and community support
5. Extensive public process needed to build community and political support

Source: National Academies of Sciences & Medicine (2020)

2.2 Leading Bicycle Signal Interval

Leading bicycle intervals (LBIs) require non-exclusive bicycle phases (shown in Figure 2-8). They allow bicyclists to have a head start when crossing at a signalized intersection, which enables them to set presence or travel through the intersection before parallel vehicles. It can be programmed into existing signals with a minimum of 3 to 7 seconds between the green signals of bicyclists and vehicles. LBIs enable bicyclists to clear or to be seen when crossing the intersections before priority is given to motorists. The head start can reduce conflicts between bicyclists and motorists and can boost the percentage of motorists who yield the right-of-way to bicyclists. LBIs can be implemented at locations where an exclusive bicycle signal is not warranted because bicycle volumes are not high enough (National Academies of Sciences & Medicine, 2020). LBIs can be given automatically with each phase or can be actuated actively with bicyclists pushing a button or passively using bicycle detectors (National Academies of Sciences & Medicine, 2020). Different types of LBIs exist, including LBI and lagging left turn and protected-permissive bike signal, or split LBI.

FIGURE 2-8

Leading bicycle interval

Source: National Academies of Sciences & Medicine (2020)

Leading Bike Interval (LBI) & Lagging Left Turn

For signalized left turns on two-way streets, priority should typically be given to bikes and through/right motor vehicles during the initial phase. Right turns should yield to both bikes and pedestrians. Subsequently, left turns should be given priority in a dedicated phase following a red signal for oncoming bikes. The goal is to reduce conflicts between bike left turns and pedestrian left turns, as shown in Figure 2-9 (NACTO, 2019).

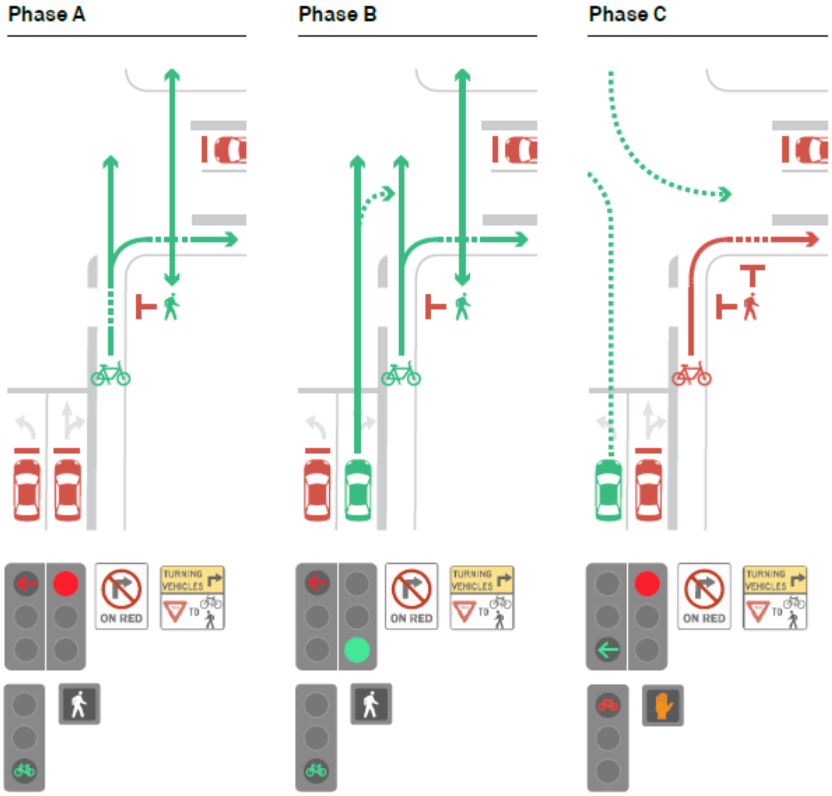


FIGURE 2-9

Leading bike interval (LBI) & lagging left turn

Source: NACTO (2019)

Protected-Permissive Bike Signal (Split LBI)

The protected-permissive signal, or split LBI, enables through bicycles to get green indication and a concurrent green indication for parallel through vehicles, while the right turn has either a red or a flashing yellow arrow turn phase, shown in Figure 2-10. This treatment can reduce the number of conflicts between bikes and turning vehicles. It can be applied at locations with moderate to high turn volumes, where vehicle storage is needed and vehicle speeds are low (at 25 mph or below). If a dedicated right turn lane is available near the bikeway, the split LBI should be considered. Otherwise, for a shared through/turn lane, the traditional LBI works better (NACTO, 2019). Thus, for the split LBI treatment only, the conflicting right turn movements are stopped when bikes are given priority. This variation of LBI enables the through movements to proceed without an increased delay. LBI and split LBI both demand vehicle compliance with right-turn-on-red restrictions (Kothuri et al., 2018).

