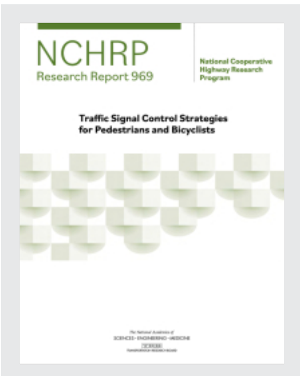

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 969

Traffic Signal Control Strategies for Pedestrians and Bicyclists

Kittelson & Associates, Inc.
Washington, DC

IN ASSOCIATION WITH

Northeastern University
Boston, MA

Accessible Design for the Blind
Asheville, NC

Wayne State University
Detroit, MI

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TRANSPORTATION RESEARCH BOARD

2022

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

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The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the FHWA. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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FOREWORD

By Camille Crichton-Sumners
Staff Officer
Transportation Research Board

NCHRP Research Report 969: Traffic Signal Control Strategies for Pedestrians and Bicyclists provides practical tools to aid in traffic signal design and the selection of operations strategies for varied geometric design configurations. The guide places emphasis on accessibility for pedestrians and bicyclists, reflecting the increased demand for active and sustainable transportation. It will be of immediate use to practitioners responsible for traffic signal design and operations.

Pedestrians and bicyclists share the road with motor vehicles, making short trips that traverse signalized intersections in urban and rural settings. Traffic signal timing is typically optimized for motor vehicles, and delays at signalized intersections tend to affect pedestrians disproportionately when compared to motor vehicles. Such delays may be attributed to many factors, including the traditional focus on prioritizing vehicular movement, geometric features and constraints, or other infrastructure-related limitations at signalized intersections. TRB's *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis* states that delays greater than 30 seconds are associated with increased frustration and risky behaviors, leading to pedestrian noncompliance. In an effort to reduce fatalities and injuries, state and local transportation agencies seek to improve traffic signal timing for non-motorized users.

Under NCHRP Project 03-133, "Traffic Signal Design and Operations Strategies for Non-Motorized Users," Kittelson & Associates, Inc., evaluated trends in traffic signal design and operations strategies for signalized intersections with multimodal infrastructure and intersections with varied geometric design configurations, then developed a guide to address the needs of non-motorized users. The research team identified tools, performance measures, and related policy issues aimed to help agencies design and operate signalized intersections in a way that improves safety and service for pedestrians and bicyclists while balancing the needs of all road users.

In addition to the published report, three PowerPoint presentations are available on TRB's website at www.trb.org by searching for "NCHRP Research Report 969." The presentations are as follows:

Summary Overview
Integrating Pedestrians and Bicycles at Signalized Intersections
Pedestrian Recall and Actuation Research: Preliminary Findings

The contractor's conduct of research report is available for practitioners on the project webpage (http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4357).

CONTENTS

CHAPTER 1

Introduction

Transportation agencies across the country are paying more attention to walking and bicycling as healthy, sustainable, economical, and practical modes of transportation. The domain of traffic signal control offers many opportunities for improving service to these historically underserved modes of travel. Until recently, traffic signal operation and design in the United States was predominantly focused on motorized vehicles, with solutions that often inadvertently harmed service and safety for non-motorized road users. While agencies across the United States and abroad have developed various strategies to improve service for pedestrians and bicyclists at signalized intersections, many of them remain poorly understood. A dearth of analytical tools and performance measures limits practitioners' ability to implement solutions that adequately address the needs of non-motorized users and implement policies, such as Vision Zero, that call for intersections that are safer for all and especially for vulnerable road users.

This guidebook provides tools, performance measures, and policy information to help agencies design and operate signalized intersections in a way that improves safety and service for pedestrians and bicyclists while still meeting the needs of motorized road users.

This guidebook focuses on **integrating** non-motorized users into the signal design and operations process, moving beyond reactionary systems where accommodations are made as issues arise.

There is a spectrum of approaches, shown in Exhibit 1-1, that agencies have taken to address the needs of pedestrians and bicyclists at signalized intersections—from complying only with minimum standards to a practice of integration in which pedestrians and bicyclists are considered in all aspects of signal control. This guidebook moves beyond accommodating pedestrians and bicyclists at traffic signals and toward a multimodal signal timing and design process that optimizes for all users. It contains a user-friendly toolbox describing 28 signal design and operations treatments that can improve the safety, comfort, and convenience of pedestrians and bicyclists while considering the needs of users in motorized vehicles. A goal of this guidebook is to help practitioners raise their minimum standards, raise the bar for serving non-motorized users, and raze the barriers for implementation, bringing agencies closer to full integration.

Practitioners designing for motorized or non-motorized users have traditionally been siloed, with one group having a limited understanding of traffic signal operations and the other having a limited understanding of pedestrians' and cyclists' needs. This guidebook is an opportunity to build bridges between these groups, providing the resources to support intersection planning and design so that the needs of non-motorized users are fully integrated. The guidebook creates connections among the technical subject matter areas of planning, design, operations, safety, and implementation to create an easily accessible and understandable toolbox for practitioners. It is tailored to serve a wide range of stakeholders and to address diverse operating environments and intersection characteristics, resource levels, and system components.

Exhibit 1-1. Approaches for non-motorized user planning and design.

1.1 Guidebook Contents

This guidebook presents a variety of treatments to address the needs of non-motorized users at signalized intersections and instructions on how to select, implement, and evaluate those treatments. Accessibility considerations are integrated throughout most treatments. The guidebook is organized into 10 chapters. Key questions addressed in each chapter include the following:

Chapter 1: Introduction

Why emphasize non-motorized users at signals? What is in the guidebook? How should the guidebook be used?

Chapter 2: Understanding User Needs and Establishing Priorities

What are pedestrian and bicyclist needs at signalized intersections? What level of priority should pedestrian and bicyclist needs be given in intersection design and operation, and how should accessibility be considered? How do funding, maintenance, personnel, equipment, and policy affect an agency's capabilities to implement various treatments?

Chapter 3: Performance Measures Related to Serving Pedestrians and Bicyclists

What performance measures can be used to indicate the degree to which user needs and other objectives are met and to evaluate the success of a treatment? How can average pedestrian delay be calculated and evaluated against a standard? What data are available for calculating performance measures?

Chapter 4: Signal Timing Basics

What are the fundamental signal timing principles for pedestrians and bicycles? What typical traffic signal controller features can be used to implement these principles?

Chapter 5: Introduction to Treatments

Considering the variety of user needs, what broad categories of treatments can be applied to meet those needs, and what treatments belong to each category? How is the toolbox organized?

Chapter 6: Treatments that Reduce or Eliminate Conflicts with Turning Traffic

What treatments can be applied to reduce or eliminate conflicts between non-motorized users and turning vehicles?

Chapter 7: Treatments that Reduce Pedestrian and Bicycle Delays

What treatments can be applied to reduce delay for non-motorized users?

Chapter 8: Treatments Offering Added Information and Convenience

What treatments can be applied to improve information and convenience for pedestrian crossings?

Chapter 9: Treatments Addressing Special Bicycle Needs

What treatments can be applied to support specific bicycle needs at signalized intersections?

Chapter 10: Techniques for Multistage Crossings

What treatments can be applied to improve pedestrian and bicycle service at multistage crossings?

1.2 Using the Guidebook

There are two principal ways this guidebook can be used: (1) project-based or site-oriented and (2) policy-oriented. In both cases, Chapter 2 provides key first steps in understanding and prioritizing user needs.

In a project-based or site-oriented approach, an agency has selected a site for improvement, whether through an external process—such as development mitigation—or a scheduled corridor improvement project or through processes that identify deficiencies in pedestrian or bicycle safety and service, such as an analysis of crash history, a bicycle or pedestrian network plan, or citizen complaints. Site-specific operational and safety deficiencies can then be identified and addressed by finding the appropriate tool in this toolbox. For example, if the problem identified is pedestrian conflicts with right-turning vehicles, the introduction to treatments in Chapter 5 has a group of treatments aimed at eliminating or mitigating conflicts with turning vehicles, with detailed descriptions found in Chapter 6. Those treatments can be reviewed, and the most appropriate alternative(s) can be chosen for the site.

In a policy-oriented approach, an agency may be seeking a more systemic way to integrate pedestrians and bicyclists into its signalized intersection design and operations. The agency may start with goals such as improving pedestrian safety, improving bicycle safety, or minimizing pedestrian and bicycle delays. Based on its chosen goals and objectives, an agency can use treatments listed in Chapter 5 to determine which strategies best suit its needs, and it can use the detailed treatment descriptions to add specific treatments to its best-practices portfolio. The agency can then make it a policy to apply these best practices whenever signals are modified, whether in connection with routine maintenance, mitigation for private development, or corridor improvement projects. Taking it a step further, an agency can initiate a program of proactively applying the chosen best practices systemwide.

CHAPTER 2

Understanding User Needs and Establishing Priorities

In the United States, traffic signal timing is traditionally developed to minimize motor vehicle delay at signalized intersections, with minimal attention paid to the needs of pedestrians and bicyclists. The unintended consequence is often diminished safety and mobility for pedestrians and bicyclists. The issue is exacerbated when practitioners rely on software tools designed to optimize signal timing by minimizing motor vehicle delay without considering pedestrian delay or safety beyond meeting minimum standards, such as pedestrian clearance time. While not all signal timing implementations follow this process, there are limited tools for practitioners to develop timing plans that incorporate a full understanding of pedestrians' and bicyclists' needs.

NCHRP Report 812: Signal Timing Manual, 2nd Edition, introduced an outcome-based approach to signal timing, which encourages practitioners to develop signal timing based on a consideration of the operating environment, users, user priorities by movement, and local operational objectives. Within this outcome-based approach, the first step is to identify the types of users present in an environment, understand users' needs and how they are affected by signal timing and intersection design, and prioritize those needs.

2.1 Identifying and Prioritizing Non-motorized Users

As a rule, pedestrians and bicyclists should be considered as intended users of intersections everywhere except where they are prohibited on the intersecting roads. At the same time, the level of priority given to non-motorized user needs should be greater on routes that are used more frequently, are critical for their mobility, or have a safety issue. The following data sources can help determine the degree to which pedestrians and bicyclists should be considered critical users at an intersection:

- **Bicycle and pedestrian counts:** Practitioners should consider collecting bicycle and pedestrian counts with all intersection turning movement counts. While pedestrian and bicycle counts are not required to implement many of the treatments in this guidebook, quantifying user types and volumes is helpful in designing some treatments, and it is important for determining their priority level in intersection design. Third-party data sources and probe data can be used to supplement traditional counts and, in some cases, can provide a broader perspective than manual counts (e.g., by providing information over longer time periods).
- **Field visits and observations:** Observing the study area can reveal the types of users present at various times of day (peak and off-peak) and days of the week. As part of a field visit, practitioners should walk and bike the intersection to gain a better understanding of user experiences within and around the study area. Consider road safety audits to conduct a more formal safety performance examination by an independent, multidisciplinary team.

- **Pedestrian calls/Traffic signal controller data:** Pedestrian detections and/or calls at an intersection can provide insights on the demand profile across the day and by direction. Traffic signal controllers with data-logging capabilities can record the number of times a pedestrian call was placed for intersections using pedestrian pushbuttons. Care must be taken when evaluating this kind of data, however, since pedestrian volumes may or may not be strongly related to pushbutton actuation counts.
- **Crash history:** Practitioners can obtain historical crash data, typically for 3- to 5-year spans, to assess potential safety concerns. The presence of bicycle and pedestrian crashes confirms user activity and may indicate a need for additional treatments to address safety risks. Many agencies utilize crash history as an initial step to identify locations with safety risks and are taking a more proactive, systemic approach to crash reduction. However, crashes alone are not always sufficient to determine user challenges, particularly on low-volume local streets where crash frequencies are low or where safety issues suppress pedestrian or bicyclist demand.
- **Conflict analysis:** Conflicts at signalized intersections are addressed by using dedicated phasing and separating conflicting movements; however, often not all conflicts are eliminated. This includes turning movement conflicts for both left- and right-turning movements. A crash history provides insights into outcomes of these conflicts, but near misses and uncomfortable pedestrian experiences are not always reported. Identifying and assessing conflicts using analysis is becoming more common, especially as technology advances. Conflict analysis can help practitioners identify potential risks, perhaps before a crash history manifests. Conflicts can be mapped manually or counted using emerging video safety analytic tools.
- **Land use context:** Pedestrian and bicycle service will be more critical where land use supports mobility by foot and by bicycle. For walking, this can include not only traditional downtowns but also suburban locations where origins and destinations are close to one another. Pedestrians should always be expected along transit corridors. Schools and other destinations oriented toward youths or older adults can be important attractors for people on foot and on bike.
- **Travel patterns:** It is important to understand non-motorized users' likely travel patterns for a variety of trip purposes. Is the intersection part of a local or regional bicycle network plan? If not, is it the only nearby direct route that cyclists can follow? Is there a trail or multiuse path nearby? Is it a pedestrian or bicycle access route to shopping, employment, or recreation destinations? At every transit stop, pedestrian crossing demand can be assumed.
- **Demographics:** Census data can assist in identifying areas with likely pedestrian or bicyclist demand or special user needs (e.g., areas with a concentration of older or low-income residents or households without access to automobiles). For example, children and older adults may have slower walking speeds and need more time to cross the street. Similarly, in communities with a high number of persons with disabilities or visual impairments, accessible routes should be prioritized.
- **Community insights:** Agencies may become aware of non-motorized user needs through public involvement activities and customer requests. Other sources on the list can help agencies evaluate these requests and concerns.

2.2 Pedestrian and Bicyclist Needs

Pedestrians and bicyclists have the same basic needs as intersection users in motor vehicles: maximizing safety and minimizing delay. They also have basic needs stemming from their vulnerability and reliance on human power. Additionally, walking is a mode of transportation that is more easily accessible to persons with vision impairments or other disabilities, so intersections must meet pedestrian accessibility needs lest they become barriers to mobility.

Pedestrian and cyclist needs that should be addressed in the design of traffic signal timing plans and traffic signal equipment can be grouped into the following four categories:

- Safety and comfort
- Minimizing delay
- Ease of use and information
- Accessibility

2.2.1 Safety and Comfort

Pedestrians and cyclists should be able to cross intersections with little risk of crash or injury. With motor traffic, safety is often measured in terms of crashes because motor vehicle volumes are typically so great that any underlying safety risk will readily be manifested in crash statistics. Because of the lower relative volume of pedestrians and bicycles on our streets, having a small number of crashes is not sufficient to prove that risk is low.

Some agencies have adopted a systemic safety approach, recognizing that even in the absence of recorded crashes at a particular location, there may still be an underlying safety problem. This can be revealed either through a systematic analysis of injury data over a wide range of similar situations or through an understanding of pertinent human limitations regarding vulnerability and ability to see, judge, and make correct decisions (Furth & Wagenbuur, 2017). For example, an intersection may have no record of bicycle crashes with left-turning vehicles, but if it fits the profile of an intersection type known to have this kind of crash, the risk should be recognized and measures should be taken to reduce it.

Comfort in the context of non-motorized users means perceived safety, which can often go beyond objective safety. For example, if pedestrians need 30 seconds (s) to cross the street and the traffic signal holds conflicting traffic for 30 s, it could be said that they are technically safe. However, if signals are timed so that the pedestrian display goes to steady Don't Walk and the countdown timer goes blank when pedestrians still have two lanes to cross, they may fear being caught in the road when conflicting traffic starts to move. Intersections should be designed so that pedestrians and bicycles can cross in both safety *and* comfort.

Comfort also means an absence of "uncomfortable" interactions with motor vehicles. Crossings often involve permitted conflicts in which turning vehicles are allowed to run at the same time as crossing pedestrians and bicycles. Rules of the road indicate that those turning motorists are supposed to yield the right-of-way. But where intersection geometry allows for high-speed turns or where turning traffic volume is high, turning motorists may be less likely to yield; this creates an asymmetric and uncomfortable challenge over who is going to stop for whom. There are several treatments in Chapter 6 of this guidebook to reduce or eliminate this kind of interaction.

2.2.2 Minimizing Delay

Just like motorists, pedestrians and bicyclists value their time and therefore want to minimize delay. Waiting can be even more onerous for pedestrians and bicyclists compared to motorists because they are exposed to the weather. And importantly, it is well-known that pedestrian and bicyclist compliance with signals diminishes when they have to wait a long time; that makes pedestrian and cyclist delay a matter not only of convenience but also of safety.

While intersection and signal timing design in the U.S. is strongly oriented around minimizing delay for vehicles, methods for pedestrian timing typically focus only on meeting safety standards (such as providing sufficient clearance time). Little or no attention is paid to minimizing pedestrian delay. The current framework of traffic signal timing design needs to be changed to one that aims to minimize pedestrian and bicycle delays as well as motor vehicle delay. Chapter 7 and Chapter 10 describe several treatments that can be used to reduce pedestrian delay, while Chapter 9 describes several treatments that can lower bicycle delay. Examples provided in those sections show that in many situations, pedestrian and/or bicycle delay can be dramatically reduced by timing plan adjustments that have little or no impact on vehicle delay.

Perhaps the greatest reason for the lack of pedestrian-friendly signal timing plans is that neither pedestrian delay nor bicycle delay is usually measured or reported at all, while vehicular delay has been the key performance measure in intersection evaluation. Software typically used for traffic signal timing does not calculate pedestrian or bicycle delay. The business maxim that "only what's measured counts" has proven true.

Consider requiring that pedestrian delay be reported as part of intersection analysis. For example, Cambridge, MA, has long required that consultants preparing traffic impact analyses for city approval report pedestrian delay and its corresponding LOS along with vehicle delay. In the Netherlands, it has long been standard practice for pedestrian and bicycle delay to be reported in any intersection analysis along with vehicle delay.

Agencies wishing to improve service for pedestrians and bicycles at traffic signals can consider establishing a policy that requires intersection analyses reporting vehicular delay to also report pedestrian and bicycle delays, along with a level of service (LOS) rating that allows a direct comparison with vehicular LOS where used. Such a policy should apply to intersection analyses that agencies perform themselves as well as to those submitted to an agency for approval, such as developer-initiated traffic impact studies. It should require reporting average pedestrian and bicycle delays by crossing and by direction for multistage crossings because a long delay for any crossing movement can indicate a safety issue. A commonly used scale for determining LOS, based on pedestrian delay from TRB's fourth edition of *Highway Capacity Manual* (HCM 2000), is reproduced below as Exhibit 2-1. No standard scale for the delay-based LOS of bicycles has been established, but the same scale used for pedestrians may be appropriate because bicyclists also are exposed to weather and exhibit significant noncompliance when waiting times are long.

2.2.3 Improving Ease of Use and Information

Pedestrians and bicyclists want the crossing experience to be easy, and they want to receive information on how the system is going to serve them, which reduces anxiety. Being detected should not require searching for a pushbutton or going out of one's way.

Just as people using an elevator appreciate the confirmation light that illuminates when they push a button, so do pedestrians and bicyclists want to see confirmation that they have been detected. Countdown displays assure pedestrians as they cross that they will have enough time to finish and help faster pedestrians decide, based on their own walking speed, whether it is safe to begin crossing. Chapter 8 describes treatments related to added information and convenience.

Level of Service	Average Pedestrian Delay (s)	Likelihood of Noncompliance
A	< 10	Low
B	≥ 10–20	
C	> 20–30	Moderate
D	> 30–40	
E	> 40–60	High
F	> 60	Very high

Source: HCM 2000, Exhibit 18–9.

Exhibit 2-1. LOS for pedestrian delay at signalized intersections.

2.2.4 Accessibility

Intersection crossings should be accessible to all pedestrians, including those with disabilities. Persons with vision impairments especially rely on walking and transit for their mobility because they may have additional challenges operating motor vehicles or riding a bicycle. Therefore, it is vital that intersection crossings be accessible to them, not only in a legal sense but also functionally. While many pedestrians with vision disabilities use audible traffic cues—for example, the initial surge of traffic departing when a signal turns green is a cue to begin crossing—the intersection design should ensure that audible cues are provided. In general, accessible pedestrian signals (APS) are needed wherever visual pedestrian signals are installed to positively convey the status of the signal to individuals with vision disabilities so they are not delayed in starting to cross the street. When the time programmed for pedestrians to start crossing is different from the time when traffic gets a green light, such as in the leading pedestrian interval, APS are particularly needed to let pedestrians with vision disabilities know that the Walk interval is not concurrent with traffic and to cue all pedestrians to the non-concurrent signal timing. Pushbutton detectors and APS should be located far enough apart from each other, yet in line with their respective crosswalk, that a person relying on a pushbutton locator tone can find the pushbutton for the right crosswalk and can distinguish which APS device is providing the Walk indication.

Many older adults, young children, and persons with walking impairments can only walk at a limited speed. Signalized crossings should make it feasible for the vast majority of the population to cross the street; without them, wide streets become impassable barriers for people on foot. A lack of signalized crossings can make not only walking but also transit infeasible as a mode of transportation, as it generally requires crossing the street either when coming or going. Traditionally, the need to accommodate slower crossers has been "met" by having engineers calculate a clearance time based on a (slower-than-average) pedestrian design speed. This guidebook urges practitioners to go beyond meeting minimum standards by *optimizing* accessibility for slower pedestrians. For example, consider evaluating signal timing plans by a performance measure that indicates the lowest pedestrian speed that will be supported in signal timing strategies.

Accessibility considerations are incorporated throughout this guidebook and are addressed as part of the description of every treatment in the toolbox.

2.3 Establishing Objectives and Priorities

The primary objective of traffic signal control is to meet user needs. To have practical force, user needs should be enumerated and expressed in terms of specific objectives for the agency—for example, to minimize pedestrian and bicycle collisions as well as auto collisions; to maximize pedestrians' and bicyclists' sense of security; to minimize pedestrian and bicycle delays as well as vehicle delay; to be an industry leader in providing information to pedestrians and bicyclists; and to make crossings accessible to as many people as possible.

For each objective, agencies can specify one or more performance measures, such as frequency of conflicts, average delay, and lowest pedestrian speed. Target values or standards for those measures should guide design and provide a means for evaluating current unmet needs as well as the success of a treatment.

Objectives for signalized intersection design will sometimes conflict with each other or at least involve a trade-off. For example, improving pedestrian and bicycle safety might involve treatments that increase vehicle delay, or a treatment that would benefit pedestrians or bicycles might involve new equipment costs. Therefore, an agency's review of user needs extends to deciding how much priority to assign to the various user needs. Greater priority to pedestrian or bicycle safety can mean, among other things, willingness to accept a greater increase in vehicle delay or equipment cost. Greater priority can also be reflected in the use of a stricter target or standard for a performance measure, such as a lower pedestrian design speed or a stricter limit on average pedestrian delay. Priorities are also an important input for project programming (i.e., determining which projects should be done first).

Possible reasons to assign greater priority to pedestrians and bicycles than motorized users include a large number of pedestrians or bicycles, regular use by pedestrians with disabilities or low walking speeds, being part of a critical route in the bicycle network, a history of injuries to pedestrians and bicyclists, and broader transportation policies calling for improved safety for vulnerable road users and/or promoting walking and bicycling. At the same time, there can be reasons to assign priority to other modes, such as high vehicular volume or the presence of a high-frequency bus route. In Amsterdam, Netherlands, planners have designated a priority network each for autos, bicycles, and transit, with the restriction that no road segment may belong to more than two priority networks; these network plans are important inputs in assigning priorities in intersection design.

Assigning a low priority to pedestrian or bicycle needs does not necessarily entail only meeting minimum standards on their behalf. Many of the treatments described in this guidebook offer substantial improvements in service and/or safety to pedestrians and bicycles with little or no detriment to vehicle capacity or delay, and many treatments can be applied with little or no cost. Even where pedestrians and bicycles are not high-priority users, signal control design should still aim to maximize their safety, minimize their delay, and maximize their convenience and accessibility.

2.4 Understanding Agency Capabilities

Agency funding, maintenance and staff demands, equipment constraints, and established policies regarding signal operations can play a role in determining whether certain treatments can be applied.

Maintenance and Staff Support. Some of the treatments described in the toolbox may require added maintenance efforts or ongoing operational support. Treatments that are experimental or have only interim approval may require staff effort or additional support in order to apply to FHWA for permission to experiment. For each treatment described in the toolbox, Considerations and Implementation Support sections provide pertinent information on its likely maintenance and staff support demands.

Costs and Constraints for Equipment and Software. Many of the treatments described in the toolbox require additional equipment, such as new signal heads. While most of the treatments can be supported with standard signal control equipment and software, some may require upgraded or specialized equipment/software or specialized programming with existing software. With each treatment, the toolbox provides pertinent information regarding controller capabilities, possible software needs, and possible new equipment needs.

Agency Policy. Many transportation agencies have established policies related to signal operation (e.g., length of Walk interval, upper and lower limits for cycle length) and mobility and safety performance targets that can support the resulting policies. Ideally, an agency's policies will support the implementation of a preferred treatment. However, where there is a conflict (e.g., an agency policy that does not allow flashing operation), practitioners may need to consider whether or how that conflict can be resolved.

FHWA provides additional resources for agencies wishing to gain a better understanding of their current capabilities and the effect of their capabilities on traffic management.

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CHAPTER 3

Performance Measures Related to Serving Pedestrians and Bicyclists

In the outcome-based approach introduced in the previous chapter, the next step after defining and prioritizing user needs is to define performance measures—also known as measures of effectiveness (MOEs)—that indicate the degree to which user needs and operational objectives are met. Performance data on existing conditions can be used to identify unmet needs. In the design stage, performance data can be used to optimize and compare alternatives; after improvements are made, they can be used for before-and-after analysis. An outcome-based approach can also help document decisions and emphasize agency priorities and community values when considering trade-offs in decision-making.

This outcome-based approach is well-established for serving vehicular intersection users, and intersection designers pay careful attention to performance measures such as volume/capacity ratio, average vehicular delay, and level of service. Pedestrians and cyclists require the same level of attention to adequately address their needs.

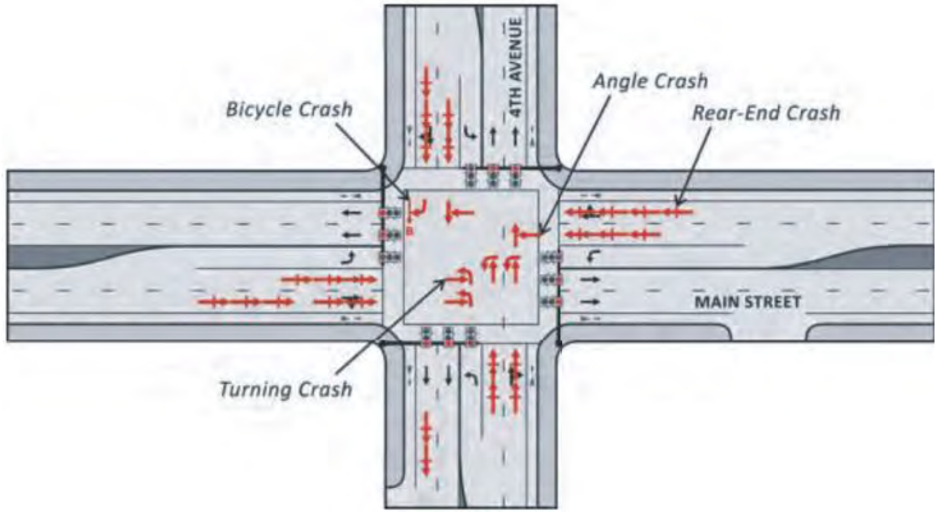
The following sections provide details on performance measures, including data such as counts and crash statistics, that are also used to quantify user needs.

3.1 Crash and Other Safety Data

Crash data is critical for assessing intersection performance relative to safety risks and diagnosing outcomes that a change in intersection design and/or operations might address. Practitioners can obtain 3–5 years of crash data and summarize the crashes by type, severity, and environmental conditions (e.g., day/night, raining). A collision diagram as shown in Exhibit 3-1 can help identify trends.

Crash statistics can tell an incomplete story about the safety of pedestrians and cyclists in part because they experience far greater vulnerability than motorists, which leads them to avoid dangerous situations. Likewise, their nimbleness can enable them to avoid collisions in situations that are nevertheless quite stressful. For this reason, site visits can be enormously valuable in helping practitioners identify undocumented needs as well as causal factors underlying crash statistics. Field observation may indicate where turns are made at unusually high speeds, where visibility is obstructed, or where pedestrians are unable to clear an intersection in time. It may reveal uncomfortable interactions with turning traffic, gaps in accessibility, or high-risk behaviors that reveal an underlying flaw in the intersection design.

A safe-systems approach acknowledges that crash counts alone are not sufficient to determine the underlying level of safety, particularly where pedestrian and bicycle volume is low. Even where there have been few crashes, trained observers may be able to note conditions that create a high risk of crashing.



Source: Urbanik et al. (2015), Exhibit 3-16.

Exhibit 3-1. Example collision diagram.

Conflict counts can also be used as a performance measure, both as a surrogate for non-motorized user crashes (which, fortunately, are rare events) and as a direct measure of perceived safety and comfort. For example, several of the treatments described in this guidebook aim to lessen conflicts between pedestrians and turning vehicles; a count of how often a pedestrian had to stop or changed course because of a non-yielding turning vehicle can be used as a performance measure related to that objective. Hubbard et al. (2007) measured the percentage of compromised pedestrian crossings and found that leading pedestrian intervals (LPIs) reduce the number of compromised crossings.

Compliance counts can also be valuable safety measures. Poor red-light compliance by pedestrians and bicyclists can indicate (1) poorly designed traffic control with excessive pedestrian or bike delay or (2) signals that tell non-motorized users not to go even when it is safe to cross. Violations of no turn on red restrictions and drivers not yielding when making permissive turns (including when turning on red) can indicate a need for stronger messaging or intersection design changes.

3.2 Pedestrian, Bicycle, and Conflicting Vehicle Counts

Counts of pedestrians, bicycles, and conflicting traffic movements can be helpful for evaluating needs, establishing priorities, choosing signalization treatments, and evaluating performance. Whenever intersection turning movements are counted, agencies should also count pedestrians by crosswalk and bicyclists by movement.

Pedestrian counts can be used, for example, to help determine whether a pedestrian phase should be pushbutton actuated or on recall and to evaluate average pedestrian delay aggregated over the different crosswalks at an intersection. High pedestrian-volumes can trigger a need to analyze crowding in the crosswalk or in queuing areas. Counts of conflicting traffic movements help determine whether a fully or partially protected crossing treatment, such as LPI, may be warranted.

Geometric elements of a crossing, including crossing islands and corner queuing areas, must be sized for a signal cycle with high demand. Where pedestrian or bicycle demand has periodic surges—such as at schools or at sports or entertainment venues—volumes per hour are misleading; counts are needed by minute or per signal cycle, and elements should be sized for a high-demand cycle.

An important limitation of pedestrian and bicycle counts to consider is that they may not represent actual demand. An absence of non-motorized users could mean the intersection or streets leading to it are not hospitable or comfortable for non-motorized users, which suppresses demand. In addition, bicycle and pedestrian counts tend to be far more sensitive to weather, special events, the school calendar, and other local factors than vehicular counts. If pedestrian and bicycle counts were made in conjunction with vehicular counts and were done on days of unusual pedestrian or bicycle demand, then substitute counts may be needed for bicycles and pedestrians.

3.3 Average Pedestrian Delay

As stated in Chapter 2, minimizing delay for all users is an important objective in intersection design; therefore, average delays of pedestrians and of bicycles are vital performance measures. Pedestrian and bicycle delays are important measures of safety performance as well as user convenience because they are closely linked to noncompliance.

Typical intersection design practice has not included measurement or reporting of pedestrian delay. For pedestrian delay to be optimized and prioritized—as vehicular delay is—it must be measured and reported as part of the intersection design process. By establishing policies to ensure that pedestrian delay is reported, agencies can go a long way toward achieving intersection designs that are more pedestrian-friendly.

Commonly used intersection analysis software does not calculate or report pedestrian delay, even though the software recommends a pedestrian signal timing and has all the data needed to calculate pedestrian delay. Therefore, if agencies begin requiring that pedestrian delay be reported, designers will have to calculate pedestrian delay in a separate analysis and provide it separately from standard reports produced by intersection analysis software. To consolidate the reporting process, agencies that specify or recommend any particular intersection analysis software should consider demanding that its developers add pedestrian and bicycle delays to its calculation and reporting functionality.

3.4 Pedestrian Delay Formulas for Pretimed, Actuated, and Multistage Crossings

For single-stage crossings with pretimed signals, the 2016 *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis* (HCM6) provides a well-established formula for pedestrian delay in Equation 3-1:

$$d_p = \frac{(C - g_{Walk})^2}{2C} \tag{3-1}$$

where

d_p = average pedestrian delay,
C = cycle length, and
g_{Walk} = the effective Walk interval.

HCM6 suggests including additional Walk time on top of actual Walk time as the effective Walk interval, recognizing that many pedestrians begin to cross in the first few seconds of the Flashing Don't Walk (FDW) interval. Equation 3-2, the effective Walk interval g_{Walk}, makes use of this:

$$g_{Walk} = WALK + \text{additional Walk time} \tag{3-2}$$

where

$WALK$ = the length of the Walk interval.

HCM6 suggests using 4 s as additional Walk time based on a study that predates pedestrian countdown timers.

For pedestrian crossings that are pushbutton actuated, the HCM6 delay formula underestimates average pedestrian delay because—unless someone who arrived earlier has pushed the button—a pedestrian arriving during the scheduled Walk interval will find the pedestrian signal in its solid Don't Walk aspect and will have to wait for the next cycle for a Walk indication.

If demand is low enough that any arriving pedestrian is likely to be the only one using that crosswalk in a cycle, average delay with pushbutton actuation is given by Equation 3-3:

$$d_p = \frac{C}{2} \tag{3-3}$$

This equation is a good approximation when there are fewer than one pedestrian per four cycles.

The extra delay or "delay penalty" due to requiring pedestrian actuation can be substantial. For example, suppose the cycle length is 100 s, the Walk interval is 7 s, and pedestrian demand is very low. In this case, average delay with actuated control is 10 s longer than it would be with pretimed control.

If pedestrian demand is high, then the pedestrian phase will come up almost every cycle; pedestrians arriving "just too late" to get a Walk signal in the current cycle if they had to push the button themselves are likely to have been preceded by others who have already pushed the button. For crosswalks with demand of three pedestrians per cycle or greater, the formula for fixed time control (Equation 3-1) is a good approximation.

For intermediate levels of pedestrian demand, practitioners can interpolate between the results given by Equations 3-1 and 3-3. Let:

vP = demand for a particular crosswalk (both directions) [pedestrians/hour (h)],
vP_{lo} = $900/C$ = demand at which Equation 3-3 applies (pedestrians/h),
vP_{hi} = $10{,}800/C$ = demand at which Equation 3-1 applies (pedestrians/h),
d_{pre} = average delay assuming pretimed control, given by Equation 3-1 (s),
d_{al} = average delay for pushbutton-actuated control under very low demand, given by Equation 3-3 (s), and
d = average delay (s).

Then delay for a pushbutton-actuated crossing can be approximated by:

$$d_p = d_{al} \text{ if } vP \le vP_{lo},$$

$$= d_{pre} \text{ if } vP \ge vP_{hi}, \text{ and otherwise,}$$

$$= d_{pre} + \left(d_{al} - d_{pre}\right) \frac{\frac{1}{vP} - \frac{1}{vP_{hi}}}{\frac{1}{vP_{lo}} - \frac{1}{vP_{hi}}} \tag{3-4}$$

For crossings that have to be made in two or more stages, pedestrian delay can be deceptively long and complex to calculate by formula (Wang & Tian, 2010; Ma et al., 2011). Instead, a simple numerical method can be applied that divides the signal cycle into 0.1-second time steps, tracks the delay a pedestrian arriving in a given time step would experience while crossing, and averages the results over all time steps (Furth et al., 2019).

This method can be applied using the Northeastern University Ped & Bike Crossing Delay Calculator, which is available for free at https://peterfurth.sites.northeastern.edu/2014/08/02/delaycalculator/ (Furth et al., 2019). The calculator can handle up to four crossing stages as well as partial crossing phases that are served twice in a cycle. A user enters crosswalk geometry and pedestrian timing data through a graphical interface; the tool then reports average pedestrian delay for both directions, including average delay at each island, and generates a progression diagram. Exhibit 3-2 shows a sample report for a three-stage crossing in Boston, MA. Note that the average delay in Exhibit 3-2 is more than 120 s, even though the cycle length is only 100 s.

A new *Highway Capacity Manual* (HCM) procedure and computational engine for measuring pedestrian delay at multistage crossings has also been developed (Ryus et al., in press), which will be included in an update of the HCM that was in publication at the time of writing. It is also possible to calculate average pedestrian delay using microsimulation models that include pedestrian modeling functionality. However, this method involves considerable time and expertise as well as the cost of the software license. If microsimulation is used, it is important to run the model long enough for it to process at least 500 pedestrians per crosswalk; this will

Source: Furth et al. (2019).

Exhibit 3-2. Delay report and progression diagram for a three-stage pedestrian crossing.

reduce variability and capture a sufficient sample size since individual delay varies depending on when in the cycle a person arrives.

3.5 Bicycle Delay and Average Operating Speed

In many cases, bicycle delay closely tracks with vehicular delay or pedestrian delay. Where bicycles follow vehicular signals, bicycle delay is usually a little less than the delay of the concurrent vehicular movement if signalized intersections are widely spaced. This is because bicycles usually have little queue delay once the traffic signal turns green. Where bicycles follow a pedestrian phase, their delay will be a little less than pedestrian delay because cyclists usually begin to cross not only during the Walk interval but also during the FDW interval.

Nevertheless, bicycle delay should be considered as a key performance measure along with average operating speed, which applies to corridors with closely spaced signals.

This guidebook highlights some common situations in which bicycle delay can be substantially different from either pedestrian or vehicle delays. One such situation is a street with closely spaced signals, as discussed in Section 9.2. Depending on the progression speed represented by the signal offsets, bicycles may or may not be able to stay in the "green wave," affecting their average operating speed. Another situation occurs when bicycles make a two-stage left turn (two square crossings, in which they stay on the outside of the intersection) rather than making a vehicular turn as discussed in Section 9.3. Bicycle delay will also depend on whether bicycles are allowed to use LPIs (see Section 6.5) or turn right on red (see Section 9.6).

3.6 Accessibility and Intersection Layout Measures

There are several indicators—in addition to the accessibility of signals—that can be measured in order to make crossings accessible, including:

- Lowest pedestrian speed designed (see Section 7.4).
- Distance between accessible pushbuttons serving different crosswalks at a single corner. The minimum separation specified by the United States Access Board public rights-of-way accessibility guidelines (U.S. Access Board, 2011) is 10 ft, but separation greater than 10 ft is preferred (see Section 8.3).
- Pushbutton offset from a crosswalk's approach path and from the curb (see Section 8.3; Section 9.4).

Other performance measures related to a crossing's physical layout include:

- Crosswalk length and related adequacy of clearance time provided (see Section 7.4).
- Depth of a crossing island and queuing area on an island versus the depth and area needed; the dimensions needed by bicycles are different from those needed by pedestrians (see Section 10.1).
- Sight distance for permitted-turn conflicts when a bicycle path is physically separated from a roadway (see Section 6.1).

3.7 Performance Data from Traffic Signal Systems

Centralized signal systems capable of automatically logging data offer the potential to generate useful performance measures from the data. Systems that have high-resolution data-logging capabilities are especially promising.

3.7.1 Using Centralized Signal Systems

Many agencies utilize centralized traffic signal systems with the capability to log data automatically and generate reports with various performance measures. Typically, data is often used for monitoring and maintenance, but it can also be used to support a performance-based improvement process. These central systems can generate system reports, which typically include various historical reports and MOEs. The reports can be predefined—with reporting intervals selected by the user—or they can be scheduled to run automatically. Some examples of these reports include vehicle detector occupancy, green time distribution, vehicle detector failures, and the number of max outs.

While traditionally the measures are more focused on vehicular performance, pedestrian volume and pedestrian detector failures can also be generated from some of the central systems and can be utilized by practitioners. In addition, customized reports and network alerts can be generated with some of these systems to gain better understanding of pedestrian and bicycle operations. For example, Clark County, WA, often programs phase splits that are less than the time required to serve pedestrians in order to maintain shorter cycle lengths and reduce delay for all users. When there is a pedestrian call, the phase is lengthened to serve it; the cycle is then forced into a transition period to recover the extra time used by the lengthened phase in order to become coordinated again. Staff members can create a summary report from the central system to identify the frequency of transitions due to a pedestrian call. At intersections where transitions occur more frequently and disrupt signal coordination, signal timing strategies are reviewed and adjusted to serve pedestrian timings within the coordinated cycles. This review process limits transitions, improves service for pedestrians, and reduces the impact on signal coordination.

3.7.2 Using High-Resolution Signal Controller Data

High-resolution detector and signal-state data can be used to automatically generate a range of signalized intersection performance measures called automated traffic signal performance measures (ATSPMs). High-resolution controller event data consist of time-stamped logs of "events" occurring in a signal controller, including detector input and signal-state changes, with a time resolution of a tenth of a second or smaller. ATSPMs are already being used by several agencies, and the Utah Department of Transportation (UDOT) developed an open-source platform that can create a series of visual reports utilizing the high-resolution data from signal controllers.

While ATSPM development has mainly focused on measures that serve vehicles, ATSPMs can also be used for measures that serve pedestrians and bicycles. The UDOT platform includes a *Pedestrian Delay* report that displays the delay between actuation of a pedestrian call and the start of the next Walk indication. This measure is closely related to average pedestrian delay; however, they are not identical because the delay of pedestrians arriving after another pedestrian has made a call is not accounted for.

UDOT's *Pedestrian Delay* report also displays the total number of pedestrian actuations (Exhibit 3-3), which is closely related to pedestrian demand. (However, as mentioned previously they are not the same because pedestrians arriving after the pedestrian phase has been called are not counted.) By indicating how often pedestrian phases are needed, the frequency of pedestrian actuations can also be helpful in designing signal timing plans. When the frequency is low, designers may use a shorter cycle length than what would be needed to account for a full set of pedestrian phases. With this kind of timing, the cycle will be lengthened whenever a pedestrian phase is served; then a transition routine is run to recover the extra time added to

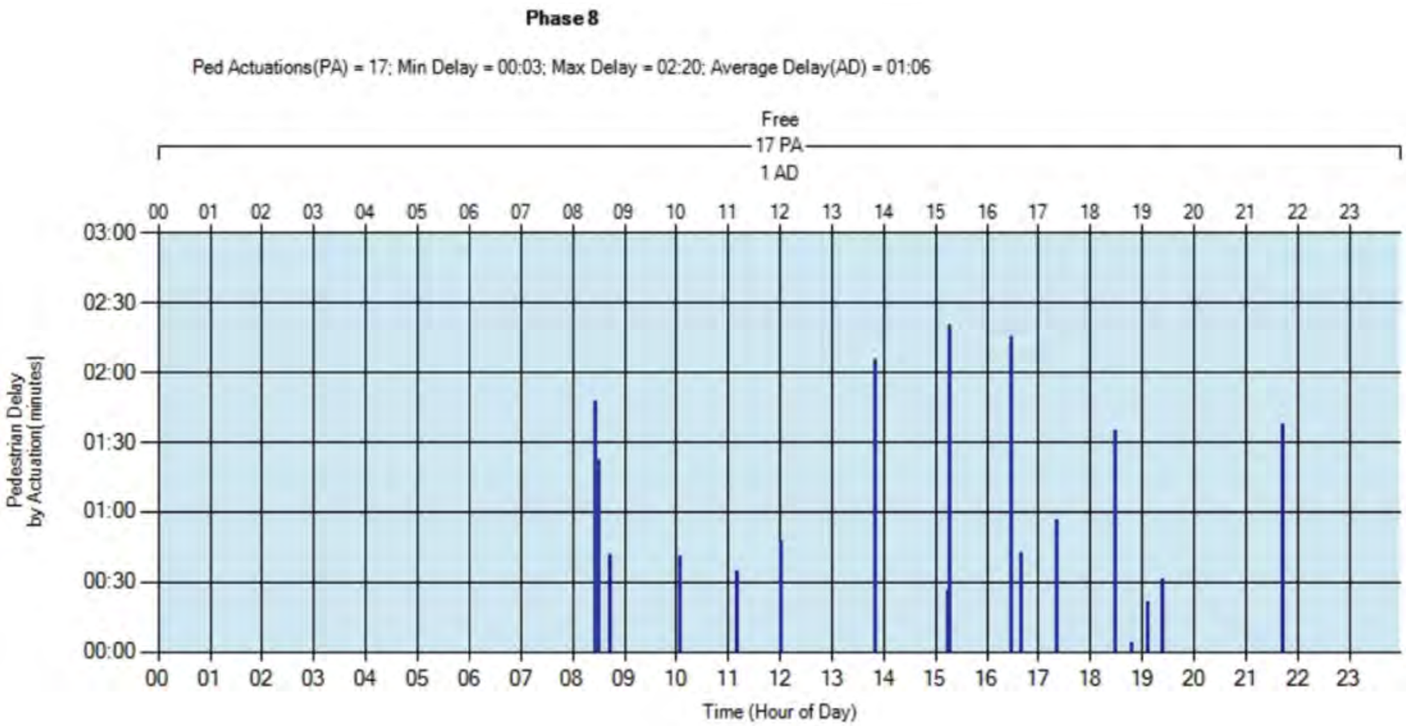
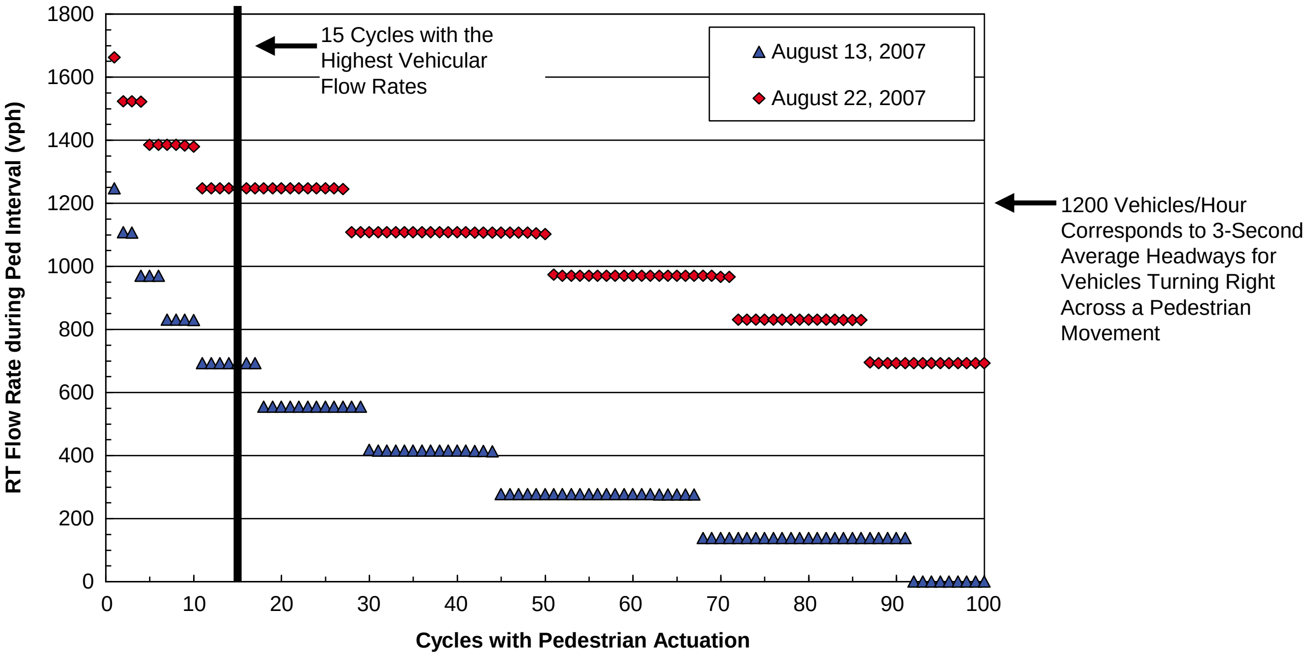


Exhibit 3-3. **Pedestrian Delay** ***report example generated by the UDOT open-source platform.***

the cycle and thus restore the intersection to coordination. When the frequency of pedestrian actuations is low, this practice can reduce delay for both pedestrians and vehicles, and it can be especially valuable when applied to a critical intersection whose cycle length governs the cycle length of a corridor. However, if the frequency of pedestrian actuations is too high, this strategy becomes inefficient due to the frequent transitions.

Unfortunately, reports based on pedestrian phase actuation data are unable to measure pedestrian activity or delay if pedestrian phases are on recall, and their accuracy in measuring pedestrian delay and activity declines when pedestrian volume is high enough that crosswalks serve multiple pedestrians per cycle.

High-resolution controller data can also be used to generate performance measures related to conflicts between pedestrians and permitted turns (either right-turn or left-turn movements). At intersections with lane-specific vehicle count detectors, which are typically located just past the stop bar, counts of permitted-turning movements can be collected by cycle. When the pedestrian phase is actuated, counts during cycles with registered pedestrians can then be isolated. An example in Exhibit 3-4 shows right-turn vehicular flow rates by cycle, limited to cycles in which the pedestrian phase is served, for two different days on a college campus. August 13 (blue) was one week prior to the start of classes, and August 22 (red) was during the first week of classes (Hubbard et al., 2008). The data are sorted from largest to smallest flow rate. The increase in right-turn volume after classes began is evident. This analysis shows that after classes began, there were 15 cycles per day with pedestrian activity, and conflicting traffic volume in those cycles was 1,200 vehicles per hour or greater; this corresponds to an average headway of less than 3 s between vehicles. This analysis helped support a decision to implement an exclusive pedestrian phase.



Source: Hubbard et al. (2008).

Exhibit 3-4. Pedestrian conflicts example: Right-turn vehicular flow rates during cycles with pedestrian actuations.

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CHAPTER 4

Signal Timing Basics

This chapter first covers signal timing principles for pedestrians and bicycles to provide a better understanding of signal timing fundamentals. Then, it provides a toolbox of signal timing and design treatments to improve pedestrian and bicycle mobility and safety at signalized intersections. Each treatment includes a detailed description as well as applications, expected operational and safety outcomes, and specific operational details for implementation.

4.1 Understanding Signal Systems

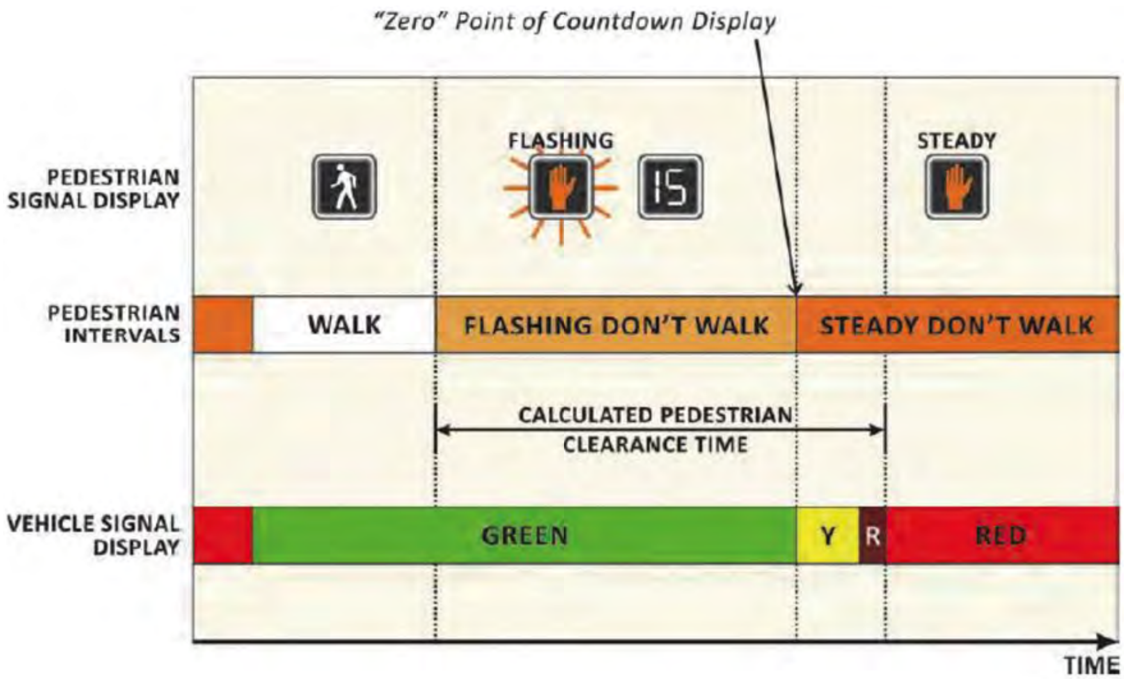
Implementing treatments for pedestrians and bicycles requires an understanding of vehicular signal system principles. Prior to exploring new treatments for non-motorized users, agencies must understand the equipment and controller(s) currently being used and how they influence operations. Existing indications, for example, may create conditions that affect how the intersection operates for all users. Agencies may be limited in what they can achieve using the existing setup to implement new treatments. The introduction to the toolbox in Chapter 5 notes which treatments are likely to require new equipment. Equipment needs are also summarized for each treatment—when applicable—in the toolbox (Chapters 6–10). For additional information on vehicular signal systems, refer to the *Manual on Uniform Traffic Control Devices* (MUTCD) and *NCHRP Report 812: Signal Timing Manual,* 2nd Edition (STM2).