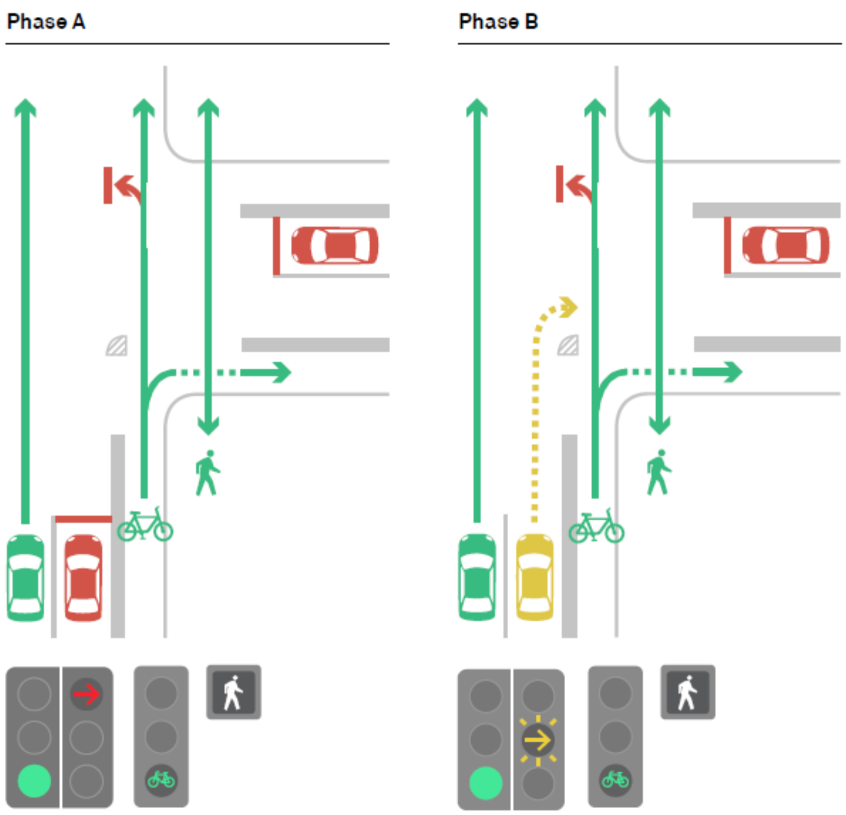


FIGURE 2-10

Protected-permissive bike signal, or split LBI

Source: NACTO (2019)

2.2.1 Criteria and Requirements for Implementation

LBIs should be implemented at these locations (National Academies of Sciences & Medicine, 2020):

- Intersections with high bicycle volumes and high turning-vehicle volumes.
- Locations where a highly used bicycle route (including shared-use path) must cross a major, signalized intersection to connect users to the rest of the route.
- Intersections with contraflow bike lanes or separated bike lanes.
- At intersections where a bicycle facility transitions from a cycle track to a bicycle lane.

2.2.2 Considerations and Conditions for Implementation

When implementing LBIs, it is important to consider or ensure the following (National Academies of Sciences & Medicine, 2020):

- Bicycle signals are clearly visible to approaching bicyclists.
- Minimum green times and clearance intervals include the slower speeds and start-up times of bicyclists' movements.
- Intersection crossing markings are present at locations where the bicycle travel path through the intersection is unusual.
- Visual variations between vehicular signal heads and bicycle signal heads are noticeable (e.g., size, backplate color).
- Actuation and passive and/or active detection for bicyclists are included with LBIs.
- Supplemental, near-side signals with smaller lenses and lower mounting height to provide additional clarity for bicyclists are used.
- Bicycle signals cost approximately $2,500–$49,999 and increase with the number of signal heads and the type of bicycle detection used. Loop detection costs approximately $5,000 and the cost of a button for active detection is around $5,000.

2.2.3 Evaluation Results, Effectiveness, and Safety Benefits

This part of the report synthetizes the evaluation results, effectiveness, and safety benefits of LBI treatments. Oh & Kwigizile (2018) assessed the positive safety effect of LBI at a selected intersection. The intersection was evaluated after adding 5 seconds of leading bicycle interval. The authors compared traditional signal timings (Based) to signal timings with LBI (Model 1) for different bike volumes. Instead of actual crashes, the authors used surrogate measurements to estimate the vehicle and bike conflicts with and without LBI at the same intersections. The results show that LBI can reduce the conflicts between vehicles and bicycles. The difference is more obvious for higher bike volumes (Figure 2-11).