4.2 Pedestrian Intervals

The pedestrian phase consists of three intervals: Walk, Flashing Don't Walk (FDW), and pedestrian phase end buffer, during which steady Don't Walk is displayed but conflicting traffic will not be released. During the rest of the cycle, the pedestrian phase is inactive, and a steady Don't Walk continues to be displayed, as shown in Exhibit 4-1. The Walk interval typically begins at the start of the concurrent vehicular green interval and is the time during which pedestrians are supposed to begin crossing. The FDW interval informs pedestrians that the crossing phase will soon end and that they should no longer begin to cross. If there is a countdown signal, it counts down during the FDW phase, reaching "0" and going blank when the FDW interval ends. During the pedestrian phase end buffer, which typically lasts only a few seconds, the display goes to solid Don't Walk to warn pedestrians that the pedestrian phase is imminently about to end. Pedestrians are expected to use this interval, along with the FDW interval, to complete their crossing.

4.2.1 Walk Interval

The Walk interval is the time window within which pedestrians are supposed to begin crossing. It should be long enough for pedestrians to perceive the phase change and enter the



Note: The figure assumes that some pedestrians will finish clearing the crosswalk during the vehicular yellow and red clearance intervals.

Exhibit 4-1. Pedestrian intervals (STM2).

street. The MUTCD (2009) recommends that the Walk interval be at least 7 s long but allows it to be as short as 4 s. In areas with pedestrian volumes great enough that pedestrians queue several rows deep, the minimum Walk interval should be longer than 7 s.

When the pedestrian phase runs concurrently with a parallel vehicular phase, the Walk interval can often run for far longer than its minimum, giving pedestrians additional crossing opportunities without constraining traffic flow (see Section 7.3).

4.2.2 Pedestrian Clearance Interval

Pedestrian clearance time needed is the time required for a pedestrian to cross the street, beginning from when they first step off the curb. It is the crosswalk length divided by a pedestrian design speed of 3.5 ft per second (ft/s), a speed attainable by more than 90% of the population. If slower pedestrians routinely use a crossing, a lower pedestrian design speed may be used. The MUTCD (2009) also describes an option—albeit rarely implemented—to use a pedestrian design speed of up to 4 ft/s in conjunction with a pushbutton that slower pedestrians may use to request a longer clearance time (see Exhibit 4-2).

The MUTCD (2009) also specifies a clearance need for pedestrians who begin crossing at the start of the Walk interval. The combined duration of the Walk interval, FDW interval, and pedestrian phase end buffer should be enough for a person to cross the street at a speed of 3 ft/s beginning at the pedestrian pushbutton, if there is one, or 6 ft from the edge of the curb. This requirement is typically constraining only for long crossings. Normal practice is to design the crossing with a preliminary pedestrian timing that ignores this second clearance need and then check whether it is satisfied; if this need is not satisfied, increase the length of the Walk interval until it is.

Section 7.4 offers more detail about pedestrian clearance needs and related pedestrian timing.

Exhibit 4-2. Example of extended pushbutton press signage.

4.2.3 FDW Interval and Pedestrian Phase End Buffer

Together, the FDW interval and the pedestrian phase end buffer supply the pedestrian clearance need. Relative to a concurrent vehicle phase, the FDW interval may end (and the phase end buffer may begin) during the green, at the onset of the yellow, during the yellow, or at the end of the yellow for the concurrent vehicle phase. The only constraint is that the remaining time until the end of the vehicle phase's red clearance, which is the pedestrian phase end buffer, must be at least 3 s. Many agencies choose to end the FDW interval at the onset of the yellow for the concurrent vehicle phase, in which case the phase end buffer will be the same length as the vehicular yellow plus red clearance time.

Once the length of the pedestrian phase end buffer has been determined, the minimum length of the FDW interval is the pedestrian clearance time needed (Equation 7-4) minus the length of the phase end buffer. Some agencies choose not to count the pedestrian phase end buffer against the needed pedestrian clearance time. This practice gives pedestrians more clearance time, which has some advantages but also some disadvantages, as discussed in greater detail in Section 7.4.

4.3 Pedestrian Call Modes: Actuated or Recall

Pedestrian phases can be actuated or on recall. If actuated, the controller places a call for the pedestrian phase when a pedestrian is detected. "On recall" means that a call for pedestrian service is placed automatically every cycle. While a number of passive pedestrian detection technologies are available today (e.g., microwave, infrared, video camera), most agencies still rely on pushbuttons for pedestrian detection due to concerns in detection accuracy.

For details on pedestrian call modes and their effect on pedestrian delay and vehicle operations, see Section 7.5.

4.4 Accessible Pedestrian Signals

Accessible pedestrian signals (APS) help persons with low vision or hearing impairments know when the Walk signal is being displayed. These signals use sound, tactile arrows, and vibrotactile feedback to communicate to pedestrians (see Exhibit 4-3). Typically, they serve a dual function as both standard pedestrian pushbuttons and APS. At signals without standard pushbuttons (e.g., pretimed intersections, phases with pedestrian recall), the need for APS can still be met by providing similar pushbutton units without requiring that the pedestrian call mode become actuated when the button is pushed. For more detail on this concept, see Section 8.4.

The MUTCD requires that APS provide both audible and vibrotactile Walk indications. Pushbuttons for APS should be located in accordance with the provisions of the MUTCD, Section 4E.08—namely, they should be located as close as possible to the crosswalk line furthest from the center of the intersection and as close as possible to the curb ramp. Additional detail on implementation can be found in the MUTCD, Sections 4E.09–4E.11.

The proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way (U.S. Access Board, 2011) includes a requirement for APS wherever pedestrian signals are installed and refers to the MUTCD standards for APS features and functioning. The guidelines have not been finalized and adopted by the U.S. Department of Justice and U.S. DOT, but they may be considered best practice. Several municipalities and states, including Minnesota and Maryland, install APS at all reconstructed or newly signalized intersections. Many jurisdictions—such as New York City; Portland, OR; and Seattle, WA—also have policies to install APS when requested by a member of the public and when the location meets other requirements. One of these requirements is typically that the location is already signalized.

Source: Harkey et al. (2011). www.apsguide.org

Exhibit 4-3. Pushbutton-integrated APS.

4.5 Signal Timing Principles for Bicycles

Traditionally, bicycles have been expected to follow general vehicular traffic signals or, on shared-use paths, pedestrian signals. Another solution that is becoming increasingly popular in the United States and already used widely in Europe is bicycle-specific signals, which allow bicycles to have a signal phase that may differ from that of vehicles and pedestrians.

Where bicycles follow a vehicular signal, signal timing for the vehicle phase should include the needs of bicycles. Cyclists typically need more time than drivers to clear an intersection, especially with large intersection crossings, due to their lower speed and acceleration. For bicycles beginning from a standing start, on a fresh green, their needed clearance time can be met by providing a sufficiently long minimum green period. For those arriving on a stale green, their clearance time need can be met by lengthening the red clearance time—a practice followed in many European countries—or by extending the green. Clearance time needs for bicycles can be met more efficiently if bikes can be detected. For more detail, see Section 9.1.

Cyclists can also follow bicycle signals, which have bike-specific signal heads that control bicycle phases. Bicycle phases may run concurrently with compatible vehicle phases or as an exclusive separate phase (e.g., for a diagonal bicycle crossing where all vehicular movements are stopped). In the U.S., using bicycle signals at this time requires approval from FHWA's MUTCD office. An interim approval for their use has been in force since 2012, and applications ("requests to experiment") that meet its terms will be approved. One of the terms that limits application of bicycle signals is that there must not be any permitted conflicts with turning vehicles, including right turns. As of March 2019, there are 480 intersections that are currently using bicycle signal faces across the United States (Monsere et al., 2019).

4.6 Traffic Signal Controller Elements Overview

Exhibit 4-4 outlines elements in most modern controllers that can be leveraged to implement various treatments for non-motorized users. Specific implementation may vary by controller type.

Exhibit 4-4. Signal controller features facilitating treatments for non-motorized users.

Feature	Definition	Use	Applicable Treatments
Timing Options			
Min. Green 2	Represents the least amount of time that a green signal indication will be displayed for a movement. Most modern controllers provide two or more minimum green parameters that can be invoked by a time-of-day plan or external input.	Bicycle detectors can activate Min. Green 2 (Bike Green), extending the minimum green time for bicyclists. Min. Green 2 for bicycle use can vary based on the size of intersection and intersection type. This is currently used in Portland, OR.	• **Bicycle Detection (Section 9.4).** • **Signal Progression for Bicycles (Section 9.2).**
Advance Walk	A pedestrian overlap configuration, programmed as a number of seconds, where the pedestrian phase starts before the corresponding vehicle phase.	Advance Walk provides a leading pedestrian interval (LPI), allowing pedestrians to enter the crosswalk before conflicting vehicles.	• **Leading Pedestrian Intervals (Section 6.5).** • **Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds (Section 6.7).**

Exhibit 4-4. (Continued).

Feature	Definition	Use	Applicable Treatments
Delay Walk	A pedestrian overlap configuration, programmed as a number of seconds, where the pedestrian phase starts after the corresponding vehicle phase.	Allows turning vehicles queued at the intersection to clear the crosswalk before pedestrians enter.	• **Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds (Section 6.7).**
Steady Don't Walk	The period of time after the Walk and FDW have completed their timing. The duration of the steady Don't Walk interval is not a programmable parameter in the controller but is simply the length of the concurrent vehicle phase minus the Walk and FDW intervals.	Part of the overall pedestrian clearance interval. Must be displayed for at least 3 s before the release of conflicting vehicles, per the MUTCD.	**N/A**
Alternate Walk/Pedestrian Clear	The amount of time the Walk indication is displayed when an alternate Walk call (for a special-needs pedestrian) is being serviced.	Alternate Walk can provide a longer Walk interval for slower pedestrians with an extended push of a pedestrian button. A supplement sign is often used to inform pedestrians of the feature. Cameras can also be used to detect user type and initiate Alternate Walk.	• **Accessible Signals without Pushbutton Actuation (Section 8.4).** • **Maximizing Walk Interval Length (Section 7.3).**
Phase Options			
Pedestrian Recall	The controller places a continuous call for pedestrian service on a phase, causing the pedestrian Walk and clearance intervals to occur every cycle.	Typically used for locations and times with high pedestrian-volumes.	• **Pedestrian Recall versus Actuation (Section 7.5).**
Rest in Walk (Actuated Rest in Walk)	The controller dwells in the pedestrian Walk interval while the coordinated phase is green, regardless of pedestrian calls.	• Often used when there are high pedestrian-volumes, such as in downtown environments or locations near schools. • Does not require any pedestrian detection (although pedestrian detection may be desirable to allow for late-night free operation). • Causes the FDW interval to extend past the yield point, delaying minor-street movements until the FDW interval has ended. The delay to minor streets is only noticeable under low-volume conditions.	• **Maximizing Walk Interval Length (Section 7.3).** • **Pedestrian Recall versus Actuation (Section 7.5).**
Pedestrian Recycle	Allows pedestrian service in the programmed ring to recycle if there is a pedestrian call registered on the phase in service or if pedestrian recall is programmed for the phase and there are no serviceable opposing calls.	• Reduces pedestrian delay by allowing for late pedestrian service and for the pedestrian phase to reservice if remaining service time allows. • Can be used under actuated and non-actuated operation.	• **Reservice (Section 7.2).**
Force Coord Pedestrian Yield Option	Forces a pedestrian phase in Rest in Walk to fully terminate in time for the coordinated phase to yield on time when there are no conflicting calls.	If used in conjunction with Pedestrian Recycle, the pedestrian phase will serve again if the coordinated phases do not yield (i.e., if there are no conflicting calls).	• **Reservice (Section 7.2).**

(continued on next page)

Exhibit 4-4. (Continued).

Feature	Definition	Use	Applicable Treatments
Bicycle Phase	Separates bicycle movements from other conflicting traffic.	• Not needed when bicycle movements can occur concurrently with other compatible vehicle phases (e.g., bicycles crossing with the concurrent vehicular movement while right-turning vehicles are stopped). • Useful for diagonal bicycle crossings in which all vehicular movements are stopped.	• **Exclusive Pedestrian and Bicycle Phases (Section 6.3).** • **Minimum Green and Change Interval Settings for Bicycle Clearance (Section 9.1).** • **Signal Progression for Bicycles (Section 9.2).**
Vehicle-Based Features			
Flashing Yellow Arrow (FYA)	A protected-permitted left-turn display that features a flashing yellow arrow in addition to the standard red, yellow, and green arrows. When illuminated, the FYA allows waiting motorists to make a left-hand turn after yielding to oncoming traffic.	FYA can be programmed with a Negative Pedestrian or Not Pedestrian condition. If FYA is on and a pedestrian call comes, the pedestrian waits. If there is time remaining in the through phase, either the FYA would terminate early or the pedestrian phase would be served in the next cycle without FYA.	• **Protected-Only Left Turns to Address Non-motorized User Conflicts (Section 6.1).**
Right-Turn Overlaps	Right-turn movements operating in exclusive lanes are assigned to more than one phase that is not conflicting (e.g., non-conflicting left-turn phase from the cross street).	Right-turn overlaps can be applied with the adjacent through green. If a pedestrian call is placed, the right turn can get an FYA or red arrow instead of the green arrow.	• **Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds (Section 6.7).**
Time of Day	Most signals have several timing plans that operate at different times of day.	Uses a “dummy phase” to allow different types of operations throughout the day, such as exclusive pedestrian phases during off-peak times.	• **Exclusive Pedestrian and Bicycle Phases (Section 6.3).**
Alternate Phases	Phase is served every other cycle (even/odd).	Typically used for split phase.	**N/A**

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CHAPTER 5

Introduction to Treatments

This guidebook describes a toolbox of treatments to better address the needs of non-motorized users at signalized intersections. This chapter introduces the treatments and provides additional instruction on treatment selection.

5.1 Treatment Organization

The treatments presented in the toolbox can be categorized in a multitude of ways, including by user, implementation types, and supported operational and safety objectives. For this document, the primary categorization is based on intended outcome. Each of the following chapters covers a different intended outcome, organized as follows:

Chapter 6: Treatments that Reduce or Eliminate Conflicts with Turning Traffic

Treatments in this chapter address conflicts with turning traffic, an important safety concern for both pedestrians and bicycles. There is a range of treatments, including some that fully separate pedestrians and bicycles from turning-vehicle movements in time, some that separate them for an initial interval (when the conflict is most intense), and warning treatments aimed at improving yield compliance.

Chapter 7: Treatments that Reduce Pedestrian and Bicycle Delays

This chapter describes treatments aimed at reducing delay for pedestrians and bicycles and at accommodating slower pedestrians. The treatments are grouped by those that reduce effective red time, treatments that increase effective green time for pedestrians, and treatments that emphasize demand responsiveness to balance vehicle and pedestrian impacts.

Chapter 8: Treatments Offering Added Information and Convenience

This chapter describes treatments aimed at providing information to pedestrians and bicycles to reduce traveler stress and uncertainty, as well as treatments aimed at improving the physical convenience of crossing a street.

Chapter 9: Treatments Addressing Special Bicycle Needs

This chapter describes treatments that address needs specific to bicyclists including change interval settings, signal progression, and detection.

Chapter 10: Techniques for Multistage Crossings

This chapter describes techniques for reducing delay and improving safety at multistage crossings.

The content for each treatment follows a consistent structure to make it easy to use and utilizes the following categories:

- **Basic Description:** Alternative Names; Description and Objective; Variations; and Operating Context;
- **Applications and Expected Outcomes:** National and International Use; Benefits and Impacts;
- **Considerations:** Accessibility Considerations; Guidance; Other Instruction; Relationships to Relevant Treatments; and
- **Implementation Support:** Equipment Needs and Features; Phasing and Timing; Signage and Striping; Geometric Elements.

Examples are embedded within each treatment description.

5.2 Overview of Treatments

Although the treatments are organized into sections by their primary objective, a given treatment may help address several objectives. Exhibit 5-1 lists the 28 treatments and whether they apply to pedestrians and/or to bicycles; the primary objective(s) they address; and whether their application is likely to require new equipment or geometric changes. Requirements indicated in this table are for the most probable, anticipated applications, given that there may be applications with greater or fewer requirements.

Exhibit 5-1. Toolbox treatments.

	Section	Treatment	Implementation Strategy	Mode	User Needs			
					Safety and Comfort	Minimizing Delay	Improving Ease of Use and Information	Accessibility
6. Reduction or Elimination of Conflicts with Turning Traffic	6.1	Protected-Only Left Turns to Address Non-motorized User Conflicts	Operational	Pedestrians and bicycles	X			
	6.2	Concurrent-Protected Crossings	Operational	Pedestrians and bicycles	X			
	6.3	Exclusive Pedestrian and Bicycle Phases	Operational	Pedestrians and bicycles	X	X		
	6.4	Channelized Right Turns/Delta Islands	Geometric/ equipment	Pedestrians and bicycles	X			
	6.5	Leading Pedestrian Intervals	Operational	Pedestrians	X			
	6.6	Delayed Turn/Leading Through Intervals	Geometric/ equipment	Pedestrians and bicycles	X			
	6.7	Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds	Operational	Pedestrians	X	X		
	6.8	No Turn on Red	Geometric/ equipment	Pedestrians and bicycles	X			
	6.9	Flashing Pedestrian and Bicycle Crossing Warnings	Geometric/ equipment	Pedestrians and bicycles	X		X	
7. Reduction of Pedestrian and Bicycle Delay	7.1	Short Cycle Length	Operational	Pedestrians and bicycles		X		
	7.2	Reservice	Operational	Pedestrians and bicycles		X		
	7.3	Maximizing Walk Interval Length	Operational	Pedestrians		X		X
	7.4	Pedestrian Clearance Settings for Better Serving Slower Pedestrians	Operational	Pedestrians		X		X
	7.5	Pedestrian Recall versus Actuation	Operational	Pedestrians		X	X	
	7.6	Pedestrian Hybrid Beacons	Geometric/ equipment	Pedestrians	X	X	X	X

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Exhibit 5-1. (Continued).

	Section	Treatment	Implementation Strategy	Mode	User Needs			
					Safety and Comfort	Minimizing Delay	Improving Ease of Use and Information	Accessibility
8. Added Information and Convenience	8.1	Pedestrian Countdown	Geometric/ equipment	Pedestrians			X	X
	8.2	Call Indicators	Geometric/ equipment	Pedestrians and bicycles	X		X	X
	8.3	Independently Mounted Pushbuttons	Geometric/ equipment	Pedestrians	X		X	X
	8.4	Accessible Signals without Pushbutton Actuation	Geometric/ equipment	Pedestrians			X	X
9. Special Bicycle Needs	9.1	Minimum Green and Change Interval Settings for Bicycle Clearance	Operational	Bicycles		X		
	9.2	Signal Progression for Bicycles	Operational	Bicycles		X		
	9.3	Two-Stage Left-Turn Progression for Bicycles	Geometric/ equipment	Bicycles	X	X	X	
	9.4	Bicycle Detection	Geometric/ equipment	Bicycles		X	X	
	9.5	Bicycle Wait Countdown	Geometric/ equipment	Bicycles			X	
	9.6	Easing Bicycle Right Turn on Red Restrictions	Operational	Bicycles		X		
10. Multistage Crossings	10.1	Multistage Crossings	Geometric/ equipment	Pedestrians		X		
	10.2	Left-Turn Overlap for Pedestrian Half-Crossings	Operational	Pedestrians		X		
	10.3	Single-Pass Bicycle Crossings with Two-Stage Pedestrian Crossings	Operational	Bicycles		X		

CHAPTER 6

Treatments that Reduce or Eliminate Conflicts with Turning Traffic

This chapter describes the following nine treatments that address conflicts with turning traffic:

Primary Function	Section	Treatment Name
Separation from left-turning traffic	6.1	Protected-Only Left Turns to Address Non-motorized User Conflicts
Separation from right- and left-turning traffic	6.2	Concurrent-Protected Crossings
	6.3	Exclusive Pedestrian and Bicycle Phases
	6.4	Channelized Right Turns/Delta Islands
Partial separation from right-turning traffic	6.5	Leading Pedestrian Intervals
	6.6	Delayed Turn/Leading Through Intervals
	6.7	Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds
Preventing turns on red	6.8	No Turn on Red
Encouraging turning traffic to yield	6.9	Flashing Pedestrian and Bicycle Crossing Warnings

Turning vehicles are one of the greatest hazards facing pedestrians and bicycles at intersections. They have variously been estimated to represent 25%–50% of pedestrian crashes at intersections (Lord et al., 1998). Bicyclists face the same hazard and are particularly vulnerable to right-turning vehicles. Conflicts with turning vehicles also create discomfort when pedestrians or cyclists have to compete for right-of-way with turning vehicles that do not readily yield.

Most of the treatments in this chapter address this safety issue by separating pedestrians and bicycles from turning vehicles in time. The essence of traffic signal control is to separate conflicting traffic movements into distinct phases; however, eliminating all conflicts by protecting all movements can cause large delays. This often leads to agencies allowing turn conflicts with pedestrians and bicycles, which can create safety issues due to their vulnerability.

Protected-Only Left Turns to Address Non-motorized User Conflicts (Section 6.1). This treatment examines whether left turns should be protected-only—that is, completely separated in time from conflicting traffic, including crossing pedestrians and bicycles. It reveals—perhaps more than any other treatment—a large difference in practice between North America and bicycle-friendly countries in Europe, where left turns across multilane roads are nearly always protected-only.

The next three treatments separate pedestrians and bicycles from right-turning as well as left-turning traffic:

Concurrent-Protected Crossings (Section 6.2). Both right turns and left turns are given their own distinct phases, controlled by turn arrows, while pedestrians and bicycles cross concurrently with parallel through traffic. The main drawback to this treatment is that it requires an exclusive right-turn lane as well as an exclusive left-turn lane.

Exclusive Pedestrian and Bicycle Phases (Section 6.3). There is one phase in the cycle for all pedestrian movements; that phase may or may not serve bicycles as well. The main drawback is its negative impact on traffic capacity, as it can force signal cycles to be long and lead to high delay for all users, including pedestrians.

Channelized Right Turns/Delta Islands (Section 6.4). Conflicts between pedestrians and right-turning traffic are removed from the main crossing. However, dealing with crossings to and from the delta islands remains a challenge. If crossings are not signalized, other factors must ensure that those crossings are safe; if crossings are signalized, they must be set up as multistage crossings, which can entail large pedestrian delay unless carefully timed.

The treatments in Sections 6.5–6.7 involve partial protection from right turns—that is, preventing right turns during an initial part of the crossing phase. Their descriptions include guidance on when full protection, partial protection, or no protection from right turns might be appropriate.

Leading Pedestrian Intervals (Section 6.5). At the start of a vehicular phase, all traffic is held for a short time while pedestrians—and bicycles in certain cities—get a head start, allowing them to establish their priority in the crosswalk before turning traffic is released.

Delayed Turn/Leading Through Intervals (Section 6.6). At the start of a vehicular phase, turning traffic is held for a short time (but typically longer than a leading pedestrian interval [LPI]) while through traffic and pedestrians—plus bicycles for certain cities—get a head start. This allows them to establish their priority in the crosswalk before turning traffic is released.

Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds (Section 6.7). The pedestrian phases of intersecting streets are allowed to overlap during an LPI or other short vehicular-hold interval, which can enable longer Walk intervals and make it possible to introduce LPIs with less capacity or cycle-length impact.

No Turn on Red (Section 6.8). This well-known treatment supplements several other treatments described in this guidebook, such as LPI, by giving pedestrians a short interval free of turning conflicts.

Flashing Pedestrian and Bicycle Crossing Warnings (Section 6.9). This treatment aims to mitigate turn conflicts by displaying flashing warnings to approaching motorists during phases with permitted-turn conflicts. Warning signs discussed include flashing yellow arrow (FYA), used for this purpose in several U.S. cities, and a flashing pictogram used in Amsterdam, Netherlands.

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6.1 Protected-Only Left Turns to Address Non-motorized User Conflicts

6.1.1 Basic Description

6.1.1.1 Alternative Names

None.

6.1.1.2 Description and Objective

Left-turning traffic is perhaps the greatest hazard that pedestrians and cyclists face at signalized intersections. A review of safety studies found that the proportion of pedestrian crashes at intersections that involved a left-turning vehicle was between 17% and 32% (Lord et al., 1998). In Cambridge, MA, 19% of all bicycle crashes (including crashes away from intersections) were with left-turning vehicles (City of Cambridge, 2014). In New York City, out of 859 pedestrian and bicycle fatalities in a 5-year period ending in 2014, 108 were killed by a left-turning vehicle (NYC Department of Transportation [NYC DOT], 2016). Left turns are also a leading cause of vehicle–vehicle injury crashes.

Protected-only left-turn phasing separates crossing pedestrians and bicycles from left-turning vehicles in time. “Protected-only” means that left turns are allowed only during a protected turn phase, in which a green arrow is displayed to left-turning traffic and no conflicting movements—including pedestrian, bicycle, and vehicular movements—run concurrently. This differs from permitted and protected-permitted left turns, in which a circular green indicates that left-turning traffic may advance after yielding to conflicting movements. The objective of making left turns protected-only is to improve safety for pedestrians and bicycles as well as for vehicles.

6.1.1.3 Variations

Not applicable for this treatment.

6.1.1.4 Operating Context

Protected-only left turns might be appropriate for:

- Multilane roads;
- Left turns across a two-way bike path running along a road;
- Intersections with limited visibility between approaching bicycles and left-turning vehicles (visibility may be limited by parking, trees, etc.);
- Skew intersections that allow high-speed left turns;
- High volume of left turns; and
- High-speed roads.

Left Turn across a Multilane Road. Protected-only left turns are safer than permitted left turns at signalized intersections, especially on multilane roads. At urban signalized intersections, the crash modification factor (CMF) for changing left-turn phasing to protected-only is 0.01 for left-turn crashes, which means it virtually eliminates left-turn crashes (*Highway Safety Manual*, 2010). At the same time, protected phasing can increase the frequency of rear-end crashes, making its CMF 0.94 when all crashes are considered. But since head-on and angle crashes associated with left turns tend to be far more severe than rear-end crashes, there is still a substantial safety benefit associated with protected-only phasing.

Permitted left turns across multiple lanes of oncoming traffic carry a particularly large collision risk. One comprehensive review of the literature found that with protected-permitted phasing, crash rates per left-turning vehicle were 3.2 times greater on roads where the left turn crosses two through lanes of opposing traffic versus a single lane (Hauer, 2003). A study of 200 urban intersections in Kentucky found that left-turn crash risk rises faster than exponentially with the number of opposing through lanes, even for a fixed volume of opposing traffic (Amiridis et al., 2017). Based on the model from the study, if there are 140 left turns per hour and opposing through volume is 700 vehicles per hour, adding a second opposing lane increases crash risk by a factor of 3.7 and adding a third lane increases it by a factor of 32.

For crossing bicycles and pedestrians, risks involved with permitted left turns are especially high on multilane roads. For left-turning drivers on roads with only one through lane per direction, finding a gap requires less attention, and as a result, they are more likely to notice pedestrians and bicycles before beginning to turn. On multilane roads, gaps are constantly forming and dissipating because vehicles in different lanes can have different speeds, which makes scanning for a gap inherently more complex. Therefore, drivers waiting to turn left tend to fixate on the road as they search for and anticipate a gap. They often start turning as soon as they find a gap in the opposing through traffic, without paying attention to pedestrians and bicycles they may encounter toward the end of their crossing maneuver.

Left Turn across a Two-Way Bike Path Running Along a Road. When a two-way bike path lies alongside a road, drivers turning left across the bike path face a conflict with bicycles coming from behind. This makes permitted left turns inherently risky (Massachusetts Department of Transportation [MassDOT], 2015).

Limited Visibility of Approaching Bicycles. AASHTO's *A Policy on Geometric Design of Highways and Streets*, 7th Edition (Green Book) recommends that left turns at signalized intersections have permitted phasing only if drivers waiting to turn left have a clear sight line to the approaching vehicles that they must yield to (i.e., vehicles on course to arrive before the turning vehicle would have cleared their path). While this criterion was written with opposing motor traffic in mind, it also applies to bicycles. On a road with separated bike lanes or a sidepath, either approaching bicycles close enough to conflict with a turning vehicle should be visible or the left turn should be separated in time from the bicycle movement. The time needed for the left-turn maneuver is given by Equation 6-1:

$$\textit{Maneuver time} = t_o + 0.04\,C \qquad (6\text{-}1)$$

where

t_o = 5.5 s if the design is for a left-turning passenger car, 6.5 s for a single-unit truck, or 7.5 s for a combination truck, and

C = additional distance, in feet, needed to clear the conflict zone beyond the distance needed to clear the first opposing lane (see Exhibit 6-5). (For this purpose, the Green Book's coefficient of 0.5 s per additional lane has been converted to 0.04 s per additional foot.)

In Exhibit 6-1, the approach zone is the area within which the left-turning driver must yield to any approaching bicycle; Equation 6-2 describes its length as:

$$L = \textit{Bicycle design speed} \times \textit{Maneuver time} \qquad (6\text{-}2)$$

Bicycle design speed may be taken to be 14.7 to 17.6 ft/s (10 to 12 mph) on level ground and greater if bicycles approach on a downgrade. Left turns should be protected-only if visibility from the left turn lane's waiting position to any part of the approach zone is obstructed.

Exhibit 6-2 illustrates an obstructed view for the left-turn maneuver. In the photo, taken from well within the approach zone, the vehicle circled in red is actually the second vehicle in the left-turn queue; the line of sight of the first vehicle waiting to turn left is completely obstructed. Fortunately, left turns at this intersection are protected-only.

Skew Intersection. Where a skew intersection angle allows left turns to be made at high speed, both the risk and severity of a crash with a crossing pedestrian, bicycle, or opposing motor vehicle is elevated.

High Volume of Left Turns. High left-turn volume increases the pressure drivers feel to turn (rather than wait). It also increases the fraction of vehicles that turn left as a follower in

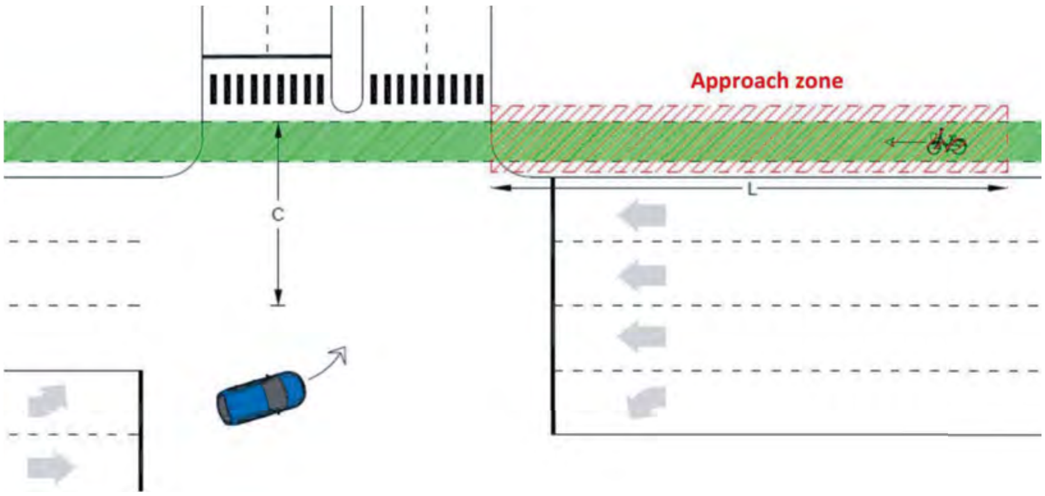

Exhibit 6-1. A left-turning passenger car versus an oncoming bicycle.

a platoon. Research done for this project found that left-turning drivers in the second or later position in a platoon were 56% less likely to yield to a crossing bicycle or pedestrian than drivers who were not immediately following another vehicle. For separated bike lanes, the MassDOT *Separated Bike Lane Planning & Design Guide* recommends, for example, a limiting volume of 50 vehicles per hour for left turns from a two-way street across two lanes and a one-way bike path. Assuming a 90 s cycle length, that is approximately one left-turning vehicle per cycle on average, thus avoiding platooned turns in most cycles.

High-Speed Roads. On high-speed roads, vehicle–vehicle crashes involving left turns are often deadly.

6.1.2 Applications and Expected Outcomes

6.1.2.1 National and International Use

In Amsterdam and other Dutch cities, protected-only phasing is used by policy at all multi-lane intersections and wherever left turns cross a two-way bike path. Permitted left turns are

Source: Peter Furth.

Exhibit 6-2. Obstructed view between waiting vehicle and the approach zone on a sidepath in Boston, MA. The circled car is the second vehicle in the left-turn queue.

allowed on streets with one lane per direction; however, protected left turns are more common in practice, except from minor-street approaches that are too narrow to have left-turn lanes.

In the United States, guidelines regarding the use of permitted left turns are comparatively less strict than in the Netherlands. For example, guidelines found in *NCHRP Report 812: Signal Timing Manual,* 2nd Edition (based on other national publications and repeated in many state guidelines) suggest using protected-only phasing only under the following conditions: a visibility issue; dual left-turn lanes; crossing four or more opposing through lanes; a speed limit of 50 mph or greater; or if experience with permitted left turns has led to an excessive number of left-turn crashes, more than roughly five per year per left-turn movement. Apart from the crash experience criterion, these are conditions that relatively few intersections meet. It also stands out that these guidelines make no explicit consideration for pedestrian or bicycle use.

Some American communities with high pedestrian- and bicycle-use have adopted policies that favor protected-only left turns. For example, at all intersections with multilane roads in Cambridge, the city has been converting permitted left turns to protected-only left turns to provide a safer operation for pedestrians, bicycles, and other vehicles (City of Cambridge, n.d.). Boulder, CO, follows a draft policy that calls for protected-only left turns across shared-use paths with a minimum volume of 30 bicycles per hour and across crosswalks with at least 100 pedestrians per hour (City of Boulder, n.d.). New York City has also recently converted several intersections to protected-only phasing.

6.1.2.2 Benefits and Impacts

Protected-only left turns improve safety for pedestrians, bicycles, and turning vehicles. A before-and-after study found that when nine intersections in New York City were converted to protected-only phasing, pedestrian–vehicle crashes fell by 28% and vehicle–vehicle crashes fell by 32%. The same study found no reduction in pedestrian–vehicle crashes after conversions to protected-permitted left turns, which were applied in Chicago, IL, and Toronto, Ontario (Goughnour et al., 2018).

Research done as part of this guidebook found that on a multilane road in situations where the only conflict is between a left-turning motorist and a cyclist during a permitted-turn phase, motorists failed to yield to bicycles more than half the time. This study examined two intersections in Boston with left turns across three lanes of traffic and a bike path offset about 10 ft from the road. In September 2019, both intersections were converted from protected-permitted phasing to protected-only. Before conversion, 164 bicycle crossings took place during the permitted phase while a left-turning vehicle was waiting to turn and no opposing traffic was blocking the left turn. The behavior of left-turning vehicles during this time is summarized as follows:

- In only 15 cases (9%) did the left-turning vehicle wait in the turn lane until both the opposing traffic lanes and bike path were clear.
- In 103 cases (63%), the left-turning vehicle claimed the right-of-way and made its turn, forcing the bicycle to stop or slow down.
- In the remaining 46 cases (28%), the left-turning vehicle began to turn and then, seeing that the cyclist was not yielding, stopped until the cyclist had cleared, blocking one or two opposite-direction travel lanes. Opposite-direction vehicles sometimes had to stop to avoid crashing broadside into these stopped vehicles.

After the left-turn phase was converted to protected-only, motorist failure-to-yield events all but disappeared. (Unfortunately, some red-light running by left-turning vehicles persisted several months after the conversion.)

Changing the left-turn mode from permitted or protected-permitted to protected-only increases delay for left-turning vehicles and, to a lesser extent, for bicycles and pedestrians, whose green duration becomes shorter. These impacts can be mitigated by using shorter cycles (see Section 7.1); lagging left turns (which can offer better progression for left-turning vehicles); or reservice for left turns, which in this context means giving left turns both a leading and a lagging phase (see Section 7.2). Research for this guidebook modeled the two Boston intersections discussed earlier and compared user delay for a base case with arterial coordination on a 120 s cycle and protected-permitted phasing against a variety of alternatives with protected-only left turns. Exhibit 6-3 compares the base case with leading protected lefts and shows that bicycle and pedestrian delays increase modestly while average left-turn delay rises by more than 45 s. However, other options result in considerably less left-turn delay, especially reservice and running free. Interestingly, for this corridor, running free results in the lowest delay for vehicles, pedestrians, and bicycles, mainly because it allows a far shorter average cycle length.

6.1.3 Considerations

6.1.3.1 Accessibility Considerations

Protected crossings benefit pedestrians with disabilities who are not in a strong position to compete with motor vehicles for right-of-way or to maneuver around vehicles that do not yield. It can be difficult for individuals with vision disabilities to distinguish the protected movement from through movements, so accessible pedestrian signals (APS) can help them begin crossing at the proper time. Protected-only left turns also make driving safer and easier for young (novice) drivers, whose driving skills are still developing, and for older drivers, whose perception abilities may be reduced.

6.1.3.2 Guidance

For separated bike lanes, the MassDOT *Separated Bike Lane Planning & Design Guide* recommends protected-only turns when turning volumes exceed those shown in Exhibit 6-4. It recommends, for example, a limiting volume of 50 vehicles per hour for left turns across two lanes and a one-way bike path. Assuming a 90 s cycle length, that is approximately one left-turning vehicle per cycle on average, thus avoiding platooned turns in most cycles (the effect of platooned turns on yielding and safety was discussed previously in the High Volume of Left Turns section).

6.1.3.3 Relationships to Relevant Treatments

Converting a left-turn phase to protected-only can create challenges that can be addressed by applying other treatments at the same time.

- If a left-turn bay is short and might spill back to block a through lane, reservice for the left-turn phase (see Section 7.2) can be considered.

Exhibit 6-3. Delay impacts of left-turn phasing alternatives, Columbus Avenue and Heath Street, Boston, morning peak hour.

	Pedestrian Delay (s)	Bicycle Delay (s)	Left-Turn Delay (s)	Intersection Vehicle Delay (s)	Average Cycle Length (s)
Protected-Permitted (Base Case)	25	18	27	40	120
Protected-Only (Leading Left)	27	32	73	58	120
Protected-Only (Lagging Left)	27	32	67	42	120
Protected-Only with Left-Turn Reservice	27	26	34	51	120
Protected-Only, Leading Left, Running Free	19	15	52	32	70

Exhibit 6-4. Turning volume criteria for protected-only left and right turns.

Separated Bike Lane Operation	Motor Vehicles per Hour Turning across Separated Bike Lane			
	Two-Way Street			One-Way Street
	Right Turn	Left Turn across One Lane	Left Turn across Two Lanes	Right or Left Turn
One-way	150	100	50	150
Two-way	100	50	0	100

Source: MassDOT (2015).

- If very heavy turning demand results in a short green window for bicycles, consider small-zone coordination to limit bicycle delay (see Section 9.2).
- An FYA operation can be used to run protected-only at certain times of day or when pedestrians are detected (see Section 6.9).

6.1.4 Implementation Support

6.1.4.1 Equipment Needs and Features

Changing the left-turn phase to protected-only may require additional signal heads, and adding signal heads may require additional mounting poles or mast arms.

6.1.4.2 Phasing and Timing

In coordinated corridors with protected-only left turns, lagging left turns often lead to less delay for left-turning vehicles because signals are typically timed for the main platoon to arrive during the green interval. With lagging left turns, most of the vehicles arriving in the main platoon are served toward the end of their arrival phase, while with leading left turns, they have to wait for the next cycle.

6.1.4.3 Signage and Striping

Not applicable for this treatment.

6.1.4.4 Geometric Elements

Protected-only left turns typically require an exclusive left-turn lane.

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6.2 Concurrent-Protected Crossings

6.2.1 Basic Description

6.2.1.1 Alternative Names

Protected right turn; left-turn overlap; split through phase.

6.2.1.2 Description and Objective

Pedestrian and bicycle crossings are concurrent with parallel through traffic, yet they can be separated in time from both right and left turns by providing turning movements with distinct phases (Exhibit 6-5). The objective is to improve safety by separating pedestrians and bicycles from conflicts with turning vehicles.

Protecting pedestrian/bicycle crossings from left turns is discussed as its own treatment in Section 6.1. The distinction of this treatment is that crossing phases are also protected from right turns. This treatment applies to protecting crossings from left turns from one-way streets as well.

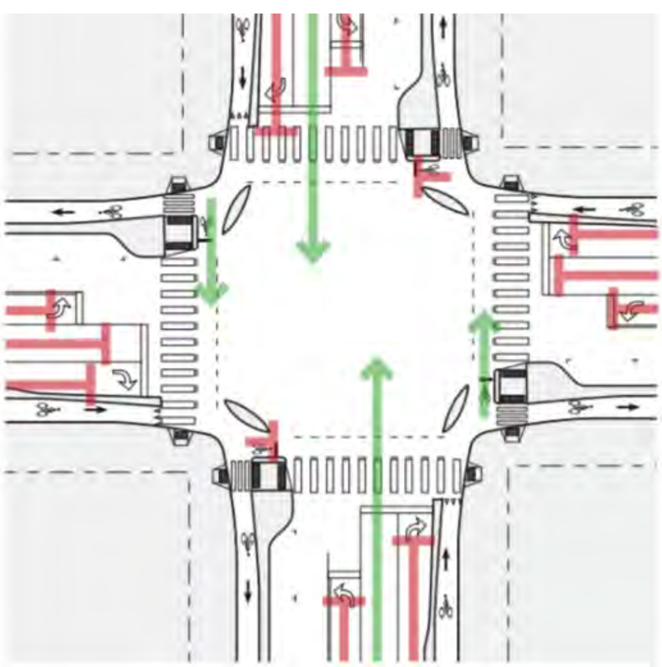

Exhibit 6-5. Concurrent-protected crossings.

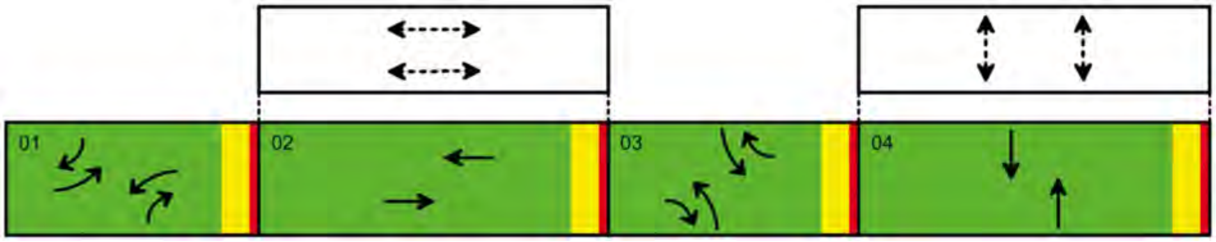

Exhibit 6-6. Right turns served with simple left-turn overlaps in a single-ring phasing plan.

6.2.1.3 Variations

Variations to this treatment arise from how the right-turn movement fits into the phasing plan. Wherever a right-turn movement has a parallel left-turn phase, it is efficient to run those turns concurrently. This scheme is illustrated in Exhibit 6-6; for example, southbound right is parallel to eastbound left, so the two movements can run together during Phase 01 (similarly, westbound right and southbound left movements can run together during Phase 03). In the controller, the right-turn phase can be programmed as an "overlap" that times concurrently with a left-turn phase.

If the right-turn movement runs only during a left-turn phase, as shown in Exhibit 6-6, it is a simple overlap. More complex overlaps can also be programmed in which the right-turn phase also runs during part of the through movement, as explained later.

In some situations, there is no left-turn phase parallel to the right-turn movement, such as on a one-way street or where the cross street does not have a left-turn phase. In such a case, a phasing scheme called split through phase can be applied. Shown in Exhibit 6-7 is a typical phasing plan used in New York City along a one-way avenue with a protected bike lane on the left side of the street. The through movement for the avenue—which in this example runs northbound—is split into two phases, with Phase 01 serving the left-side protected bike lane crossing and Phase 02 serving left-turning vehicles.

6.2.1.4 Operating Context

This treatment is useful whenever certain conditions make it more desirable to separate crossings in time from right turns as well as left turns. Such conditions include heavy right-turn volumes, intersection geometry that allows high-speed right turns, and bicycle crossings with limited visibility.

This treatment can also be useful when pedestrian crossings are so heavy that right-turn flow would be blocked unless right turns are given a distinct phase separated from crossing pedestrians, which might occur in a downtown area or near a major transit station.

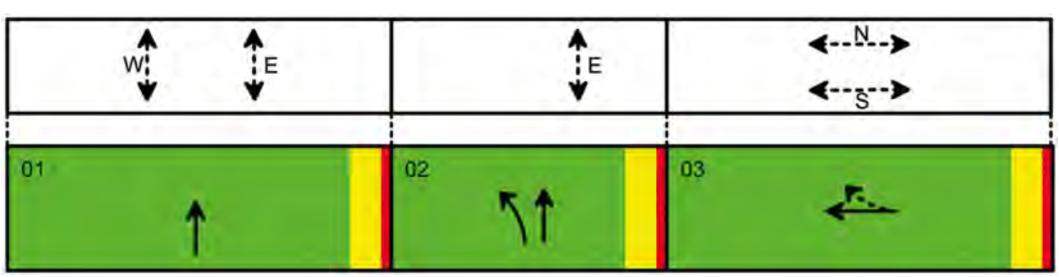

Exhibit 6-7. Split through phase as applied along one-way avenues in New York City.

This treatment also requires an exclusive right-turn lane. At intersections without exclusive right-turn lanes, it may be possible to create an exclusive right-turn lane by widening an intersection approach, converting a parking lane into a turn lane, or converting a shared through-right lane into an exclusive right-turn lane and adjusting signal timing accordingly.

6.2.2 Applications and Expected Outcomes

6.2.2.1 National and International Use

In Dutch cities, where protected bike lanes are common, it is typical to have concurrent-protected crossings. A road with only one travel lane per direction that widens to three lanes as it approaches an intersection is common: one lane each for left turns, through vehicles, and right turns. This allows the bicycle and pedestrian crossings to be given phases that are separated in time from those of the right turns and left turns.

In the U.S., concurrent-protected crossings using left-turn overlaps and split through phases are well-established techniques, though not as commonly applied. Application has grown as cities including Portland, OR; Long Beach, CA; New York; Boston; and Cambridge, MA, have used this treatment over the last 15 years to create safer bicycle and pedestrian crossings.

The experiences and policies of Amsterdam; New York City; and the island of Montreal, Québec, are instructive for understanding the trade-off between protection and delay when protecting bicycles from right-turn conflicts. In Amsterdam, concurrent-protected bicycle and pedestrian crossings became the norm in the 1970s. This led to long signal cycles and, as an unintended consequence, long delays for bicycles (and for right-turning motorists). Complaints and high rates of noncompliance led to a change in policy in the early 1980s. Since then, right-turn conflicts have become permitted at most intersections, although concurrent-protected phasing is still used on approaches with high right-turn volumes or high right-turn speeds and anywhere that right turns can be served with a simple left-turn overlap (Linders, 2013).

New York City's policy regarding protected crossings evolved similarly to Amsterdam's. Caution over implementing the nation's first parking-protected cycle tracks in 2007 resulted in concurrent-protected crossings at nearly all intersections with protected bike lanes. After several years, high cyclist noncompliance at intersections with low turn volumes led officials to recognize that at such locations, conflicts with permitted left turns were not a significant hazard. As a result, many concurrent-protected crossings were converted to the delayed-turn treatment (see Section 6.6) in which the bicycle crossing is protected-only during an initial interval (e.g., 10 s or 15 s), after which conflicting left turns (from a one-way street) are allowed and governed by an FYA (see Section 6.9) to alert drivers of a potential conflict. New York City's current policy prefers concurrent-protected crossings only where there is high volume or high-speed turn conflicts (provided a turn lane is available or can be created). Without these conditions, if a turn lane can be provided then delayed turn is preferred; where no turn lane can be created, an LPI is preferred (see Section 6.5) (D. Nguyen, personal communication, October 10, 2019).

Montreal approached the protection-delay trade-off from the other direction. Montreal has long used the delayed-turn treatment (see Section 6.6) at intersections throughout its downtown. When a downtown two-way bicycle path was created in 2007 along the left side of Avenue de Maisonneuve, a one-way street, delayed turn was applied. Bicycles had a protected crossing for the first 9 s but were concurrent with through traffic after that, and left turns across the bicycle path were permitted during the rest of the through phase. However, over the years, bicycle volume increased, and motorists could not find enough safe gaps to turn left, particularly since the bike path is two-way; this led to unsafe turning behaviors, such as drivers forcing a gap. In the face of mounting complaints, signals were changed in 2019 to make crossings concurrent-protected using split through phasing. The left lane was converted to an exclusive left-turn lane, leaving only one lane for through traffic. Initial implementation led to complaints of large increases in cyclist delay, leading the city to commit to improving bicycle progression (see Section 9.2).

6.2.2.2 Benefits and Impacts

While exclusive pedestrian and bicycle phases (see Section 6.3) and concurrent-protected crossings both provide fully protected crossings, concurrent-protected phasing usually provides more vehicular capacity, allows shorter cycles, and results in less delay for all users, especially where right turns can be served using left-turn overlaps. A simulation study of a four-leg intersection in Boston currently operating with exclusive pedestrian and bicycle phases found that by using left-turn overlaps, concurrent-protected phasing would reduce the needed cycle length from 135 s to 93 s while lowering average delay by 17 s for vehicles and by 22 s for pedestrians (Furth et al., 2014).

Concurrent-protected crossings eliminate turn conflicts, which makes them safer than crossings with permitted right-turn conflicts. Other impacts include increased delay to vehicles (especially those turning right), increased delay to bicycles and pedestrians, and an enlarged intersection footprint to facilitate a right-turn lane. In many cases, however, concurrent-protected crossings can be implemented with no footprint impact. When the junction of Broadway and Galileo Galilei Way, Cambridge, was converted in 2017 to concurrent-protected phasing, two of the approaches already had right-turn lanes; on the other two approaches, the rightmost through lanes were converted to exclusive right-turn lanes. The through phases still had sufficient capacity, in spite of having one fewer lane, because right-turning traffic and pedestrian interference were removed. Cycle length was left unchanged, and the level of service for vehicles was also unchanged. However, the treatment has been called a “night and day” improvement for pedestrians because they can now cross without danger from right-turning cars (P. Baxter & C. Seiderman, personal communication, December 19, 2018).

There is almost no delay impact to pedestrians or bicycles when right turns can be served using simple overlap with a left-turn phase; if this is not possible, concurrent-protected crossings can increase pedestrian and bicycle delays by limiting their crossing phase to only part of the through phase. Delay impacts will vary from site to site and are difficult to generalize. One study, based on the junction of NW Broadway and NW Lovejoy Street in Portland, found that providing a protected crossing increased average cyclist delay by 4 s to 16 s, depending on traffic volumes (Furth et al., 2014).