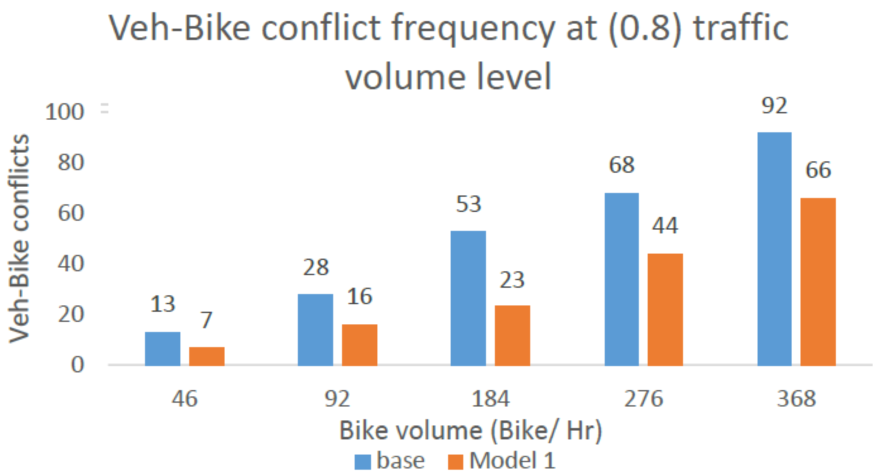


FIGURE 2-11
Evaluation results of LBI

Source: Oh & Kwigizile (2018)

LBIs can have systemic safety potential and can be used "as a spot treatment and on specific corridors where turning motorists may conflict with high bicycle through-traffic" (National Academies of Sciences & Medicine, 2020). They may increase safety for bicyclists and pedestrians but may increase delay for other modes, as shown in Table 2-10.

TABLE 2-10 *Potential Effects of LBIs on Travel Modes*

Mode	Effect
Motorists	• May increase delay
Bicyclists	• May increase safety • May reduce delay
Pedestrians	• May increase safety similar to a leading pedestrian interval (Fayish and Gross 2010) • May reduce delay
Large Trucks	• May increase delay

Source: National Academies of Sciences & Medicine (2020)

LBIs are applicable for when motorists turning into the path of bicycles and pedestrians (Table 2-11). They can be highly effective for all circumstances (tiers) and require no public process.

TABLE 2-11 ***Applicable Countermeasures to Various Issues***

Countermeasure	Effectiveness			Public Process	Motorist Traveling Straight							Motorist Turning			
	Tier 1: Supports motorist yielding	Tier 2: Requires intervention to induce motorist yielding	Tier 3: Separate modes or require motorists to stop	1 to 5 scale: 1 = no public process and 5 = extensive public process	Motorist failed to yield to pedestrian	Pedestrian failed to yield	Pedestrian dash	Bike crossing paths with uncontrolled motorist	Bike rides through/out – STOP sign	Motorist drives out into bike – STOP controlled	Bike rides through/out – signalized intersection	Motorist left turning into pedestrian parallel path	Motorist right turning into pedestrian parallel path	Motorist right turning into bike – same direction	Motorist left turning into bike – opposite direction
Crossing Islands	H	H	H	3	●	●	●	●	●		●	●			●
Curb Extensions	M	M	M	1	●	●	●	●	●	●	●	●	●	●	●
Curb Radius Reduction	M	M	M	1									●	●	
Gateway Treatments (R1-6 Signs)	H	M	L	1	●	●	●	●							
Grade-Separated Crossings	L	M	H	5	●	●	●	●	●	●	●	●	●	●	●
High-Visibility Crosswalk Markings	H	H	H	1	●	●	●	●	●	●		●	●	●	●
In-Street Pedestrian Crossing Signs	H	M	L	1	●	●	●	●	●						
Leading Bicycle Interval	H	H	H	1								●	●	●	●
Leading Pedestrian Interval	H	H	H	1								●	●	●	●
Lighting	H	H	H	4	●	●	●	●	●	●	●	●	●	●	●
Mini-Traffic Circles	M	M	M	4	●	●	●	●	●	●	●	●	●	●	●
Mixing Zone Treatments	M	L	L	3										●	
No Turn on Red Signs	H	H	H	1									●	●	

Note: H = High, M = Medium, L = Low

Source: National Academies of Sciences & Medicine (2020)

LBIs have positive safety, operation, and user comfort benefits for both bicyclists and pedestrians (Table 2-12). The relative cost of an LBI is between $2,500 and $49,999.