6.2.3 Considerations

6.2.3.1 Accessibility Considerations

The surge of traffic by right-turning vehicles using a protected right-turn phase may be incorrectly interpreted as the beginning of the parallel through-traffic phase and the simultaneous onset of the Walk interval by individuals who cannot see the Walk signal. The complexity and potential changes in signal phasing for each cycle also can be confusing to such pedestrians. Provide an APS to provide instruction for these users.

6.2.3.2 Guidance

There is no national guideline for an acceptable volume of permitted right-turn conflicts. Both the State of Massachusetts and Boston recommend protected pedestrian crossings where concurrent right turns would exceed 250 vehicles per hour (which is approximately seven vehicles per cycle, since most intersections have a cycle length of 100 s). Dutch guidelines set the limit at

150 vehicles per hour for one-way cycle tracks and recommend that two-way cycle tracks avoid all permitted conflicts (an increasing number of exceptions to this latter rule can be found in the Netherlands).

6.2.3.3 Relationships to Relevant Treatments

Protected-only left turns to address non-motorized user conflicts (see Section 6.1) and no turn on red (NTOR) (see Section 6.8) are necessary parts of this treatment.

Exclusive pedestrian and bicycle phases (see Section 6.3) are an alternative treatment that provides fully protected pedestrian crossings.

Delayed turn/leading through intervals (see Section 6.6) are an alternative treatment that provides partially protected crossings.

Channelized right turns (see Section 6.4) also provide concurrent-protected crossings, but they allow right turns to run at the same time as crossing bicycles and pedestrians because their conflict is resolved in advance of the intersection.

6.2.4 Implementation Support

6.2.4.1 Equipment Needs and Features

New right-turn phases will need signal heads and support structures.

6.2.4.2 Phasing and Timing

Exhibit 6-6 presents an example of how concurrent-protected crossings with left-turn overlaps can be arranged using a single ring. This is the phasing plan used in Cambridge at the junction of Broadway and Galileo Galilei Way, as described earlier. It is most appropriate when the left- and right-turn movements that run concurrently have similar volumes.

The same sequence can be arranged in a dual ring, offering greater flexibility to match phase lengths to demand (see Exhibit 6-8). It is the same as the standard dual ring, except that right turns run with their parallel left turn instead of their parallel through movement. Notice how any given crossing in Exhibit 6-8 (e.g., the north-side crossing, running during Phase 02) has a clear sequence: The conflicting left turn leads (Phase 01), the crossing is in the middle (Phase 02),

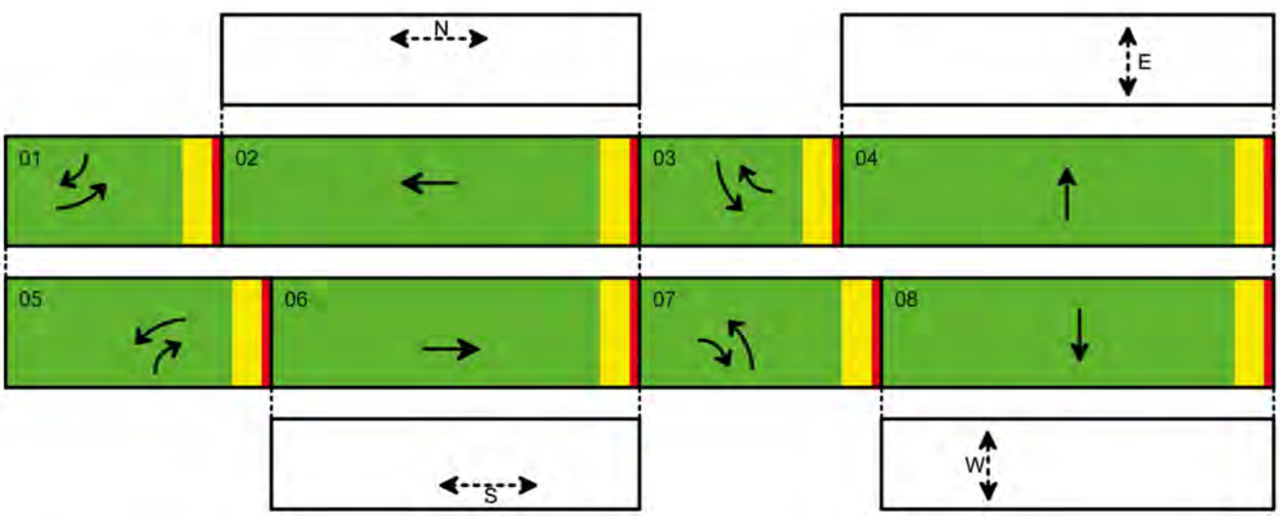

Exhibit 6-8. Dual-ring phasing using simple left-turn overlaps to serve right turns.

and conflicting right-turn lags (Phase 03). As with any dual-ring structure, phase sequence can be reversed so that the conflicting right turn leads and the conflicting left turn lags.

Exhibit 6-9 has the same ring-barrier structure, but with right turns served using complex overlaps, providing additional flexibility to serve right-turn demands. For this example, left turns are lagging and right turns are leading. Each through movement has been subdivided into two phases; for example, westbound through is served by Phases 09 and 02, which together comprise Overlap A. During the first part of Overlap A (i.e., Phase 09), westbound right turns can run; during the latter part (Phase 02), the north-side crossing runs fully protected. Westbound right turns are served not only during Phase 09 but also during Phase 07, concurrent with a parallel left turn. The two phases serving westbound right turns comprise Overlap H. This example has four overlaps for the through movements (A, B, C, D) and four overlaps for right turns (E, F, G, H).

This more complex ring structure allows phase lengths to more freely adapt to demand—in particular, it allows right turns to run longer than their parallel left turn, which can be helpful for serving streets whose dominant flow direction changes between morning and evening peaks. This ring structure, like all the others presented in this section, can be used with either pretimed or actuated control.

With any of these phasing plans, bicycle delay will be minimized if the conflicting right-turn phase is actuated so any time that is not needed by right-turning vehicles can revert to the crossing phase. This is most easily accomplished by sequencing right turns to precede the protected crossing (Furth et al., 2014).

Where the conflicting crossing is short, the crossing phase and/or right-turn phase can appear several times within a cycle, a technique called reservice (see Section 7.2).

6.2.4.3 Signage and Striping

Not applicable for this treatment.

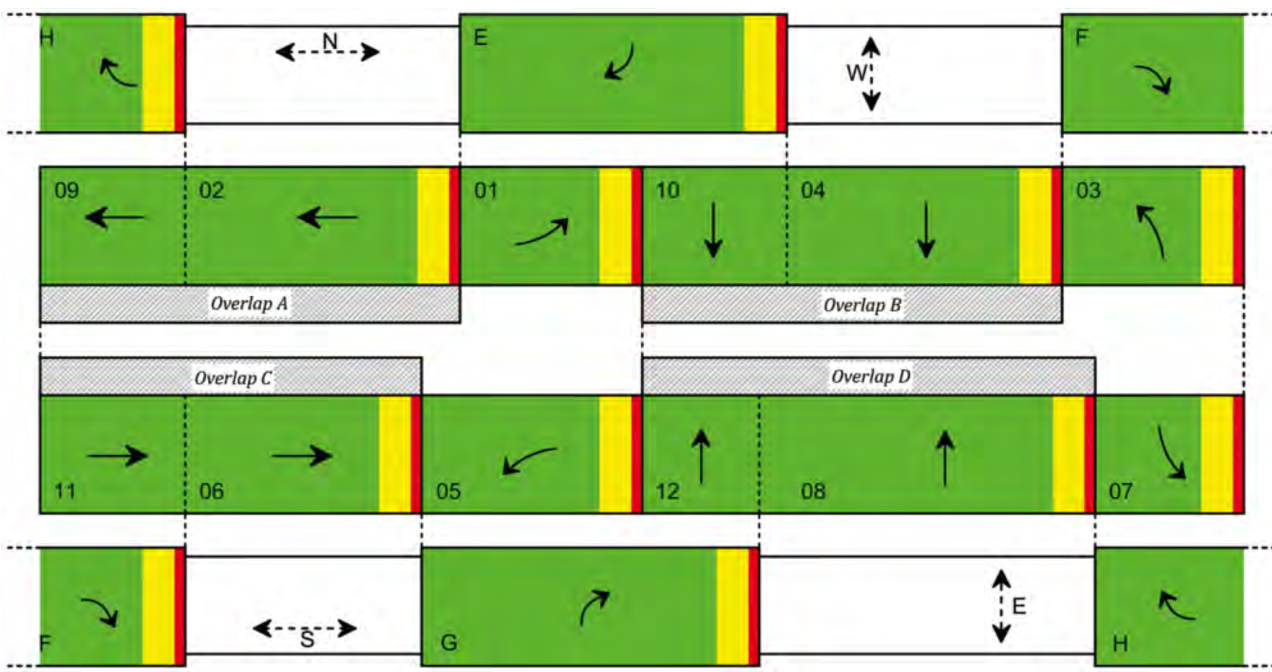

Exhibit 6-9. Using complex overlaps to create a full set of concurrent-protected crossings.

6.2.4.4 Geometric Elements

Concurrent-protected crossings require exclusive right-turn lanes. In some cases, a through lane can be converted into a right-turn lane while still providing sufficient through capacity.

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6.3 Exclusive Pedestrian and Bicycle Phases

6.3.1 Basic Description

6.3.1.1 Alternative Names

Pedestrian and/or bicycle scramble; Barnes Dance.

6.3.1.2 Description and Objective

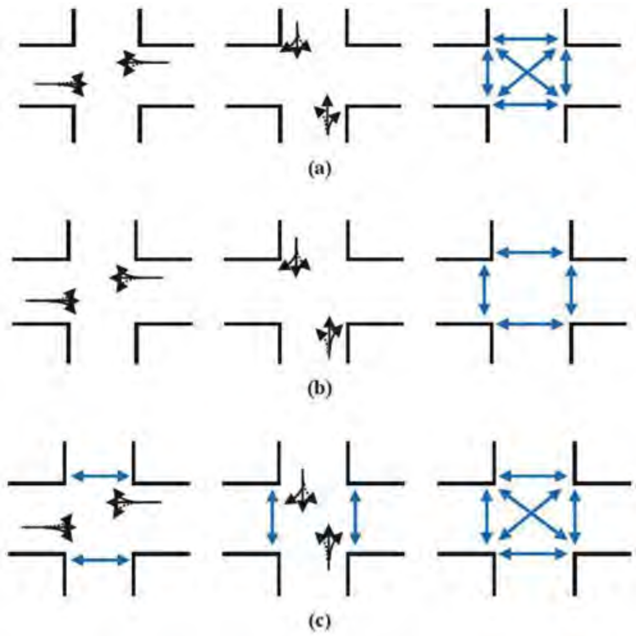
With exclusive pedestrian or bicycle phases, the pedestrian/bicycle crossings phase occurs while all vehicular movements have a red indication. This treatment aims to increase pedestrian/bicycle safety by eliminating turn conflicts. It is also sometimes used to increase capacity for right turns when high flows of pedestrians block concurrent right turns, to increase pedestrian capacity when pedestrian volumes are high, and to enable pedestrians and/or bicycles to make diagonal crossings.

6.3.1.3 Variations

Exclusive phases may or may not include diagonal crossings (Exhibit 6-10[a] and Exhibit 6-10[b], respectively). Where diagonal crossings are formally allowed, an exclusive pedestrian phase can be called a pedestrian scramble or Barnes Dance. Even when a diagonal crossing is not formally provided, many people still cross diagonally.

If exclusive pedestrian phases are provided, pedestrians can also be allowed to cross concurrently (i.e., concurrent with the parallel vehicular movement), as illustrated in Exhibit 6-10(c). This option results in high pedestrian-crossing capacity and less waiting time for pedestrians, but pedestrians are not protected from permitted turns during concurrent phases.

Exclusive pedestrian phases are common; exclusive bicycle phases less so. In the U.S., exclusive bicycle phases typically permit only certain non-conflicting bicycle movements (e.g., a diagonal crossing); in the Netherlands, all bike directions are allowed, which creates cross-direction conflicts that bicyclists appear to resolve informally without any safety issues. Exclusive phases shared by pedestrians and bicycles are even less common, although bicycles often run informally during exclusive pedestrian phases.



Source: Kattan et al. (2009).

Exhibit 6-10. Typical phase sequences with an exclusive pedestrian phase: (a) with diagonal crossings, known as pedestrian scramble or Barnes Dance; (b) without formal diagonal crossings; and (c) with pedestrians also allowed to cross concurrently.

6.3.1.4 Operating Context

There are several contexts for which exclusive pedestrian or bicycle phases might be appropriate:

- Where either high-speed right turns, a high volume of right turns, or frequent right-turning trucks make concurrent crossings unsafe, and it is not possible to provide a dedicated right-turn lane;
- At intersections with very high pedestrian-volumes—as might be common near a busy transit station—where concurrent crossings would conflict with right-turning traffic to the point of creating tension and/or overly restricting right-turn capacity;
- At intersections with very high pedestrian-volumes—where pedestrians need the green for a large part of the cycle—by combining an exclusive pedestrian phase with concurrent crossings (see Exhibit 6-10[c]);
- Where there is high demand for diagonal pedestrian crossings; or
- To serve an important diagonal bicycle crossing, such as when a bicycle path switches from one side of the road to another.

6.3.2 Applications and Expected Outcomes

6.3.2.1 National and International Use

Exclusive pedestrian phases are used widely in North American cities, most often in downtowns.

While many applications formally provide for diagonal crossings, some do not. This is because diagonal crossings require a longer pedestrian clearance time. For example, downtown Denver, CO, has many intersections with exclusive pedestrian phases that originally featured diagonal crossings. However, several years ago, the city retimed its signals for a crossing speed of 3.5 ft/s instead of 4 ft/s, and diagonal crossings were formally removed to avoid having to lengthen pedestrian phases.

Several intersections in downtown Toronto have exclusive pedestrian phases in addition to concurrent crossings during a parallel vehicle phase (see Exhibit 6-10[c]), resulting in high capacity and low delay for pedestrians. In downtown Washington, DC, the same treatment can be seen at the intersection of 7th Street NW and H Street NW.

In Massachusetts, exclusive pedestrian phases have long been the default treatment for intersections on state highways, and they are also common at local, municipal intersections. However, they typically involve long pedestrian waiting times and poor pedestrian compliance; therefore, pedestrian advocates generally prefer concurrent crossings, except where right-turn volumes are high or turns are made at high speeds due to intersection geometry.

New York City has more than 80 exclusive pedestrian phase locations, typically where skewed geometry allows for high-speed right turns, where there is a strong desire for pedestrians to cross diagonally to and from major transit stations, or where there is a high volume of turning vehicles. The city also has 386 "T-away" intersections, which are T-intersections where the cross street is one-way headed away from the intersection, making the cross-street phase a de facto exclusive pedestrian phase (NYC DOT, 2017).

Exclusive bicycle phases are far less common. One type is a phase that serves a diagonal crossing—such as where a bicycle path switches from one side to another—and other bicycle movements are not allowed during that phase. Most often, pedestrian movements are also not allowed. Portland has two such applications, including one at North Interstate Avenue and Oregon Street. At 9th Avenue North and Westlake Avenue North in Seattle, WA (see Exhibit 6-11), the diagonal bike crossing phase doubles as an exclusive pedestrian phase; however, other bike movements are held.

The other type of exclusive bicycle phase is a bicycle scramble phase, in which bicycles in all directions get a green signal. This treatment is used at 28 intersections in Groningen, Netherlands, and at a few intersections in other Dutch cities, where it is called "All Directions

Source: Kittelson & Associates, Inc.

Exhibit 6-11. Diagonal bicycle crossings at 9th Avenue North and Westlake Avenue North in Seattle, Washington.

Green." The main impetus for applying this treatment has been to protect cyclists from conflicts with turning traffic. Where it has been applied in Groningen, it has eliminated fatal bicycle–motor vehicle collisions; bicycle–bicycle conflicts, which are resolved without formal rules, have not been a safety problem. In some applications, pedestrians also cross during the exclusive phase. In order to minimize bicycle delay, the bicycle phase comes up twice per cycle wherever intersection capacity allows; about 25% of the Groningen intersections with bicycle scramble have two bicycle phases per cycle all day long, and at a few others, bicycles get two phases per cycle outside of peak hours (City of Groningen, 2019; J. Valkema, personal communication, November 20, 2019).

6.3.2.2 Benefits and Impacts

Exclusive pedestrian phases have been shown to reduce collisions and conflicts involving pedestrians. One study found that at intersections in New York City where concurrent crossings were replaced with exclusive pedestrian phases, pedestrian crashes fell 50% versus a 4% decrease for a control group. At the same time, however, vehicle crashes increased 10% at the treatment site, while they decreased 12% at the control sites (Chen et al., 2014). At an intersection in Oakland, CA, that had been converted from concurrent crossings to an exclusive pedestrian phase, pedestrian–vehicle conflicts in which one party had to stop or change course unusually to prevent collision fell from 11.8 to 6.4 conflicts per 1,000 pedestrians (Bechtel et al., 2004). A similar study of two converted intersections in Calgary, Alberta, Canada, also found a significant decrease in pedestrian–vehicle conflicts (Kattan et al., 2009).

Because exclusive pedestrian phases decrease the time available for vehicular movements, they can increase the necessary cycle length substantially, increasing delay for pedestrians and vehicles alike. If an exclusive phase will last 20 s, for example, that may require increasing the cycle length by 40 s or more to maintain vehicular capacity, since the vehicular phases will have longer red periods and will therefore require longer green periods. For some intersections, adding an exclusive pedestrian phase will put intersections over capacity. On the other hand, there can be a countervailing effect if pedestrians create so much right-turn blockage that the saturation flow rate declines precipitously with concurrent crossings. In such a case, isolating pedestrians within a single phase can make the vehicular phases much more efficient; this reduces the negative capacity and delay impacts of exclusive pedestrian phases, particularly where right-turn blockage affects both intersecting streets.

The increase in delay caused by exclusive pedestrian phases is not only a drawback in itself; it can also promote pedestrian noncompliance, diminishing the technique's safety benefits. The Oakland and Calgary studies (Bechtel et al., 2004; Kattan et al., 2009) both found a large increase in pedestrian noncompliance, with many people crossing concurrently with the parallel vehicular phase. Another NYC study found that applying exclusive pedestrian phases with diagonal crossings at five intersections with high pedestrian-volumes increased waiting times for all roadway users, interrupted pedestrian walking flow, and led to sidewalk overcrowding (NYC DOT, 2017).

6.3.3 Considerations

6.3.3.1 Accessibility Considerations

Exclusive pedestrian phases may not be recognized by pedestrians who are visually impaired or who have low vision if APS are not installed. They will typically cross with the movement of concurrent vehicles in the absence of accessible signal information. The *Manual on Uniform Traffic Control Devices* (MUTCD) (2009) notes this as an issue when considering APS in Part 4, Section E.09, Part 03.

6.3.3.2 Guidance

The Toronto Transportation Division developed the following guidelines for implementing exclusive pedestrian phases. The treatment should be implemented only if one or more of the following conditions are satisfied (Kattan et al., 2009):

- The intersection experiences a high volume of pedestrians (3,000 per hour for an 8-hour period).
- There is a combination of a moderate volume of pedestrians (2,000 per hour for an 8-hour period) with high turning-vehicle volumes (30% of the total vehicular traffic).
- There is moderate pedestrian volume with high pedestrian–vehicle collisions (three collisions over the past 3 years).
- There is moderate pedestrian volume, and 25% of pedestrians desire to cross diagonally.
- The intersection geometry is unusual (e.g., highly skewed; five or six legs).

6.3.4 Implementation Support

6.3.4.1 Equipment Needs and Features

Not applicable for this treatment.

6.3.4.2 Phasing and Timing

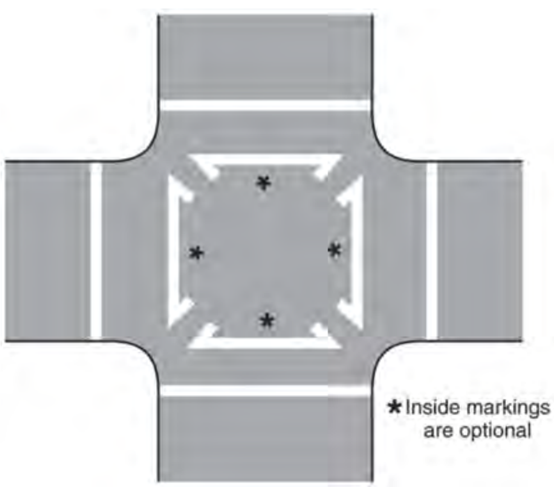
Not applicable for this treatment.

6.3.4.3 Signage and Striping

Restrictions for NTOR (see Section 6.8) should be applied through either a static sign or a blank-out sign that is active during the exclusive phase.

If diagonal crossings are permitted during an exclusive pedestrian phase, diagonal striping to indicate those movements is recommended, as shown in Exhibit 6-12.

At intersections where bicycles are permitted to use exclusive pedestrian phases, signage may be required to inform cyclists that crossings are allowed during the exclusive phase.



Source: MUTCD (2009), Figure 3B-20.

Exhibit 6-12. Example of crosswalk markings for an exclusive pedestrian phase that permits diagonal crossing.

6.3.4.4 Geometric Elements

If bicycles will be allowed to use an exclusive phase with pedestrians, it is preferable for the intersection to be configured so that the paths of bicycles and cross-direction pedestrians meet outside the crosswalks that are regulated by traffic signals. An example of this is when bicycles are in a shared-use path or in protected bike lanes offset far enough from the curb that pedestrians have a waiting platform between the curb and the protected bike lane.

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6.4 Channelized Right Turns/Delta Islands

6.4.1 Basic Description

6.4.1.1 Alternative Names

Pork chop islands; right-turn slip lane.

6.4.1.2 Description and Objective

A channelized right-turn lane is a lane that diverges from through lanes as it reaches an intersection, forming a delta island between them. The delta island, also called a pork chop island, serves as a pedestrian refuge and may also serve as a bicycle refuge (Exhibit 6-13).

Where right-turn volumes are high, channelized right turns result in shorter main crossings that are fully protected from right turns and, by making traffic flow more efficient, can enable a shorter cycle length and/or a smaller footprint for the intersection.

At the same time, channelized right turns also pose challenges to pedestrians and cyclists that can make it advantageous to eliminate them. When channelized right turns are unsignalized, replacing them with a conventional intersection layout with square corners forces right turns to be made at a lower speed. When channelized right turns are signalized, they create multistage crossings that, if not timed carefully, can entail extremely long pedestrian and cyclist delay (see

Source: Google.

Exhibit 6-13. Channelized right turn in Boulder (US 36 at Baseline Road) with delta island that serves as a refuge for a shared-use path.

Chapter 10). The suitability of small delta islands as pedestrian and/or cyclist refuge islands is often questionable, and eliminating channelized right turns can free up space in intersection corners that can be used to make a safer crossing layout.

6.4.1.3 Variations

Channelized right turns can be controlled by traffic signals or by Stop signs, and they can also be under Yield control (either signed or, since the crosswalk has priority, implicit). Where under Stop control or Yield control, the corner geometry should promote low turning speeds and yielding compliance using measures such as sharp turning radius, raised crossings, and prominent signs, as seen earlier in Exhibit 6-13. Where signalized, signals should be timed to provide good progression for pedestrians and bicyclists, who will have to make a multistage crossing.

Delta islands can serve as a refuge for pedestrians only, for a shared-use path, or for pedestrians and bicycles separately. A separate bike lane through a delta island can be called a protected pocket lane. If the slip lane is signalized, bicycles will have a presignal that allows them to cross the slip lane. Exhibit 6-14 shows a protected pocket lane and a bicycle presignal at a Copenhagen, Denmark, intersection.

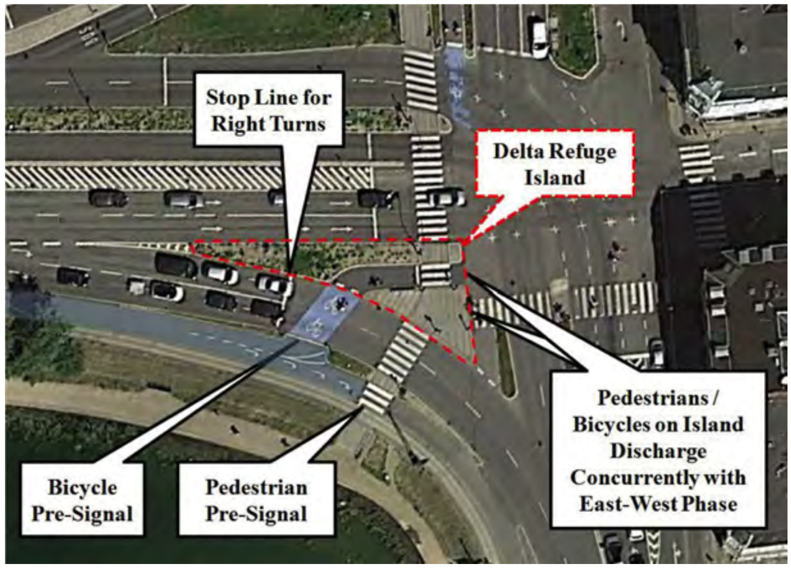
6.4.1.4 Operating Context

Channelized right-turn lanes with delta islands might be appropriate where:

- A moderate or heavy right-turn flow calls for a protected bicycle/pedestrian crossing. (An alternative treatment is a concurrent-protected crossing without a slip lane [Section 6.2].)
- There is a sharp right turn and a need to accommodate large design vehicles. In such a case, a channelized right turn can make the crossing much shorter.

Signalizing the crossing of a delta island might be appropriate where:

- Right-turn volume is high.
- A skew angle allows right turns to be made at high speed.
- There are poor sight lines between right-turning vehicles and crossing pedestrians/bicycles.
- Less restrictive measures to ensure crossing safety and compliance, such as raised crossings and prominent signs, have not been successful.



Source: Bachiochi & Furth (2016).

Exhibit 6-14. Delta island in Copenhagen (Fredensbro and Øster Søgade) with bicycle presignal and protected pocket bike lane.

6.4.2 Applications and Expected Outcomes

6.4.2.1 National and International Use

In the U.S., channelized right turns are common, particularly on wide, higher speed roads. Most were not made for the benefit of pedestrians or bicyclists but rather to reduce motorist delay by increasing turning speed. Most channelized right turns are unsignalized, but signalization is not unusual. Boulder has been a leader in improving the design of channelized turns that involve a shared-use path crossing. Some U.S. cities, including Chicago, IL, have announced plans to remove all channelized right-turn lanes due to safety issues.

Channelized right turns are rarely used in Dutch cities because the slip-lane crossings either become a safety problem if left unsignalized or create unacceptable delay for pedestrians and bicycles if signalized (S. Linders, personal communication, August 1, 2018). On the other hand, Copenhagen has a prominent application at an intersection that is heavily used by bicycles and pedestrians (see Exhibit 6-14).

6.4.2.2 Benefits and Impacts

A study of about 400 intersections in Canada found that intersection approaches with channelized right-turn lanes and those with shared through/right lanes had around 70%–80% fewer pedestrian crashes than approaches with conventional right-turn lanes (Potts et al., 2014).

However, channelized right-turn lanes can also have negative consequences for bicycles and pedestrians. Where the crossings are unsignalized, they can involve high speeds and consume space that might be used to lay out safer crossings. For example, the channelized right-turn lane in Exhibit 6-15 consumes most of the available right-of-way in the intersection corner, forcing the shared-use path to abut the curving roadway with no offset. This creates a blind conflict for bicycles who have to turn 90 degrees to enter the crossing—they have to look behind them for conflicting traffic. At the same time, motorists have no warning of whether an approaching

Source: Google.

Exhibit 6-15. Channelized right turn with a shared-use path immediately next to the curb, creating a conflict with poor visibility for cyclists and insufficient opportunity for drivers and cyclists to react.

cyclist intends to turn into the crossing. Eliminating those channelized right turns could free up enough space to create a protected intersection layout in which the shared-use path is offset several feet from the road, improving visibility between bicycles and right-turning vehicles.

When protected crossings are needed, channelized right turns enable more efficient traffic flow than either concurrent-protected crossings or exclusive crossings because they allow through traffic, right-turning traffic, and the main crossing movement to all run concurrently. The shorter main crossing can also help enable a shorter cycle length (see Section 7.1). A micro-simulation study showed that the use of yield-controlled channelized right-turn lanes can reduce vehicle right-turn delay by 25% to 75% in comparison to intersection approaches with conventional right-turn lanes (Potts et al., 2014).

Channelized right turns that are not signalized have little impact on pedestrian and bicycle delays. However, if they are signalized, crossings for pedestrians and bicycles become multistage, which can lead to far greater pedestrian and bicycle delays unless the crossing phases are timed to give bicycles and pedestrians good progression. Pedestrian/bicycle progression through delta islands can be especially poor when slip lanes have no dedicated right-turn signal and instead follow the through movement's signal. Research done in developing this guidebook found that at one such intersection, a shared-use path had an average bicycle delay of 66 s, while it would be 10 s if the slip lane were unsignalized and 14 s if it were signalized in a way that offers good progression. When delay is that long, poor compliance can be expected, which can negate any safety benefit hoped for by adding signals.

6.4.3 Considerations

6.4.3.1 Accessibility Considerations

APS must be carefully installed and adjusted when used at channelized right turns (see MUTCD, Section 4E.13). Design of the channelizing island should consider how pedestrians who are visually impaired will approach to ensure that the APS are clear.

The channelizing island may add an unsignalized pedestrian crossing to a signalized crossing if the right turn is free or yield-controlled. The accessible pushbutton should be located on the channelizing island to avoid implying that the crosswalk between the edge of the road and the island is also protected.

NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities provides assessment materials to determine if channelized right-turn lane crossings are accessible to users with disabilities and, depending on the results of the assessments, suggested treatments (Schroeder et al., 2017). Channelization and different materials in the non-walking area are recommended on the island to provide wayfinding direction to pedestrians.

6.4.3.2 Guidance

MUTCD (2009) guidance on crossing distance is to provide crossing from the curb/edge of a shoulder to the far side of a traveled way. This can be interpreted to mean from one channelizing island to the next, as this is the distance needed for a user to cross to a safe spot.

6.4.3.3 Relationships to Relevant Treatments

If channelized right turns are signalized, they create multistage crossings (see Chapter 10)—this requires evaluating pedestrian and bicycle delays (see Sections 3.4 and 3.5) and using signal timing treatments such as reservice (see Section 7.2) to create good progression for pedestrians and bicycles.

Independently mounted pushbuttons are also needed where right turns are signalized (see Section 8.3).

FYAs can also be used with channelized right turns to warn of conflicts with crossing pedestrians and bicycles (see Section 6.9).

6.4.3.4 Other Considerations

In most cases, the pedestrian benefit to channelizing islands (i.e., reducing main crossing distance) can be achieved by reducing the curb radius and making the intersection smaller overall. This will have the additional benefit of reducing the conflict speed between turning vehicles and pedestrians. This may not be possible in cases such as highly skewed intersections or large design vehicles. In these cases, a well-designed channelizing island can be used.

Drainage, paving, and snow removal should be considered when exploring the use of channelized right turns.

6.4.4 Implementation Support

6.4.4.1 Equipment Needs and Features

If right-turn lanes are signalized, it is preferable that they be controlled by their own signal heads (rather than following a green ball given to the through phase) and have a detector used to actuate the turn phase to minimize pedestrian delay.

6.4.4.2 Phasing and Timing

Where channelized right turns are signalized, it makes the pedestrian—and sometimes bicycle—crossings multistage, which can result in long delays unless signals are timed for good progression for crossing pedestrians and cyclists. This is a challenge because four different streams of pedestrian movements cross any given channelized right-turn lane (i.e., people walking northbound, southbound, eastbound, and westbound), all arriving or departing at a different time. Creating good progression requires either limiting the right turn to a short phase or providing multiple crossing phases (and therefore multiple right-turn phases) per cycle, a tactic called reservice (see Section 7.2).

When a right turn and its crossing have no conflicts except with each other, they can be controlled as an independent intersection running free, with short, alternating phases served on demand. An example is the control planned for a channelized right-turn lane in Boston where Tremont Street turns onto Melnea Cass Boulevard. The right turn will end whenever the pedestrian pushbutton is actuated, and it is subject to a 10 s minimum green for the right turn, guaranteeing a short wait for pedestrians. Because the crossing phase lasts only 12 s, right-turning vehicles also experience low delay.

Exhibit 6-16 shows the phasing plan used for the Copenhagen intersection shown earlier (in Exhibit 6-14), with a channelized right turn in its northeast corner. The right-turn phase is actuated, so it gets only the time that it needs to clear the queue; for the rest of the cycle, the crossing

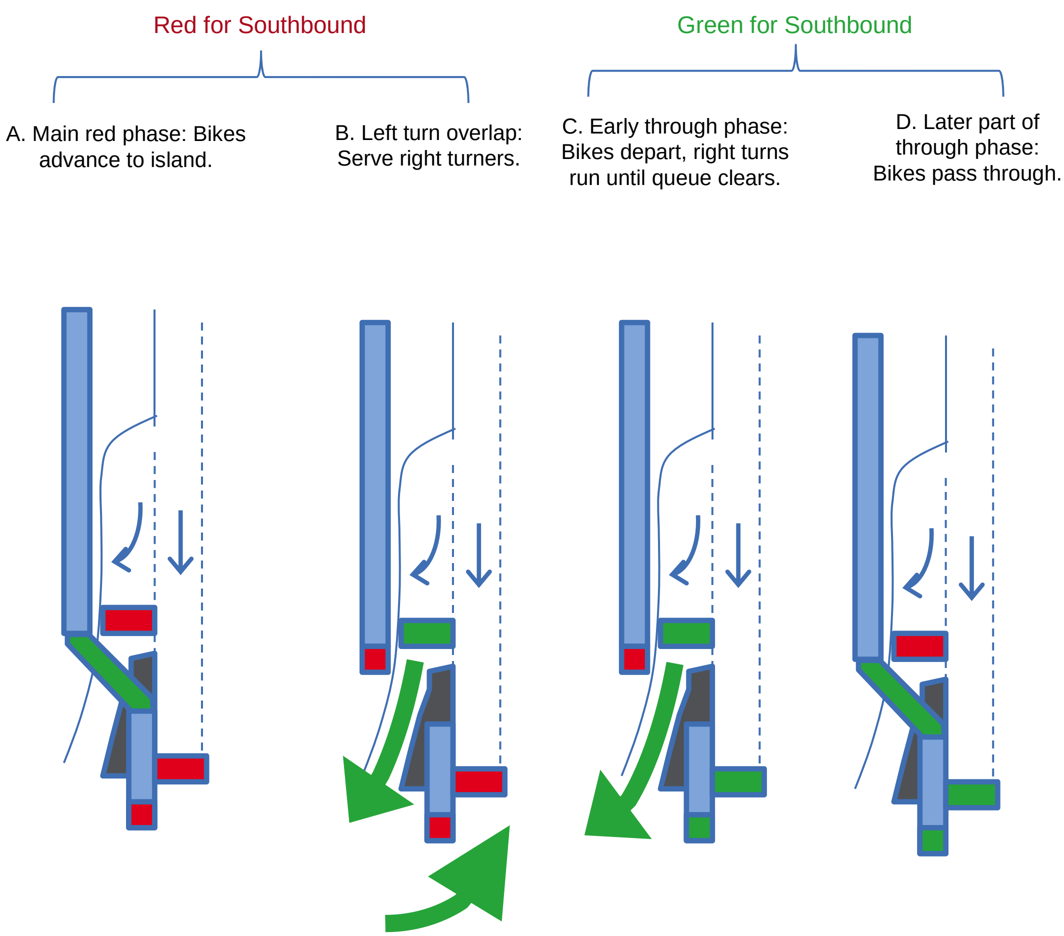


Exhibit 6-16. Phasing/progression plan for Copenhagen intersection for channelized right turns.

phase runs. In addition, the timing gives bicycles two progression windows per cycle. Bicycles arriving during Interval A cross the island, wait a short time, and depart during Interval C. Bicycles arriving during Intervals B and C, when right-turning traffic runs, cross to the island and pass straight through during Interval D, the latter part of the parallel traffic green. This greater pedestrian-crossing time (for the main crossing) makes it impossible to provide pedestrians with two progression windows per cycle, but they still get reasonably good progression. Southbound pedestrians use the early progression window described earlier for bicycles. Northbound pedestrians have even better progression, entering during Interval C and departing during Interval D or Interval E.

6.4.4.3 Signage and Striping

Some channelizing islands are simply painted, without a physical median. These allow for larger truck movements, but they do not provide protection for pedestrians. Painted islands are not detected or recognized by pedestrians who are visually impaired, so they might cross outside the crosswalk area.

If a channelized turn-lane crossing is unsignalized and will be used by bicycles, signs are needed to inform motorists to yield to bicycles (unless motorists have a Stop sign), since the presence of a crosswalk is not sufficient to establish that obligation.

6.4.4.4 Geometric Elements

Delta islands must be large enough to hold the pedestrians and/or bicycles who are expected to wait on them during high-demand cycles. Where periodic demand surges occur (e.g., at schools or sports venues), demand per cycle during such a surge should be accounted and designed for in the timing strategy. According to AASHTO's *A Policy on Geometric Design of Highways and Streets*, 7th Edition (Green Book), a delta island should be no less than 50 square ft in urban areas (75 square ft in rural areas); delta islands larger than 100 square ft are preferable. The Green Book recommends that sides be at least 12 ft long (15 ft preferred) after rounding corners; however, this dimension can be overly restrictive since it implies an island area of at least 80 ft. Cut-through crosswalks are preferred over ramps and should follow ADA guidance for sidewalks.

The raised crossing; prominent signs; and alignment of the turn lane with good visibility of crossing pedestrians/cyclists and a non-tangential turn at the end all help promote low-speed turns and yielding compliance. The shared-use path approach angle affords ideal visibility, and the island size makes it a suitable waiting area.

Where channelized right-turn lanes are not signalized, their geometry should help promote motorist yielding to crossing pedestrians and bicycles. Helpful elements include a small turning radius; a narrow, channelized roadway; raised crossings; and having the turn lane meet the cross street at a near right angle. If a raised crossing is used, detectable warning surfaces are required across the entire area that is level with the roadway.

When bicycles use a delta island, their approach should avoid sharp or sudden turns and should enable them to see conflicting traffic without looking over their shoulder (contrast Exhibit 6-13 with Exhibit 6-15). Locating the crosswalk near the center of the island and turn is preferred for pedestrian sight distance and visibility. Guidance through landscaping or other features can help pedestrians who are visually impaired or have low vision cross at the correct location (Schroeder et al., 2017).

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6.5 Leading Pedestrian Intervals

6.5.1 Basic Description

6.5.1.1 Alternative Names

Pedestrian head start; partially protected crossing.

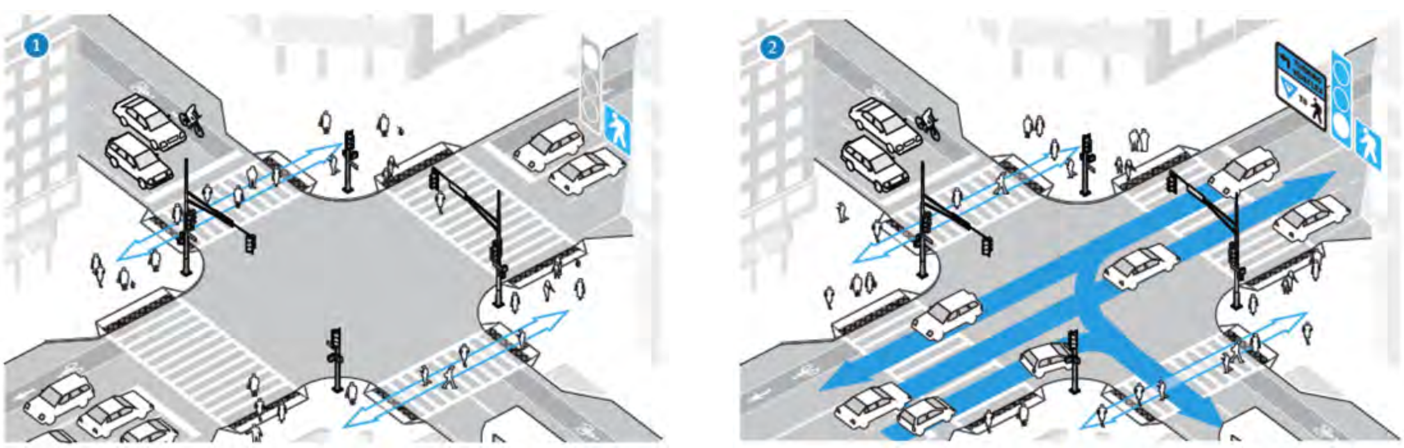
6.5.1.2 Description and Objective

In an LPI, a Walk signal indication is shown to pedestrians a few seconds earlier than the start of green for the concurrent vehicular movement. The crossing is protected-only during this initial interval; for the remainder of the pedestrian phase, turning conflicts are allowed, making it a partially protected crossing. Exhibits 6-17 and 6-18 show the pedestrian and vehicular movements during and after the leading interval and how these movements are aligned in time (City of Boston, 2013).

The main objective of an LPI is to enable pedestrians to arrive at the conflict point before the first right-turning vehicle in order to reinforce the priority that pedestrians have over turning vehicles. This improves pedestrian safety and comfort by promoting yielding compliance on the part of turning motorists and reducing pedestrian–vehicle conflicts.

6.5.1.3 Variations

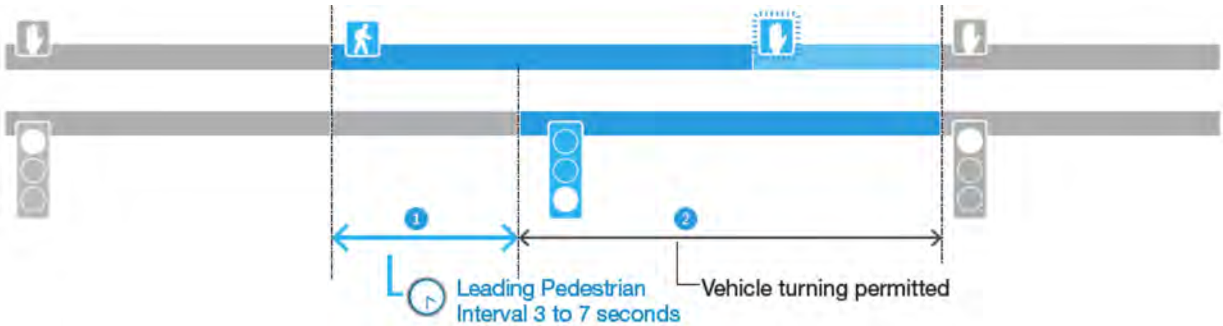
LPIs can also be leading bicycle intervals, serving bicycles as well as pedestrians, if local laws or enforcement policies support that function.



(a) During the leading interval **(b) During the rest of the pedestrian phase**

Source: City of Boston (2013).

Exhibit 6-17. Pedestrian and vehicular movements involved in an LPI.



Source: City of Boston (2013).

Exhibit 6-18. Pedestrian phase and its parallel vehicular phase during and after an LPI.

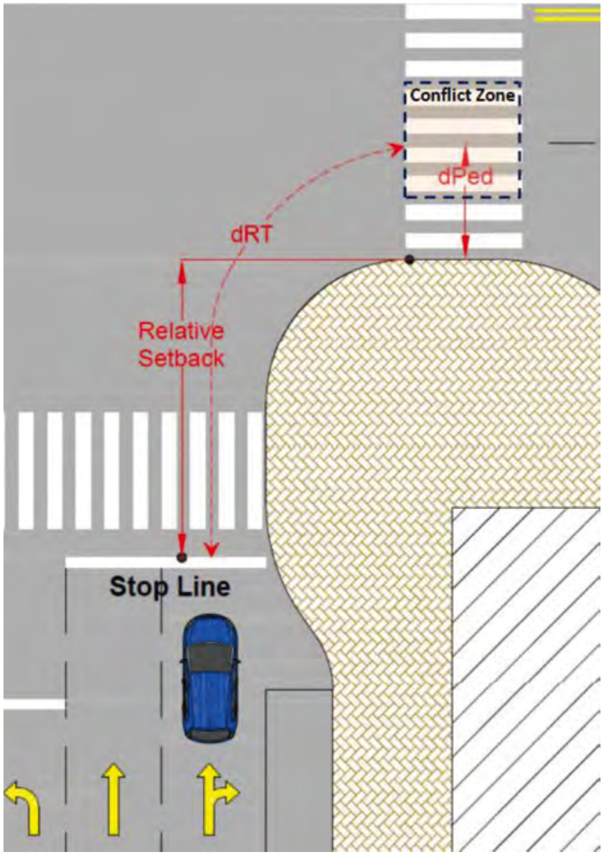
6.5.1.4 Operating Context

An LPI might be appropriate where pedestrian crossings are concurrent with a parallel vehicular phase, where right turns (in this report, "right turns" also includes left turns from a one-way street) are permitted to conflict with crossings, and the following four criteria are met:

1. There is no exclusive right-turn lane. If there is a right-turn lane, it is more appropriate to use the delayed-turn technique (see Section 6.6), which holds turning vehicles while allowing through vehicles to run during the leading interval. (Where there is no right-turn lane, delayed turn can still be considered as an alternative to LPI; see Section 6.5.3.3.)
2. The intersection layout fails to give pedestrians an adequate head start in space. When the vehicular stop line is set back approximately 50 ft from the curb where pedestrians wait—often called a "protected intersection" layout (National Association of City Transportation Officials, 2019), as shown in Exhibit 6-19—pedestrians get a head start in space. Details on how to evaluate the head start in space afforded by a large vehicular setback are given at the end of this list.
3. Conflicting right-turn volume is low or moderate. When right-turn volume is high, there will be a lot of conflict between pedestrians and turning vehicles, even with an LPI. Therefore, in such cases it may be more appropriate to use a treatment that provides a fully protected crossing, such as concurrent-protected phasing (see Section 6.2), exclusive pedestrian phases (see Section 6.3), or channelized right turns and delta islands (see Section 6.4). If turn volume is low to moderate, LPI can be appropriate; however, delayed turn (see Section 6.6) may still be preferred—even where there is no right-turn lane—because it limits the impact on motor vehicle delay, thereby providing longer protected intervals for pedestrians.
4. There is any level of pedestrian volume. Where pedestrian volumes are low, pedestrian phases can be actuated—with the LPI occurring only when a pedestrian phase runs—thus avoiding unnecessary delays on vehicle traffic.

An LPI might also be appropriate when these four criteria are met and there are T-junctions or junctions with one-way streets that have no opposing through traffic to shield pedestrians from left turns during the early part of the pedestrian phase. An LPI can be considered as a means of partial protection from left turns in these cases; however, a longer LPI may be required.

In Dutch cities, LPIs tend to be very short (1 s or less), and most intersections have none because the typical Dutch intersection layout has a large stop-line setback that gives pedestrians a large head start in space (S. Linders, personal communication, August 2, 2018). To determine



Note: *dPed* = the distance a pedestrian covers to reach the middle of the conflict zone
dRT = the distance a right-turning vehicle covers to reach the middle of the near edge of the conflict zone

Exhibit 6-19. Protected intersection layout, in which pedestrians have a large head start in space.

the needed length of an LPI, engineers identify the conflict zone (i.e., the area where pedestrians and turning cars conflict) and measure two distances (see Exhibit 6-19):

dPed = distance for a pedestrian to reach the middle of the conflict zone, which is then converted to a time, *tPed,* by dividing by a design walking speed, such as 3.5 ft/s.

dRT = distance a right-turning car must cover to reach the near edge of the conflict zone; this can be converted to a time, *tRT*, by assuming a typical right-turning speed, such as 15 ft/s (10 mph).

After converting those distances to times, the needed LPI duration is provided in Equation 6-3 as t_{LPI}:

$$t_{LPI} = \max(tPed - tRT, 0) \tag{6-3}$$

That is, if $tRT \geq tPed$, no LPI is needed because even without an LPI, pedestrians will be able to establish their priority in the crosswalk before turning cars reach the conflict zone; otherwise, the green start for vehicles is delayed by ($tPed - tRT$).

To illustrate the method, suppose *dPed* = 14 ft and *dRT* = 45 ft. Using the suggested speeds given earlier, *tPed* = 14/3.5 = 4.0 s, while *tRT* = 45/15 = 3.0 s. Therefore, the needed length of LPI is 4.0 – 3.0 = 1.0 s.

6.5.2 Applications and Expected Outcomes

6.5.2.1 National and International Use

LPI has been applied in the U.S. since the 1990s and has become ever more popular due to its pedestrian safety benefits. New York City has implemented LPIs at more than 2,200 intersections, after a pilot study from pre-2011 installations found that LPIs led to a 13% decrease in pedestrian and cyclist injuries and a 62% decrease in pedestrians and cyclists killed or seriously injured in crashes involving turning vehicles (NYC Department of Transportation, 2016). (An interactive map of current locations in New York City with LPI can be found at http://www.vzv.nyc.) Cambridge, MA, uses LPIs at most of their intersections, and many other cities in the United States and Canada make extensive use of LPIs. In U.S. practice, LPI is not limited to high pedestrian-volume locations; for example, in Charlotte, NC, LPI is a standard treatment for arterials in suburban parts of the city (for more detail, see Section 6.6).

In North America, the typical length of an LPI is 3 to 7 s. In New York City and Montreal, most LPIs last 7 s; in Cambridge and Washington, DC, they commonly last 3 s. In Dutch cities—where the typical protected intersection layout gives pedestrians a large head start in space—LPIs tend to be very short, often 1 s or less. As U.S. cities reconstruct intersections with corner bulb-outs, protected bike lanes, and other features that help create a substantial setback of the vehicular stop line relative to the curb where pedestrians wait to cross, they may also find that they can use very short LPIs to accomplish their objective.

6.5.2.2 Bicycle Use of LPIs

By default, bicycles in the U.S. may not use LPIs because bicycles are supposed to follow vehicular signals, not pedestrian signals. New York City and Washington, DC, are exceptions, with local laws that allow bicycles to follow pedestrian signals (in Washington, this only applies during an LPI). New York's law, enacted in 2019, followed a successful six-month pilot program in which 50 intersections were signed to allow bicycles to follow the pedestrian signal.

In cities like Chicago and Cambridge (and New York before 2019)—where LPIs are common and there is a general understanding that cyclists will not be ticketed for going on an LPI—bicycle use of LPIs has become routine. Recognizing this practice, Cambridge's traffic signal engineers implemented LPIs that are 7 s long (longer than the usual 3 s) on a street with protected bike lanes, with the intention of protecting bicycles as well as pedestrians.

In the Netherlands, bicycles use LPIs because they are controlled by bicycle signals, which are programmed to release bicycles simultaneously with pedestrians. In the U.S., FHWA interim guidance prevents bicycle signals from being used in connection with LPIs, since it forbids the use of bicycle signals where vehicular turn conflicts are permitted. As a result, formally allowing bike use of LPIs with bike signals would require either an exception from FHWA or a change in FHWA guidance regarding bicycle signals and permitted-turn conflicts.

6.5.2.3 Benefits and Impacts

Benefits and impacts discussed in this section include:

- Reduction in pedestrian crashes and injuries;
- Improved motorist yielding, which makes crossings less stressful; and
- Traffic capacity decrease, delay increase, and possible cycle-length increase.

A comparison of 26 intersections in New York State found that LPIs reduced pedestrian crashes with turning vehicles by 28%; the reduction was 64% after adjusting for crash severity (King, 2000). The *Highway Safety Manual* assigns a CMF of 0.413 for applying LPI based on a study of 10 intersections in State College, PA, where a 59% reduction in pedestrian–vehicle crashes was found (Fayish & Gross, 2010). Other studies have found that LPIs reduce the percentage of compromised pedestrian crossings (Hubbard et al., 2007); reduce the frequency of pedestrians yielding to turning vehicles (Van Houten et al., 2000); reduce the number of vehicles turning in front of pedestrians in a crosswalk (San Francisco Municipal Transportation Agency Pedestrian Program & University of California Traffic Safety Center, 2008); and reduce the number of observed pedestrian–motor vehicle conflicts (Van Houten et al., 2000).