TABLE 2-12 *Design Trade-offs of Safety Countermeasures*

	Spatial Impact	Estimated Cost	Maintenance Cost	Public Process	Motorists			Pedestrians			Bicyclists		
					Operations	User Comfort	Safety	Operations	User Comfort	Safety	Operations	User Comfort	Safety
High-Visibility Crosswalk Markings	Small	$	$	1	+ / -	+	+ / -	+	+	+	+	+	+
In-Street Pedestrian Crossing Signs	Small	$	$	1	+ / -	-	+ / -	+	+	+	+	+	+
Leading Bicycle Interval	Small	$$	$$	1	-	+	+ / -	+	+	+	+	+	+
Leading Pedestrian Interval	Small	$	$	1	-	+	+ / -	+	++	+	+	++	+
Lighting	Small	$$	$$	4	+	+	++	+	+	++	+	+	++
Mini-Traffic Circles	Large	$$	$$	4	-	-	+	-	-	+	-	-	+ / -
Mixing Zone Treatments	Moderate	$$	$$	3	+	+ / -	+ / -	+ / -	+ / -	+ / -	+ / -	-	+
No Turn on Red Signs	Small	$	$	1	- -	+ / -	++	++	++	++	++	++	++
Parking Restrictions at Crossing Locations/ Daylighting	Moderate	$	$	2	+ / -	+	++	+	+	++	+	+	++
Passive Bicycle Signal Detection	Small	$$	$$	1	+ / -	+ / -	+ / -	+ / -	+ / -	+ / -	++	++	+
Pedestrian Countdown Signals	Small	$$	$$	1	+ / -	+ / -	+ / -	+	++	++	+	++	++
Pedestrian Hybrid Beacon	Small	$$$	$$$	4	-	+	+	+	++	++	+	++	++
Protected Intersections	Large	$$$$	$$$$	3	-	++	+	+	++	++	++	++	++
Protected Phases	Small	$	$	4	- -	++	+	- -	++	++	- -	++	++
Raised Crossings	Moderate	$$	$$	3	-	-	+	++	++	++	++	++	++

KEY

++ very positive benefit
\+ positive benefit
\+ / - neutral
\- disbenefit
\- - strong disbenefit

Relative Cost
$ = <2,500
$$ = 2,500–49,999
$$$ = 50,000–150,000
$$$$ = >150,000

Public Process
1. No public process, engineering decision
2. Public notice, engineering decision
3. Minimal public process, engineering decision
4. Moderate public process needed to build partner agency and community support
5. Extensive public process needed to build community and political support

Source: National Academies of Sciences & Medicine (2020)

SECTION 3 Selected and Innovative Case Studies

Bicycle signal heads or faces are widely used in Europe and China, as well as in some US cities, including Davis, CA, San Luis Obispo, CA, San Francisco, CA, Portland, OR, New York, NY, Alexandria, VA, Washington, DC, and Austin, TX, as shown in Figure 3-1 (NACTO, 2011).

FIGURE 3-1

Examples of bicycle signal operations at various places

Source: NACTO (2011)

It can be seen in Figure 3-2 that bicycle signal faces are similar for different locations with some variations (use of arrows) for the ones in Utrecht, Netherlands, and Shanghai, China.

FIGURE 3-2

Examples of international bicycle signal faces

Source: Monsere et al. (2019)

Beijing, China
Credit: D. Hurwitz, Oregon State University, used by permission

Lima, Peru
Credit: A. Clarke, Toole Design Group, used by permission

Shanghai, China
Credit: D. Hurwitz, Oregon State University, used by permission

Utrecht, Netherlands
Credit: A. Clarke, Toole Design Group, used by permission

Vancouver, B.C. Canada
Credit: C. Monsere, Portland State University, used by permission

London, United Kingdom
Credit: S. Kothuri, Portland State University, used by permission

This section summarizes a few implementations of bicycle signal operations, including LBIs, in the nation and across the world. Looking at these innovative examples from across the world and understanding the differences and similarities can offer more insights into the future and widespread implementation in Florida.

3.1 Portland, Oregon

Portland, having many implementations of bicycle signals, is among the pioneers of bicycle infrastructure and bicycle signal operations in the United States. One example is the implementation of the protected bicycle signals on Naito Parkway (Figure 3-3), a major bike corridor connecting Waterfront Park and downtown (Maus, 2017). The bicycle signals on Naito Parkway improve the overall bicycle network in the area.

FIGURE 3-3

Example bicycle signal in Portland

Source: Maus (2017)

In downtown Portland, most of the signals are timed with a progression speed between 11 and 12 mph, which is a typical bicycling speed. Portland has also imported a new type of bicycle signal from the Netherlands that has been installed at a few intersections in the city, such as on Naito Parkway. The new signal type provides bikers with information that shows they have been detected and shows a countdown of the time left that they need to stop (Figure 3-4).

FIGURE 3-4

New type of bicycle signal imported from the Netherlands to Portland

Source: Griggs (2022)

3.2 New York City, New York

New York City has implemented and evaluated the effectiveness of various intersection treatments for bicyclists, including mixing zone, fully split phase, delayed turn, and offset crossing. Figure 3-5 shows the full split phase and delayed turn and Table 3-1 gives the description of each of the four treatments.