When the timing of the minor-street phase is governed by pedestrian needs, adding an LPI has almost no impact on traffic operations; it can be viewed as simply shifting some of the minor street's unused time from the end of the phase to the start of the phase. New York City has had an aggressive program of applying LPIs to signalized crossings matching this context (D. Nguyen, personal communication, August 16, 2019). However, where the concurrent vehicular phase's timing is dominated by vehicular needs—as is typically the case for a crosswalk parallel to a major street—adding an LPI can have a significant impact on traffic capacity, or it can require a longer signal cycle. The shorter the LPI, the smaller the impact is, which results in using short LPIs for some jurisdictions.

A way to accomplish the objective of an LPI without the negative capacity or cycle-length impact is to alter intersection geometry so that pedestrians get enough of a head start in space that they need either no LPI or a very short LPI, as described earlier. A study of Boston's Melnea Cass Boulevard corridor found that with 6 s LPIs, the cycle length would have to be 110 s in order to have enough capacity. However, by rebuilding the corners using a protected intersection layout, pedestrians would have enough of a head start in space that an LPI would not be needed, and the needed cycle length would then be only 80 s. The capacity and cycle-length impacts of LPIs are greatest where, as in this Boston example, cross streets have high traffic volumes and therefore cannot easily give up green time for an LPI.

When a minor street's volume is low, using pedestrian overlaps with LPIs (see Section 6.7) can make it possible to create an LPI for the major street without any adverse capacity impact.

6.5.3 Considerations

6.5.3.1 Accessibility Considerations

LPIs should include APS to notify visually impaired pedestrians of the LPI because otherwise visually impaired pedestrians—who may rely on the sound of starting traffic to know when the green begins—may miss an LPI and begin to cross with the vehicular movement, when motorists are less likely to yield to them (City of Boston, 2013; Alexandria Department of Transportation and Environmental Services, 2015).

LPI is especially suitable at locations with a large population of older adults or schoolchildren who tend to walk slower (Saneinejad & Lo, 2015; Staplin et al., 2001) and thus need more time to establish themselves in the crossing.

6.5.3.2 Guidance

The MUTCD cites LPIs as an option; it speaks of considering LPI when there are "high pedestrian volumes and high conflicting turning vehicle volumes," conditions repeated by several other publications (City of Boston, 2013; Van Houten et al., 2000; King, 2000; Staplin et al., 2001). However, as cities like Charlotte have found, pedestrian volume is less applicable since the cost of the treatment is nominal, and for pedestrian phases that are actuated, there will be an impact to traffic only when the pedestrian phase is called. Furthermore, as explained earlier, LPI is appropriate where the conflicting turning volume is moderate or low but not where it is high. With high turning volumes, full protection from conflicting turns is preferred to partial protection. The right-turn volume threshold for preferring fully protected versus partially protected crossings is 200 vehicles per hour for New York City (D. Nguyen, personal communication, August 16, 2019) and 250 vehicles per hour for Boston (City of Boston, 2013). In Montreal, that threshold is 200 vehicles per hour where the crossing length is 20 m (67 ft) or more. For shorter crossings, the threshold increases to 500 vehicles per hour where the crossing length is 8 m (27 ft) or less (City of Montreal, 2017).

The MUTCD (2009) recommends a minimum LPI length of 3 s. This is a reasonable minimum for traditional U.S. intersections, considering the objective of giving pedestrians a head start. However, when intersections are configured with a large stop-line setback—as in the protected intersection layout—LPIs as short as 0.5 s can be appropriate to supplement the head start in space that pedestrians have. From Dutch experience, there does not appear to be any unintended negative consequences of using short LPIs.

Among techniques that provide partially protected crossings, New York City prefers delayed turn over LPI if an exclusive turn lane can be provided. Montreal prefers delayed turn even when turn lanes cannot be provided and uses LPI only when there is a moderately high turning volume and no turn lane.

6.5.3.3 Relationships to Relevant Treatments

Delayed turn (see Section 6.6) is a partial protection treatment, just like LPI. Both treatments protect pedestrians from conflicting turns during an initial part of the crossing phase; however, delayed turn allows through traffic to move during the initial interval, and therefore it has less impact on traffic operations (Furth & Saeidi Razavi, 2019). As a result, delayed turn typically provides a longer protected interval for pedestrians.

NTOR (see Section 6.8) should be applied to both streets whose right turns cross a treated crosswalk. In other words, for an LPI parallel to the north–south street, NTOR should apply to both the north–south street and the east–west street, since both streets face a red signal during the LPI and right-turning drivers from both streets would otherwise go. Hubbard et al. showed that without NTOR, LPI may lose its intended benefits (Hubbard et al., 2008). Where right turn on red (RTOR) is important for capacity or delay, Section 6.8 discusses how to apply NTOR only during certain parts of a signal cycle.

The desire for short cycle lengths (see Section 7.1) can be in conflict with LPIs because LPIs introduce lost time into the cycle that can force a cycle length to be longer. This conflict can be mitigated using pedestrian overlaps (see Section 6.7) and by altering corner geometry to give pedestrians a greater head start in space, thereby reducing the need for a head start in time.

6.5.3.4 Other Considerations

LPIs are geared mainly toward helping pedestrians establish their priority over permitted right turns during the early part of the crossing phase. Protection against permitted left turns is typically not a consideration because during the early part of the crossing phase, permitted left turns are typically blocked by opposing through traffic. However, at T-junctions and junctions with one-way streets, there is no through traffic in one direction, therefore LPIs can provide the same support against permitted left turns. At T-junctions, the needed LPI may be considerably longer, since the conflict zone with an auto approaching from one's rear is in the far half of the intersection. Geometric treatments that promote lower speeds and yielding by left-turning motorists—including median islands, raised centerlines, and in-street Yield to Pedestrians signs—can also be helpful in this regard.

6.5.4 Implementation Support

6.5.4.1 Equipment Needs and Features

Nearly all controllers manufactured after 2005 are programmed to allow LPIs, so no special equipment is needed.

6.5.4.2 Phasing and Timing

Where LPIs are used in connection with an actuated pedestrian phase, the LPI will come up only when the pedestrian phase comes up.

Where left turns are permitted during the through phase, an LPI that holds traffic in one direction must be matched with a concurrent LPI that holds traffic in the opposite direction as well. Otherwise, left-turning vehicles from the direction that is not held will pose a conflict during the LPI.

With LPIs, it is better for protected left-turn phases to be lagging rather than leading (City of Boston, 2013; Department of Transportation and Environmental Services, 2015; Saneinejad & Lo, 2015). This is because if the protected left-turn interval is leading, the LPI will begin as the left-turn signal changes from protected to permitted, and left-turning drivers will be tempted to continue moving because opposing through traffic continues to stand still to serve the LPI.

6.5.4.3 Signage and Striping

Not applicable for this treatment.

6.5.4.4 Geometric Elements

Intersection layout determines how much of a head start pedestrians get in space, and therefore it can affect how long an LPI (i.e., head start in time) is needed. A large stop-line setback, a curb bulb-out, and a short crossing distance from the curb to the middle of the road all lead to a shorter required LPI.

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6.6 Delayed Turn/Leading Through Intervals

6.6.1 Basic Description

6.6.1.1 Alternative Names

Leading through arrow; leading bicycle interval.

6.6.1.2 Description and Objective

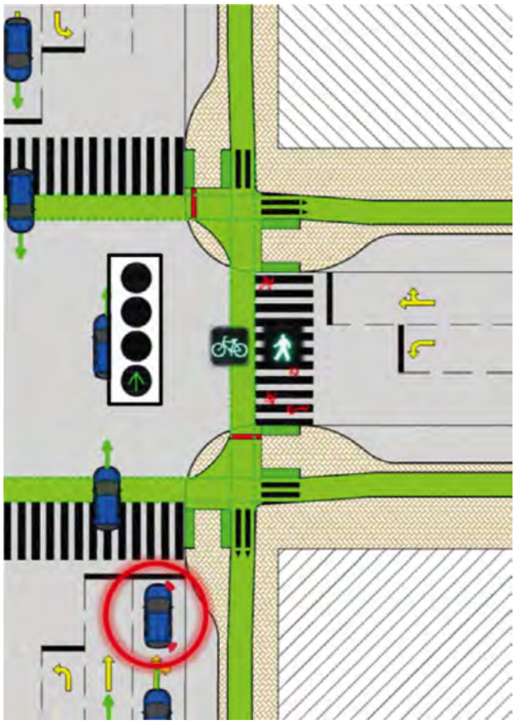
At the start of a vehicular through phase, pedestrians, bicycles, and through vehicles are allowed to go while turning movements (right turns, left turns, or both) are held for an interval called a leading through interval (LTI) or leading bike interval. This interval typically lasts 7 to 13 s. After the leading interval, the hold on turning movement(s) is lifted, allowing a permitted conflict with the bicycle and pedestrian crossings. Like LPI, delayed turn provides a partially protected crossing, meaning the first part of the crossing phase is conflict-free. However, it differs from LPI in that during the leading interval, only turning traffic is held whereas the through movement is permitted. This allows a longer protection interval, since only the turning vehicles are held. Exhibits 6-20 and 6-21 show the movements allowed during and after the leading interval.

The objective of this treatment is summarized as follows:

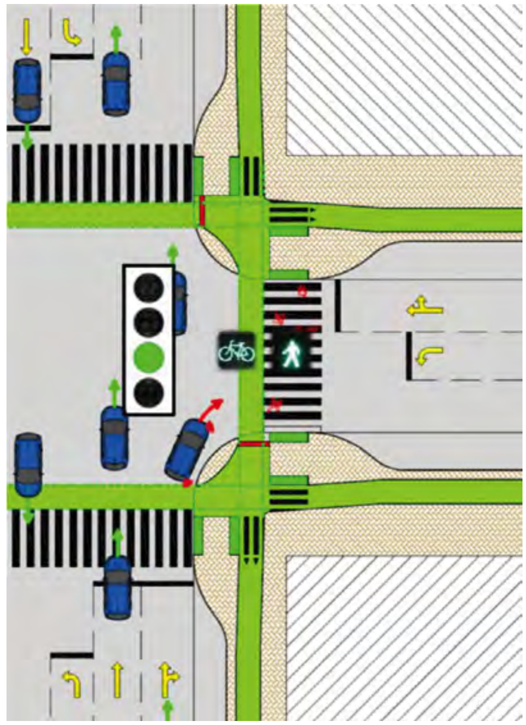
- To give pedestrians a partially protected crossing with less traffic capacity impact than would occur with LPI;
- To give pedestrians a longer initial protected interval than would be practical with LPI;
- To give bicycles a partially protected crossing, providing the first flush of waiting bicycles conflict-free passage through the intersection (note that, in general, bicycles are not legally allowed to use leading pedestrian intervals—New York City and Washington, DC, are exceptions that allow bicycles to legally use LPIs); and
- To reduce delay to bicycles, pedestrians, and turning traffic while providing partial protection at intersections where it is safe to have permitted-turn conflicts after a conflict-free initial interval.

6.6.1.3 Variations

Delayed turn can be applied with or without an exclusive turn lane for the turn(s) being held. In Montreal, delayed turn is widely applied where there are no exclusive turn lanes; in New York



(a) During LTI



(b) After LTI

Exhibit 6-20. Pedestrian, bicycle, and vehicular movements during and after an LTI.

City and Charlotte, it is applied only with an exclusive turn lane. Where turning vehicles share a lane with through vehicles (e.g., in Montreal), through vehicles can be blocked by turning vehicles ahead of them during the initial protected interval.

Two variations of signal displays have been used to implement delayed turn. In New York and Charlotte, where turning traffic is always in an exclusive turn lane, a red turn arrow is employed during the leading interval along with a circular green, changing to FYA (see Section 6.9) during the permitted-turn period. In Montreal, only a through green arrow is displayed

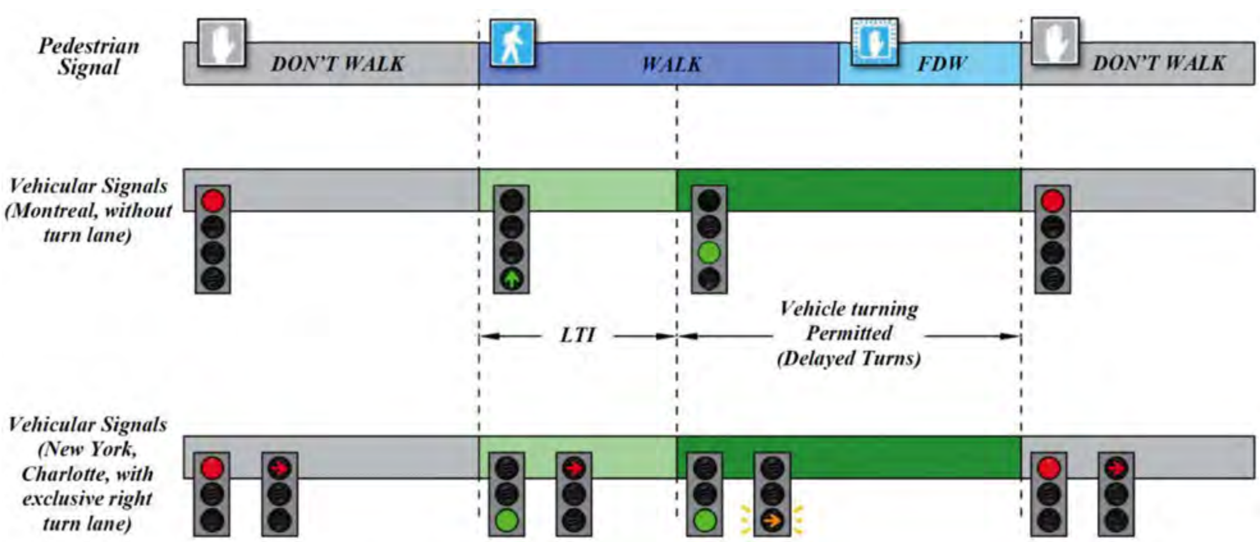


Exhibit 6-21. Alignment of pedestrian and concurrent vehicular phases with delayed turn/LTI.

Source: Peter Furth.

Exhibit 6-22. Through green arrow followed by a circular green in Montreal.

during the leading interval, and a circular green is displayed during the permitted-turn interval (see Exhibit 6-22). Whether a through green arrow alone is enough to prohibit turning movements will depend on state/provincial law.

6.6.1.4 Operating Context

Delayed turn may be appropriate in connection with concurrent pedestrian and bicycle crossings:

- Where there is a need to provide partially protected crossing for bicycles as well as pedestrians without causing high delays for vehicles and pedestrians/bicycles; and
- Where there is a low or moderate turn volume, and intersection geometry affords good visibility and prevents high turning speed.
  - If turn volume is high, turning speed is high, or there is poor visibility for the conflict between turning cars and crossing bicycles/pedestrians, a treatment offering full protection should be considered (see Section 6.2; Section 6.3; and Section 6.4).

Where there is an exclusive turn lane, delayed turn is a superior alternative to LPI. Where there is no exclusive turn lane, delayed turn can be considered as an alternative to LPI if the turning volume is low, intersection capacity is a concern, or there is a desire to have a long leading protected phase in order to improve safety and comfort for far-side crossers. Where there is a high turning percentage and there is no exclusive turn lane, blockage (i.e., turning vehicles blocking through vehicles) can be so frequent that it may be more desirable to use an LPI.

6.6.2 Applications and Expected Outcomes

6.6.2.1 National and International Use

In Montreal, delayed turn—known locally as leading through arrow—has been a standard treatment for more than 15 years throughout the downtown area and at other intersections with moderate or high pedestrian-traffic (Montreal Department of Transportation, 2017; J. Hamaoui, personal communication, June 5, 2018). It is used at more than 100 intersections where the leading interval is between 7 and 13 s long. Almost none of the application sites have exclusive turn lanes. During the leading intervals, both right and left turns are held. Most of the intersections where it is used have only pedestrian crossings; however, it is also used where there are bicycle crossings.

In New York City, delayed turn has been used since approximately 2015—usually with a 10 s leading through interval—and always in conjunction with FYA during the permitted-turn interval. New York has at least 37 intersections where this treatment has been installed (NYC Department of Transportation, 2016). It has become the city's preferred treatment for protected bike lane crossings wherever a short turn lane can be created (usually by removing parking) and turn volume is not high. Where turn volume exceeds 200 vehicles per hour, the city prefers to use concurrent-protected crossings (see Section 6.2). Delayed turn is also used at intersections with moderately heavy pedestrian-volumes where a turn lane can be provided (D. Nguyen, personal communication, August 16, 2019).

New York developed the delayed-turn treatment based on its experience with concurrent-protected bicycle crossings. When creating the nation's first parking-protected bike lanes, they were cautious about intersection safety and used fully protected bicycle crossings. However, they found that at intersections with low turn volumes, many cyclists were running the red during the turn phase due to the long waiting times without a noticeable safety impact. This resulted in implementing the delayed-turn treatment at certain intersections to lower both bicycle and vehicle delay. Initially, the turn volume threshold for switching from full protection to partial protection was 120 vehicles per hour; after a few years' experience, that threshold was raised to 200 vehicles per hour (D. Nguyen, personal communication, August 16, 2019).

In one downtown corridor, Montreal recently changed signals from delayed turn to concurrent-protected, which is the opposite of New York's experience. Boulevard de Maisonneuve, a one-way street through downtown with a bidirectional cycle track on the left side, had been using delayed turn since the cycle track opened in 2007. However, as bicycle traffic grew, left-turning drivers were not finding enough safe gaps and were turning unsafely, sometimes resulting in a collision. The bidirectional nature of the cycle track—with bicycles arriving in both directions and sometimes arriving late during the green period, as modulated by upstream traffic signals—made it more difficult for turning drivers to find safe crossings. The change to fully protected crossings required converting one of the boulevard's two lanes into a left-turn lane.

Charlotte uses delayed turn at about 10 intersections, and roughly another 10 are in progress (N. Conrad, personal communication, December 26, 2018; see Exhibit 6-23 for an example). Delayed turn is the basic element of a local program called LPI+, for which the city won an ITE innovation award in 2016 (North Carolina Section of the Institute of Transportation Engineers,

Source: North Carolina Section of the Institute of Transportation Engineers (2016).

Exhibit 6-23. An LTI in Charlotte. During the permitted-turn interval, the red arrow is replaced by an FYA. The sign reading "No Turn on Red" is blank except during the LTI.

2016). Unlike New York and Montreal, Charlotte has only applied delayed turn outside of its business district, typically on wide arterials where the pedestrian phase is actuated. As part of the LPI+ program, during periods of the day with low turning volumes, the LPI encompasses the entire pedestrian phase and becomes a concurrent-protected crossing (see Section 6.2). Where no right-turn lane is available, the city uses an LPI (see Section 6.5), typically lasting 3 to 5 s and up to 10 s for some crossings at schools.

Kothuri et al. (2018) report that in a survey of professionals regarding bicycle signal control strategies, out of 69 respondents, about half were aware of the delayed-turn technique, but only one respondent's city had used it.

6.6.2.2 Benefits and Impacts

Benefits and impacts discussed in this section include:

- Safety and comfort as they relate to the length of the protected interval;
- Inclusion of bicycles in a partially protected crossing;
- Safety as observed by traffic conflicts; and
- Capacity and delay impacts to vehicular traffic.

For pedestrians, the delayed turn improves safety and comfort by providing them with a conflict-free head start, which enables them to establish themselves in the crosswalk before turning traffic arrives at the conflict point. This leads to improved yielding behavior by motorists during the permitted-turn period. This is the same benefit provided by LPIs, except that delayed turn is usually considerably longer (because it has less impact on intersection capacity) and offers greater protection. While LPIs are usually only long enough for near-side crossers to establish their priority before turning vehicles arrive, delayed turn is sometimes long enough to also enable far-side crossers to reach the conflict zone before turning vehicles.

For bicycles, delayed turn improves safety and comfort, enabling the first flush of bicycles to pass through an intersection conflict-free. Note that in general, LPIs cannot be used legally by cyclists.

Delayed turn can be more effective than LPI in reducing bicycle–motor vehicle conflicts. In New York City, a left-side, parking-protected bike lane runs along 6th Avenue. At its intersection with 23rd Street, the crossing treatment was changed from LPI (which some bicycles used) to delayed turn with a 7 s leading interval. The treatment also included adding a left-turn lane (by removing parking) and FYA during the permitted-turn interval. Exhibit 6-24 shows results of a before-and-after study, with reported results normalized to indicate conflicts per 1,000 bicycles. The two most important conflicts, near misses and collisions that would have happened had there been no evasive action, both show a strong decline. There was a small increase in the frequency of cyclists who had to ride around a car, such as when a vehicle interrupts its turn for crossing pedestrians (Kothuri et al., 2018).

Exhibit 6-24. Bicycle-vehicle conflicts with LPI versus delayed turn, 6th Avenue at 23rd Street, New York.

	Leading Pedestrian Interval	Delayed Turn with Added Left-Turn Lane and FYA
Bicycles	1,952	1,300
Per 1,000 bicycles:		
Near misses	4	0
Collisions if no evasive action taken	75	35
Bicycle rode around car	32	41

Source: Kothuri et al. (2018); the project team's analysis of that data.

If turns are from an exclusive lane, then delayed turn should not affect the delay for any movements other than the turns that are held during the leading interval. If turns are from a shared through-turn lane, as in Montreal, then a small amount of additional delay to through traffic should be expected, increasing with the volume of turning traffic.

Kothuri et al. used a simulation to measure delay impacts of a 5 s delayed turn at a Portland intersection under various demand scenarios. The affected approach had an exclusive right-turn lane. As expected, additional delay to through traffic and to cross-street traffic was either undetectable or less than half a second. Additional delay to right-turning vehicles was also less than a second because RTOR was allowed during all red periods except the delayed turn, leading to very little queuing in the right-turn lane (Kothuri et al., 2018).

A simulation study of delayed turn/LTI with no exclusive turn lanes contrasts the capacity impact of LTI versus LPI (Furth & Saeidi Razavi, 2019). The results showed that while LTI's capacity loss increases with the proportion of right turns, its impact on intersection capacity is still far lower than the capacity loss due to an LPI, especially on multilane approaches. In one example scenario—a three-lane approach in which 20% of the traffic turns right, the rightmost through lane is shared with right turns, and pedestrian demand is such that they block the crosswalk for 10 s—an LTI of 15 s has the same capacity impact as an LPI of 3 s. The far lower capacity impact of LTI means that the leading interval can be considerably longer, affording better pedestrian and bicycle protection.

6.6.3 Considerations

6.6.3.1 Accessibility Considerations

At intersections with delayed turns, APS can be helpful for notifying visually impaired pedestrians of when the Walk interval begins. Without APS, visually impaired pedestrians may be confused by the delayed start of traffic in the nearest lane, as they tend to listen to the sound of traffic parallel to the crosswalk to know about the start of a Walk interval. The through lane is farther away and can be harder to hear.

6.6.3.2 Guidance

New York City's policy makes delayed turn a preferred treatment for crossings on roads with protected bike lanes. It is only applied where they have, or can create, an exclusive turn lane. There is no minimum turn volume for applying delayed turn. The upper limit, above which they prefer fully protected crossings, is 200 vehicles per hour (during the peak hour). Where heavy bicycle-/pedestrian-crossing activity leaves limited gaps for turning vehicles, they prefer fully protected crossings (this criterion was critical for Montreal's recent change on Boulevard de Maisonneuve, as described earlier). The pedestrian-volume threshold, below which delayed turn is preferred and above which fully protected crossings are preferred, is 700 vehicles per hour in Manhattan and 300 vehicles per hour elsewhere. If the turn bay is too short to hold the turn queue, the city uses delayed turn where a fully protected crossing would otherwise be warranted. There is no lower limit for bicycle or pedestrian volume; unless bicycle/pedestrian volume is moderately high, they will not remove parking to create a turn lane (D. Nguyen, personal communication, 2019).

Use of a through green arrow to prohibit turns without a red turn arrow, as practiced in Montreal, is not explicitly addressed in the MUTCD but is consistent with MUTCD (2009) guidance on traffic signals. Section 4D.04, subsection A2, states:

> Vehicular traffic facing a GREEN ARROW signal indication, displayed alone or in combination with another signal indication, is permitted to cautiously enter the intersection only to make the movement indicated by such arrow, or such other movement as is permitted by other signal indications displayed at the same time.

If a state's vehicle code is consistent with this section of the MUTCD in prohibiting turns when the only signal displayed is a green arrow, then the display used in Montreal (a through green arrow without any red arrows) should be sufficient, although an effort may be warranted to promote driver understanding and compliance. The MUTCD explicitly prohibits displaying a circular red in combination with a through green arrow.

6.6.3.3 Relationships to Relevant Treatments

Delayed turn/LTI is similar to LPI (see Section 6.5) in that both offer partial protection for crossings. The main differences are that delayed turn has less traffic impact, generally has longer protected leading intervals, and can serve bicycles as well as pedestrians. However, it may require an exclusive turn lane.

Delayed turn can be combined with FYA (see Section 6.9) and displayed during the permitted-turn interval.

NTOR (see Section 6.8) should apply during the leading interval (at a minimum).

6.6.4 Implementation Support

6.6.4.1 Equipment Needs and Features

New signal heads may be needed for turn arrows or through arrows. Wherever a red turn arrow is used, it can also be configured to include an FYA for the permitted-turn phase.

6.6.4.2 Phasing and Timing

New York City's policy is that delayed turns should be 10 s long, but they can be as short as 7 s if needed for traffic capacity. Charlotte also uses 10 s durations. Montreal's delayed turns/LTIs range from 7 to 13 s and often match the Walk interval. The city has found that with LTIs longer than 13 s, motorist frustration at being blocked by a turning vehicle (due to lack of exclusive turn lanes) leads to complaints and unsafe behavior (J. Hamaoui, personal communication, 2018).

When pedestrian or bicycle phases are actuated, delayed turn is invoked only when the pedestrian or bicycle phase gets a green phase.

6.6.4.3 Signage and Striping

NTOR signs may be needed to prevent turns during the LTI. Even if a red arrow is used during the initial interval, NTOR signs may still be needed where state law does not prohibit right turn on a red arrow (e.g., Oregon, Washington, Florida, and Massachusetts) or where compliance is poor. Where RTOR is desired during other parts of the signal phase, dynamic blank-out signs can be used during the leading interval only, as applied in Charlotte (see Exhibit 6-23).