■ FIGURE 3-5

Examples of fully split phase and delayed turn in New York City

Source: Sundstrom et al. (2018)

TABLE 3-1 *Summary of the Bicycle Signal Treatments in New York City*

SUMMARY OF PROTECTED BIKE LANES INTERSECTION DESIGNS

	Mixing Zone **Primary treatment**	**Fully Split Phase** **Primary treatment**	**Delayed Turn** (AKA Split LBI) **Pilot treatment**, not in widespread use	**Offset Crossing** **Pilot treatment**, not in widespread use
Description	Parking is removed on the approach to the intersection to create visibility between bicyclists and turning motorists. Motorists are provided yield signs and markings while the bicycle lane converts to a shared area where motorists and bicyclists negotiate their movements.	Provides a dedicated turn lane adjacent the bicycle lane. Turning movements across the bike lane happen in a dedicated phase with a green turn arrow during which bicyclists are held with a red bicycle signal.	Bicycles receive a conflict free head start (10 sec. min.) with a green bicycle signal. Following this head start, turning drivers receive a Flashing Yellow Arrow (FYA) and may turn after yielding to people walking and bicycling.	Dutch style treatment within the intersection that features a tight corner radius to slow vehicle turns and a modest deflection of the bike lane to allow for reaction time and queuing space. The conflict between cyclists and motorists is constrained to middle of intersections.
Benefits	Bicyclists receive all of the through phase green time, reducing their delay. Removes the turning vehicle from the through lane allowing the driver to focus on bicycle and pedestrian traffic.	Complete separation in time and space between through bicyclists and turning vehicles. Removes turning vehicles from through lanes improving traffic capacity.	Bicyclists proceed with no conflict for part of through phase. Allows for the installation of Leading Pedestrian Intervals with no capacity impacts for through vehicles.	Slowed turn with a short conflict zone between bicyclists and turning vehicles. A continuous bike lane enhances the sense of security and creates more predictable movements.
Parking loss	Medium	High	High	Low
Challenges	The shared space in advance of intersection can increase bicyclist stress levels. The design creates unpredictable bicycle movements.	Little green time for bicyclists (1 of 3 phases) creates delay and can result in frequent non-compliance by bicyclists. High loss of parking and typically a reduced turning vehicle capacity.	Driver comprehension of the FYA may be low. The placement of the bike lane between the curb and turning path of vehicles places bicyclists in a potentially unexpected and less visible location. High parking loss.	A new, unfamiliar design where drivers may recognize bicyclists late in turn. Requires an amount of street space that may not always be available and turning vehicles may block the through lanes.
Typical use	One-lane cross streets where a Leading Pedestrian Interval (LPI) is not needed.	Multi-lane cross-streets; higher speed roadways; locations with no gap in pedestrian traffic; in conjunction with a LPI.	Where a LPI is needed but some curbside use needs to be retained compared to Fully Split; moderate pedestrian and turning volumes.	Cross streets with a low turning volume and sufficient roadway width for design.
				

Source: Sundstrom et al. (2018)

The result of the safety effectiveness of the treatments with available crash data demonstrates a decrease in bicycle crashes per bicyclist at those intersections (Table 3-2). Guidelines on when and where to use each of the four treatments in New York City are included in Table 3-3.

TABLE 3-2 *New York City Intersection Treatments Evaluation Results*

Change in Intersection Injury Bicycle Crashes per Million Bicyclists from *before* PBL installation[1]

Treatment	Study Sites	Before	After	Crash Rate Change
Current Generation Mixing Zone[2]	71	1.9	1.4	-27%
First Generation Mixing Zone[2]	55	2.1	1.7	-21%
Fully Split Phase	53	4.3	2.0	-54%
All Study Intersections[3] (Mixing Zones and Fully Split Phase)	184	2.5	1.7	-30%

1) Calculated from 2000-2017 bicycle crashes and volumes
2) The first generation mixing zones are designed with a longer shared lane between cyclists and turning vehicles
3) Includes 5 non-Mixing Zone or Fully Split Phase intersections

Source: Sundstrom et al. (2018)

TABLE 3-3 *Intersection Design Matrix for the Bicycle Treatments*

INTERSECTION DESIGN MATRIX FOR ONE-WAY PBLS

Application Considerations[1]		Mixing Zone	Fully Split Phase	Delayed Turn (AKA Split LBI) Continue with limited use under specific conditions	Offset Crossing
Along a one-way street with cross-street lanes:	1	Preferred for higher turn volumes	Preferred when a gap in ped traffic is required to process traffic	Possible for turn volumes <150/hr where a LPI is needed	Preferred for turn volumes <120/hr
	2+	Possible with turn volumes <60/hr	Preferred	Possible with turn volumes <60/hr where a LPI is needed	Possible with turn volumes <60/hr
Cross-street is two-way		Possible with turn volumes <80/hr and LTTC	Preferred	Possible with turn volumes <150/hr and LTTC	Possible with turn volumes <80/hr and Left Turn Traffic Calming (LTTC)
PBL is along a two-way street[2]		Consider when left turns <50/hr[3]	Consider when left turns >50/hr	Consider when left turns <50/hr[3]	Consider when left turns <50/hr[3]
Leading Pedestrian Interval		Possible with sign: 'Bikes May Use Ped Signal'	Possible	Possible	Possible with bike signal or sign: 'Bikes May Use Ped Signal'
Curb space needed (parking/loading loss)		Typically 90 ft	Typically 130 ft - Based on 85th percentile queue	Typically 110 ft	Typically 25 ft on mainline and 20 ft on narrow cross-streets
Speed limit ≥30mph		Not recommended	Preferred	Not recommended	Not recommended
Other considerations		• The current, shorter design should be used • If used at multilane cross-streets, traffic calming and visibility measures should be included • Consider context (e.g. schools, paths, etc.) where more comfortable designs with the tradeoffs such as higher delay may be desirable	• Turn lane/bay is req'd, of a length that can store all turning vehicles • Consider where a lower stress connection is preferable • Where multiple turn lanes/turning movements cross the impacted crosswalk/bike facility • No gap for turning vehicles due to high pedestrian and bike volumes • If several split phases are used along a corridor, a progression speed for bicyclists should be considered	• **Continue with limited use when a LPI without delaying through traffic is needed – must meet conditions in this table** • **Preferred installation is at a two-way cross-street w/ LTTC due to additional maneuvering space before conflict** • **Not recommended at downhill locations where cyclist speed may be higher** • Moderate turning volumes, but minimal storage space for turning lane/bay • High through volumes that would be delayed by a standard LPI • A turn lane or bay is required	• A 15 ft offset requires approximately 17 ft from curb to edge of travel lane • If used at multilane cross-streets, traffic calming and visibility measures should be included (i.e. high visibility markings, LTTC) • If a turn lane is provided, the full 15 ft offset may be reduced • Operationally not recommended on streets with >300 through veh/lane/hour • Truck and bus routes require additional care • Requires 40 ft of clear distance on approach to the Point of Curvature

1. This table provides planning guidance for typical intersection conditions, site specific conditions may require different design approaches
2. This threshold may be increased if there is only one opposing lane
3. On a two-way street, the right turn treatment should be selected separately
NOTE: As the knowledge base is always evolving, the design matrix will be updated periodically to reflect new information and best practices.

Source: Sundstrom et al. (2018)

3.3 Washington, DC

In 2014, Washington, DC, published its transport master plan called MoveDC that promoted safe bicycling in the city (Buehler, Teoman, & Shelton, 2021). As part of the plan, the bicycle network is anticipated to be expanded to 136 miles of bike lanes, 72 miles of protected bike lanes, and 135 miles of trails built by 2030. The plan also encourages the implementation of actuated bicycle signalization and special bicycle signals at key locations (Buehler et al., 2021). Currently, bicycle infrastructure and bicycle signals are increasingly being implemented throughout the district. For example, Figure 3-6 and Figure 3-7 are examples of recent images (taken in 2024) of some bicycle signals in the area.

FIGURE 3-6
Example of bicycle signals in Washington, DC

FIGURE 3-7
Example of bicycle signals and infrastructure in Washington, DC

3.4 Phoenix, Arizona

The City of Phoenix has implemented its first bicycle traffic signal at the intersection of 12th Street and Campbell Avenue, which also includes LBI. The bicycle signal and LBI (Figure 3-8) reduce conflicts between bicyclists and turning motorist traffic and allow bicyclists to change lanes or turn left. In Phoenix, as well as in other large bicycle-friendly cities such as Washington, DC, and Portland, Oregon, “the LBI uses a three-step stoplight process that is only triggered after a bicycle approaches the intersection and waits in the bike lane” (City of Phoenix).

FIGURE 3-8
Bicycle signal and LBI in Phoenix, Arizona

Source:
City of Phoenix

3.5 Tucson, Arizona

The first bicycle signal was installed in Tucson, Arizona, in 1998 at the intersection of Third Street Bicycle Boulevard and Country Club Road. Third Street Bicycle Boulevard runs east of the University of Arizona and sees 3,000-plus cyclists and 500 motor vehicles per day, while Country Club Road is a busy four-lane arterial with a traffic volume of 30,000-plus vehicles per day. The signal, which is activated by cyclists with a push button, provides a signal protected crossing for bicyclists and pedestrians on roads that prioritize non-motorized traffic. The signal and center median were placed at a cost of $400,000. The data evaluation demonstrated a 100% increase in bicycle traffic on Third Street Bicycle Boulevard. Several other bicycle signals were installed at intersections in Tucson, but at minimized costs (NACTO, 2011).

FIGURE 3-9

Tucson, Arizona, first bicycle signal

Source: NACTO (2011)

3.6 Davis, California

A bicycle signal head was installed in Davis, California, which was found to be effective for both motorists and bicyclists in reducing conflicts between the various modes passing through the intersection. The effectiveness of the bicycle signal head was also confirmed when the crash data was evaluated. For example, at the intersection of Sycamore and Russell, considering two years before and after installation, the bicycle and motor vehicle crashes decreased from 16 to zero (NACTO, 2011).

3.7 London, United Kingdom

London has introduced the United Kingdom's first low-level traffic signals for cyclists, inspired by continental practices. Following successful off-street trials in collaboration with the Department for Transport, the signals have been installed at Bow Roundabout. These signals, aligned with Mayor Boris Johnson's £913m "Vision for Cycling," aim to enhance safety by displaying signals at cyclists' eye level. Transport for London (TfL) has sought permission to extend the trial across the city. While welcomed by cycling advocates, the London Cycling Campaign emphasizes that low-level lights alone cannot address fundamental safety issues, citing concerns at Bow Roundabout regarding cyclists' vulnerability to turning traffic. However, they aim to improve the conditions for bicyclists (BikeBiz, 2014). This roundabout intersection design was inspired by the Dutch design and is shown in Figure 3-10 and Figure 3-11. The first figure shows the proposed LCC Bow Roundabout design with bicycle signals and bike lanes in blue, while the second figure shows the intersection design in Chorlton, Greater Manchester, with green lanes denoting bicycle lanes and crossings.

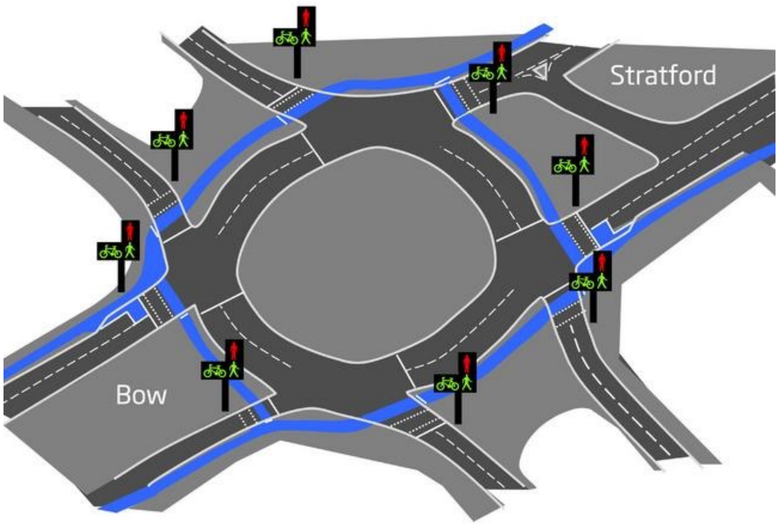


FIGURE 3-10
LCC Bow Roundabout bicycle design

Source: Macmichael (2011)

FIGURE 3-11
Proposed CYCLOPS junction in Chorlton, Greater Manchester

Source: Reid (2019)

3.8 Amsterdam, Netherlands

The Dutch have been pioneers in advancements and implementations of bicycle infrastructure, including bicycle signals and leading bicycle intervals. A lot of countries and cities have taken the example of the Dutch roundabout bicycle intersection, which facilitates smoother bicycle turning movements/maneuvers and reduces conflicts between vehicular traffic and bicyclists. Traffic controlled junctions with a separate cycle path and fully segregated signalized junction (roundabout type design) with bicyclist eye level signals are some of the designs implemented in multiple intersections in the Netherlands (Figure 3-12 and Figure 3-13).

FIGURE 3-12
Traffic light controlled junction

Source: BicycleDutch (2014)

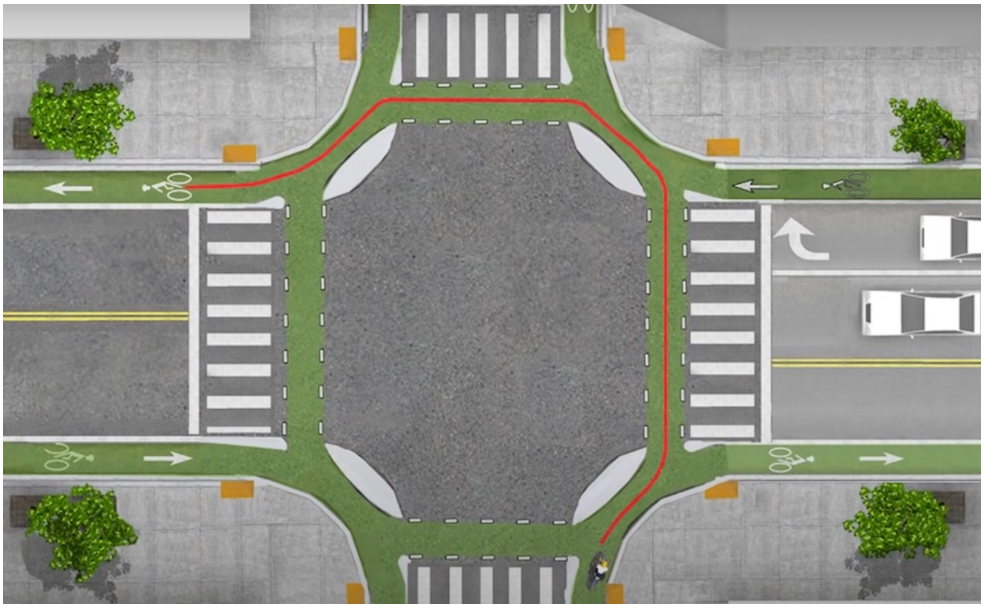


FIGURE 3-13
Fully segregated signalized junction

Source: BicycleDutch (2012)

3.9 Copenhagen, Denmark

Copenhagen, known for its bike-friendly environment, is revamping its traffic signaling system with 380 intelligent lights, including bicycle signals covering every downtown intersection. This $8.8 million investment prioritizes signaling based on approaching road users, aiming to ease traffic flow and reduce congestion. The online lights, a first in Scandinavia, specifically cater to bikes and public transit, ensuring dedicated signaling. Anticipated benefits include a 5–20% reduction in bus travel times and a 10% decrease in bike travel times. Copenhagen's initiative reflects a commitment to modernize its traffic system, enhancing efficiency and promoting sustainable modes of transportation in response to evolving urban needs (Angus, 2016).

3.10 Frankfurt, Germany

The City of Frankfurt in Germany has a plan to link neighborhoods to downtown. As part of that endeavor, the City installed bicycle traffic signals at the intersections of major roadways (Buehler et al., 2021). The year 2019 was a significant milestone for cycling in Frankfurt. As part of the work, the redesign of 15 major intersections to better adapt cyclists through infrastructure measures and signal timing was planned. This connection allows the City to provide direct, fast, and safe cycling routes (Buehler et al., 2021).

SECTION 4 Conclusion

This project evaluated bicycle signal operations with more focus on leading bicycle signal intervals (LBIs). A comprehensive literature review was conducted to gather information on bicycle signals in general and LBIs in particular. In addition to the general information, details were given related to the implementation criteria, requirements, considerations, and conditions of the bicycle signal operations and LBIs. During the review, various implementation cases were assessed and information on selected cases was also summarized in this report.

The findings from the project can be summarized as follows:

- Bicycle signals should be implemented at signalized intersections with high bicycle volumes, high turning-vehicle volumes, with bicycle lanes, or separate bicycle facilities (i.e., cycle track).
- They may also be considered for complex intersections that are difficult for bicyclists to navigate.
- Bicycle signals should be visible and must be installed with actuation and appropriate detection for bicyclists.
- Bicycle signals should be installed with bicycle signal signs, passive bicycle detection sign, and bicycle detector pavement markings.
- Despite the many safety benefits of the various strategies explored in this report, it should be noted that bicycle signal treatments (both protected bicycle signal phases and LBIs) can lead to more delays for motorists and for some non-motorists.
- LBIs and split LBIs can be used at intersections that do not need protected bicycle signals because of the volumes (can be applicable for moderate turn volumes) or where concurrent movements of bicyclists and motorists are needed. They can be used for spot or systemic treatments. The treatments can enhance the safety of bicyclists with reduced delays for other modes. LBI and split LBI both demand vehicle compliance with right-turn-on-red restrictions. Thus, their implementations with no-turn-on-red signs may be useful. For shared through/turn lane, the traditional LBI works better.
- If a dedicated right turn lane is available, then split LBI or protected bike signal can be used.
- Designing the signal progressions to bicycle speeds can also help reduce bicyclist delays created due to separate turn movements.

Overall, bicycle signal treatments can enhance the safety of bicyclists, encourage bicycling, and lead to more livable and sustainable communities. Example implementations of bicycle signals are available across the world and in the

United States. The report summarizes the bicycle signal implementations at a few locations across the world. Some of the places have a long history of bicycle infrastructure and some are recently focused on developing and enhancing the infrastructure. Some innovative practices are also included as part of the summary. The case study locations considered in the report include:

- Portland, Oregon
- New York City, New York
- Washington, DC
- Phoenix, Arizona
- Tucson, Arizona
- Davis, California
- London, United Kingdom
- Amsterdam, Netherlands
- Copenhagen, Denmark
- Frankfurt, Germany

Future Research

Future research could conduct more in-depth case studies for further guidance of widespread implementation in Florida. Innovative practices could be identified and their effectiveness should be assessed. An inventory of the different bicycle signal treatments in Florida could be done to see what would be useful for Florida. The study could help develop specific guidelines for extensive bicycle signal implementations in Florida, especially with the inclusion of bicycle signal faces in the 11th edition of MUTCD.

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PREPARED BY

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University of South Florida

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