If no red arrow is applied during the leading interval, as in Montreal, there is no "red" period to which RTOR laws could apply. Nevertheless, drivers accustomed to turning on red may need supplemental signage to reinforce that turns are prohibited during that interval.

6.6.4.4 Geometric Elements

If implemented as in New York and Charlotte, an exclusive right-turn lane is needed to prevent through drivers from being blocked by turning vehicles that are held during the initial protected interval. With the Montreal-style application, no turn lane is needed unless right-turn demand is substantial.

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6.7 Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds

6.7.1 Basic Description

6.7.1.1 Alternative Names

None.

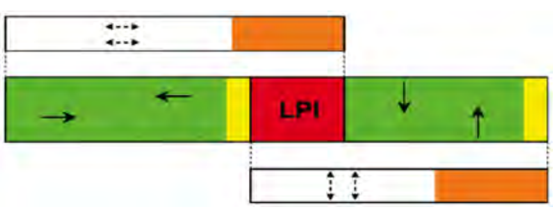
6.7.1.2 Description and Objective

During an LPI or another short interval in which all vehicular phases are held in red, pedestrian phases in all directions can overlap. For example, in Exhibit 6-25(a), the north–south phase has an LPI; during that LPI, the east–west pedestrian phase can be extended, overlapping the LPI. In Exhibit 6-25(b), both through vehicular phases have LPIs, and all pedestrian phases are extended by overlapping them with an LPI for the perpendicular direction. The objective is either to have longer pedestrian phases or to have more efficient phasing, which can lead to shorter cycles or can allow LPIs to be introduced with less capacity impact.

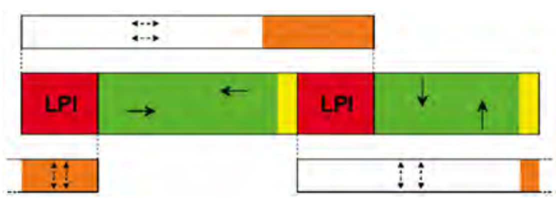
6.7.1.3 Variations

Pedestrian phases can also overlap during partial vehicular holds that are not LPIs, in which at least one vehicular movement has green, but other vehicular movements that could run in parallel with it are held. An example is illustrated in Exhibit 6-26, in which a left-turn and right-turn movement are running, but the vehicular movements that normally run concurrently—in this example, northbound through and southbound left—are held, allowing the two crosswalks shown to run without conflict.

An informal overlap occurs when the LPI for one street is used as part of the pedestrian phase end buffer for the previous pedestrian phase. At several intersections in Cambridge, MA, pedestrian phases are programmed to end their FDW at the end of the yellow; this allows the following



(a) Overlapping one LPI



(b) Overlapping two LPIs

Exhibit 6-25. Pedestrian phases overlapping vehicular holds (LPIs).

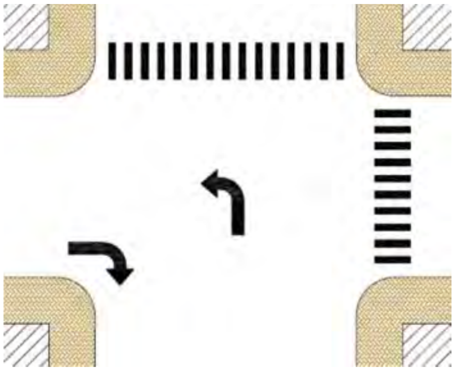


Exhibit 6-26. Pedestrian movements that can overlap a left-turn phase (example of a partial vehicular hold).

LPI to count as part of the pedestrian phase end buffer, which enables the pedestrian phases to have a longer Walk interval compared to ending FDW at the start of the yellow. This reduces pedestrian delay and creates additional crossing opportunities for slower pedestrians. While this is not programmed in the controller as an overlap, it has the same function.

6.7.1.4 Operating Context

Pedestrian overlaps with LPI and other vehicular holds can be considered:

1. Wherever LPIs are used. See Exhibit 6-25(a) (LPI on one street) and Exhibit 6-25(b) (LPI on both streets).
2. Where a minor intersecting street is dominated by pedestrian timing needs while the major street is dominated by vehicular needs. In such a situation, there might be some reluctance to provide an LPI for the major street because taking time from its phase to create an LPI could have a significant capacity impact. By having the LPI overlap the intersecting street's pedestrian phase, it may be possible to create time for the major street's LPI without taking any time from the major street's vehicular phase, as illustrated in an example in Section 6.7.2.
3. During low-volume periods in which both intersecting streets are dominated by pedestrian timing needs. In such a case, pedestrian overlaps can permit a shorter cycle, as illustrated in an example in Section 6.7.2.
4. Where demand for a left turn is high compared to the demand for the opposite direction's left turn. Running a single left turn as the only vehicular movement during part of the cycle can allow two crosswalks to overlap with it, as illustrated in Exhibit 6-26.
5. Where there are multistage crossings. Introducing a short vehicular hold with pedestrian overlaps can lengthen pedestrian phases enough to create good progression for pedestrians through multiple crossing stages.

6.7.2 Applications and Expected Outcomes

6.7.2.1 National and International Use

In U.S. practice, except with exclusive pedestrian phases (see Section 6.3), pedestrian phases are generally treated as "children" of a "parent" vehicular phase; and where parent phases are in conflict, their "children" are usually treated as if they are in conflict as well. But pedestrian phases are never really in conflict with one another. The recent proliferation of LPIs has created opportunities for pedestrian overlaps that did not exist before, and have rarely been taken advantage of, as with the informal overlaps used by Cambridge, MA, described earlier.

In the Netherlands, where pedestrian and bicycle phases are programmed as independent phases rather than as children of a vehicular phase, pedestrian overlaps with full and partial vehicular holds occur frequently. An example of an overlap with a partial vehicular hold is in Amsterdam, at the junction of Nobelweg (considered the north–south street) and Kammerlingh Onneslaan. When the only demand for the east–west street is for eastbound left, that vehicular movement is served alone; and the non-conflicting eastbound and northbound bicycle crossings, along with the pedestrian crossings next to them, run concurrently (if they have a call), as in Exhibit 6-26.

6.7.2.2 Benefits and Impacts

Benefits of pedestrian overlaps with LPIs and other vehicular holds include:

1. Making it possible to introduce an LPI to a major street without reducing its capacity (if the minor street is well below capacity);
2. Shortening signal cycles in low-traffic periods when pedestrian timing needs may dominate;
3. Facilitating progression through multistage crossings; and
4. Increasing pedestrian phase lengths, reducing delay, and helping slower pedestrians.

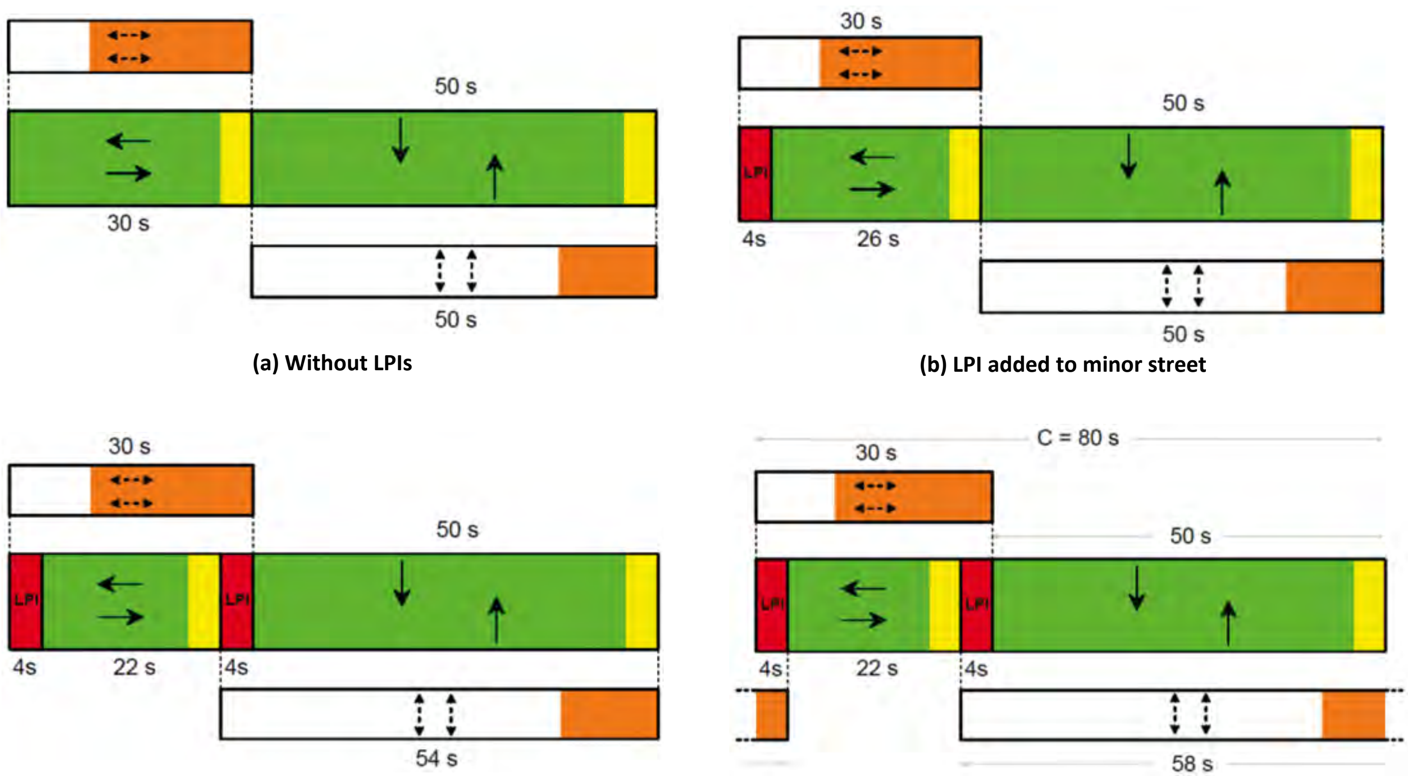
1. Making it possible to introduce an LPI to a major street. At the intersection of a minor street with a major street, it is well understood that adding an LPI to the minor street can be done with almost no impact on traffic operations. If traffic volume on the minor street is low, pedestrian overlaps with LPIs can make it possible to also add an LPI to the major street—with its attendant safety benefits—without taking time from the major street's green phase. The following example illustrates this idea:

Major-minor intersection, with low traffic on the minor street. Consider an intersection with an 80 s cycle whose phase diagram is as shown in Exhibit 6-27(a). To serve its traffic, the major street needs a 50 s split; the minor street could serve its traffic with a 20 s split but needs 30 s to serve the pedestrian crossing. Change intervals are 4 s:

- Inserting an LPI of 4 s on the minor street by starting its green later (Exhibit 6-27[b]) will have very little impact on traffic. However, since the major street cannot afford to give up 4 s of green, there is no LPI on the major street.
- Because the minor street has available capacity, it can afford to give up an additional 4 s of vehicular green time and have its vehicular green end 4 s early. During this interval, while all traffic is held for 4 s, the minor street's pedestrian phase can still run while an LPI begins on the major street (Exhibit 6-27[c]). There is no capacity impact to the major street, whose vehicular phase is unchanged. At the same time, the pedestrian phase along the major street becomes 4 s longer than it was in the original case.
- Adding a second pedestrian overlap, during the minor-street LPI, further improves pedestrian service by making the major street pedestrian phase 8 s longer than it originally was (see Exhibit 6-27[d]). Note that this final step will not be possible if the intersection includes left-turn phases.

2. Shortening signal cycles. For periods in which vehicular volumes on both intersecting streets are low enough that pedestrian timing needs dominate, letting pedestrian phases overlap with LPIs can enable a shorter cycle length with less pedestrian delay and little impact on vehicular traffic. A simulation study of an intersection in Boston found that introducing LPIs with pedestrian overlaps in such a situation allowed a 22% reduction in cycle length, with average pedestrian delay falling from 24 s to 18 s and no perceptible change in vehicular delay (Furth et al., 2012).

3. Facilitating progression through multistage crossings. Where there are multistage crossings, a short vehicular-hold interval overlapped by pedestrian phases can be the key to creating good progression for pedestrians. An example is described in Section 10.1.



(a) Without LPIs

(b) LPI added to minor street

(c) LPI added to major street, with overlap

(d) Second overlap added, lengthening the N-S Walk phase

Exhibit 6-27. Introducing LPIs and pedestrian overlaps in a way that leaves the lengths of major street (north–south) vehicular phase and minor-street pedestrian phase unaffected.

4. Lengthening pedestrian phases, reducing delay, and helping slower pedestrians. Several of the examples already provided show how overlapping pedestrian phases with LPIs can increase the length of pedestrian phases, reduce delay, and make intersections more accessible for slower pedestrians.

6.7.3 Considerations

6.7.3.1 Accessibility Considerations

As described in Section 6.5 on LPIs, APS are recommended wherever LPIs are used because otherwise visually impaired pedestrians, who often take their cue from the sound of starting traffic, will not know when the pedestrian phase begins. Without an accessible signal, they would likely begin crossing when vehicular traffic is released, exposing them to greater conflict with turning traffic.

6.7.3.2 Guidance

Not applicable for this treatment.

6.7.3.3 Relationships to Relevant Treatments

As described earlier in this section, this treatment relates to LPI (see Section 6.5), short cycle length (see Section 7.1), pedestrian clearance settings for serving slower pedestrians (see Section 7.4), and multistage crossings (see Chapter 10).

6.7.3.4 Other Considerations

Not applicable for this treatment.

6.7.4 Implementation Support

6.7.4.1 Equipment Needs and Features

Not applicable for this treatment.

6.7.4.2 Phasing and Timing

As an example of how pedestrian phases might be programmed as overlaps, consider the example in Exhibit 6-25(b). It might have the following phase and overlap assignments:

- Phase 1: east–west LPI;
- Phase 2: east–west vehicular movement;
- Phase 3: north–south LPI;
- Phase 4: north–south vehicular movement;
- Overlap A, consisting of Phases 1, 2, and 3: east–west pedestrian movements; and
- Overlap B, consisting of Phases 3, 4, and 1: north–south pedestrian movements.

To effectively use the second LPI in each of the overlaps, the through phases (Phases 2 and 4) must either be pretimed or coordinated in such a way that the ending time is known in advance.

Overlaps like this are only possible where a through movement immediately follows another through movement. Therefore, it is not possible to have two such overlaps where an intersection has left-turn phases.

6.7.4.3 Signage and Striping

Not applicable for this treatment.

6.7.4.4 Geometric Elements

Not applicable for this treatment.

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6.8 No Turn on Red

6.8.1 Basic Description

6.8.1.1 Alternative Names

None.

6.8.1.2 Description and Objective

NTOR refers to a restriction on right turns during red intervals that are otherwise allowed. This section is limited to consideration of NTOR to enhance pedestrian and bicycle safety.

NTOR addresses not only collisions with crossing pedestrians and bicycles, but also the inconvenience and hazard that occurs when right-turning drivers block the crosswalk while checking for a sufficient gap in traffic to finish their turn. Drivers often wait with their gaze fixed to their left, which may keep them from noticing a pedestrian or bicycle approaching from their right—even when the crossing person is directly in front of the vehicle—creating a high-risk situation, especially for pedestrians or bicycles with a low profile such as children and people in wheelchairs.

6.8.1.3 Variations

Some states allow left turns on red from a one-way street to another one-way street. Similar guidance applies for these movements as well.

NTOR can be implemented with time restrictions (e.g., 7 a.m. to 7 p.m.) or "when pedestrians are present." It can also be applied during certain phases of a signal cycle by using dynamic blank-out signs.

6.8.1.4 Operating Context

Some contexts in which NTOR may be appropriate to protect pedestrians and bicycles include:

- Crossings with a moderate or high pedestrian-/bicycle-volume or with a significant volume of vulnerable crossers (e.g., children or older adults);
- Where the crosswalk location is such that drivers turning right block the crosswalk while waiting for a gap; and
- Crossings used by bicycles approaching from the right side (e.g., from a two-way path).

NTOR is also necessary in conjunction with LPI (see Section 6.5), delayed turn (see Section 6.6), exclusive pedestrian/bicycle phases (see Section 6.3), and concurrent-protected crossings (see Section 6.2). These treatments all aim to hold right-turning vehicles during certain phases, so NTOR should be in effect during those phases.

6.8.2 Applications and Expected Outcomes

6.8.2.1 National and International Use

This treatment is widespread throughout the United States. New York City and Montreal are the only places in the U.S. and Canada that prohibit RTOR by default. Everywhere else, the restriction must be signed. In some cities—including Washington, DC; Seattle; and Alexandria, VA—adding NTOR restrictions is part of their Vision Zero plans.

Several agencies—including those in Ithaca, NY; Charlotte; and Portland—use dynamic blank-out signs to apply NTOR during selected phases in the signal cycle. Charlotte uses dynamic NTOR signs to hold right-turning traffic during pedestrian-crossing phases, which are generally pushbutton actuated. Wherever it applies the delayed-turn technique (see Section 6.6), when there is a pedestrian call, the through phase begins with an interval lasting about 10 s in which, in addition to a green ball, a red right-turn arrow and a dynamic NTOR sign are displayed. For the remainder of the through phase, the dynamic sign reads "Yield to Pedestrians" and the red turn arrow is replaced with an FYA (Thomas et al., 2016).

6.8.2.2 Benefits and Impacts

Several studies have shown that permitting RTOR increases crashes with pedestrians and bicycles. Preusser et al. (1982) found that RTOR increases right-turning crashes with pedestrians by 43% to 107% and with bicycles by 72% to 123%, resulting in a CMF ranging from 1.43 to 2.08. A CMF of 1.69 is given in the *Highway Safety Manual* for bicycle and pedestrian crashes when RTOR is changed from prohibited to permitted. However, applying NTOR restrictions has not produced evidence of a strong safety effect. According to Harkey et al. (2006), NTOR signs are estimated to reduce crashes by about 3%, with a CMF of 0.97.

A review of Fatality Analysis Reporting System data showed that in the 10-year period between 1982 and 1992, less than 1% of all national traffic fatalities involved a right-turning vehicle at an intersection that permits RTOR; however, bicyclists or pedestrians were involved in more than half of those fatal crashes (NHTSA, 1994). California conducted a comparable study of its crash data and found similar results, suggesting that its current policy of selectively restricting RTOR was better than a blanket ban at all intersections (Fleck & Yee, 2002).

A 2002 study in Arlington, VA, found that NTOR restrictions conditioned on time of day are far more effective than those conditioned on pedestrian presence (Retting et al., 2002). At five previously unrestricted intersections treated with signs reading, "No Turn on Red, 7 a.m.–7 p.m., Mon–Fri," there was a large decrease in RTOR, a large increase in vehicles stopping before turning, and a large decrease in pedestrians yielding to vehicles turning right on red. At five other previously unrestricted intersections with fluorescent yellow-green reflective signs reading "No Turn on Red—When Pedestrians are Present," observations only from when a pedestrian was present found only a small decline in RTOR vehicles, little change in the fraction of RTOR vehicles stopping before they turned, and little change in the number of pedestrians yielding to RTOR vehicles. A recent study conducted by Lin et al. (2016) found that driver compliance was the highest with signs readings "No Turn on Red" (70%) compared to "Right on Red Arrow after Stop" (67%), "Turning Vehicles Yield to Pedestrians" (67%), and "Stop Here on Red" (55%).

In one study, dynamic NTOR blank-out signs used only during school crossing periods or other critical times were found to be only slightly more effective than static NTOR signs (Zegeer & Cynecki, 1986). However, a study of different treatments at a Miami, FL, intersection found dynamic NTOR signs were considerably more effective than static signs (Pecheux et al., 2009). Violations were high with two different static signs—"No Turn on Red" and "No Turn on Red When Pedestrians in Crosswalk,"—but fell significantly when dynamic signage was used.

Note: The ongoing NCHRP Project 03-136 is currently evaluating the performance of RTOR operations at signalized intersections. The project aims to develop methods and tools that consider all modes and inform planning and operations decisions for practitioners. Learn more by visiting the project webpage (https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4549).

Prohibiting RTOR will increase delay for right-turn vehicles. Because right turns typically have extra capacity, it is less likely for RTOR restrictions to significantly impact traffic capacity. Where right-turn volumes are so great that prohibiting RTOR may substantially affect intersection operations, adjusting the signal timing may address the issue, since vehicles turning right on red can only do so when there is a gap in the conflicting traffic, indicating potential to take some green time from the cross street.

6.8.3 Considerations

6.8.3.1 Accessibility Considerations

Allowing RTOR makes it harder for visually impaired pedestrians to identify the surge of traffic at the onset of the vehicular green phase on the street parallel to the crossing direction, therefore it increases the need for APS. Because visually impaired travelers, in the absence of APS, wait to hear a vehicle traveling straight across the intersection to determine if the signal has changed, they are frequently delayed in initiating crossing where vehicles can turn right on red (Barlow et al., 2003).

6.8.3.2 Guidance

The MUTCD (2009) indicates six conditions for when an NTOR sign should be considered. The conditions that include non-motorized considerations include:

- Geometrics or operational intersection characteristics that might result in unexpected conflicts;
- An exclusive pedestrian phase or LPI;

- An unacceptable number of pedestrian conflicts with RTOR maneuvers, especially if they involve children, older pedestrians, or persons with disabilities; and
- More than three RTOR crashes reported in a 12-month period for that particular approach.

The MUTCD also provides guidance for the design of various types of NTOR regulatory signs. Detailed discussion is provided in Section 6.8.4.

6.8.3.3 Relationships to Relevant Treatments

NTOR should be used in combination with the following treatments, either as a dynamic restriction or as a restriction of RTOR only during phases in which the treatment is active:

- Concurrent-protected crossings (see Section 6.2);
- LPI (see Section 6.5);
- Delayed turn/LTIs (see Section 6.6); and
- Exclusive pedestrian/bicycle phases (see Section 6.3).

6.8.3.4 Other Considerations

If RTOR is prohibited, more vehicles will turn right during a green phase, when they could conflict with pedestrians making a concurrent crossing. This concern can be mitigated by using LPI or delayed turn.

6.8.4 Implementation Support

6.8.4.1 Equipment Needs and Features

NTOR could be implemented with static and dynamic blank-out signs. There are several variations of NTOR signs allowed by the MUTCD, as shown in Exhibit 6-28. NTOR signs with a red ball (R10-11) have been shown to be more effective than standard black-and-white signs.

While the MUTCD (2009) indicates that RTOR is intended for use while a circular red ball is displayed but not while a red turn arrow is displayed, state laws are not uniformly consistent with this distinction. Even where they are, many motorists often do not understand the law that applies in their state. To avoid ambiguity and improve compliance, it may be advisable to provide signage for NTOR in conjunction with red arrows as well as with circular red indications.

Dynamic blank-out signs can be activated during programmed phases and powered from the controller cabinet. Considerations for mounting signs near the signal head include visibility as well as weight and wind loads.

6.8.4.2 Phasing and Timing

Not applicable for this treatment.

6.8.4.3 Signage and Striping

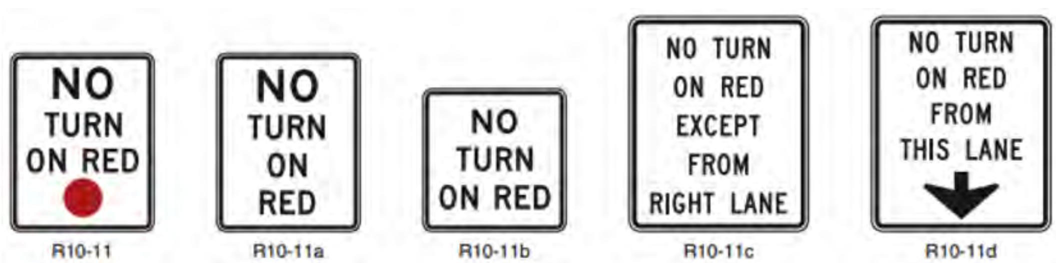

Exhibit 6-28. NTOR signs (R10-11 Series) in MUTCD (2009).

6.8.4.4 Geometrics

This treatment can be applied with and without exclusive right-turn lanes.

NTOR is an effective countermeasure when (1) the skew angle of the intersecting roadways makes it difficult for drivers to see traffic approaching from their left or (2) geometrics or operational characteristics of the intersection result in unexpected conflicts, such as between a right-turning vehicle and a left-turning vehicle entering the same departure leg.

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6.9 Flashing Pedestrian and Bicycle Crossing Warnings

6.9.1 Basic Description

6.9.1.1 Alternative Names

FYA; flashing right-hook warning.

6.9.1.2 Description and Objective

A flashing pedestrian/bicycle crossing warning is a flashing signal that warns turning motorists of a possible conflict with crossing pedestrians or bicycles and reminds them of their obligation to yield. Some types of flashing warnings include images of a pedestrian or a crosswalk.

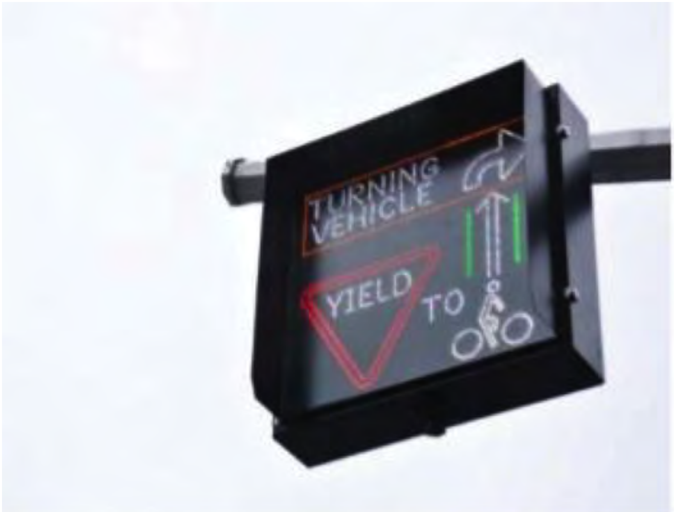
Source: NYC Department of Transportation (2016).

Exhibit 6-29. FYA in New York warning of a permitted conflict with adjacent bicycle and pedestrian crossings.

6.9.1.3 Variations

FYA is the only commonly used flashing warning in the U.S. FYA is widely used to warn left-turning motorists of potential conflicts with oncoming traffic. FYA can also be used with right turns—and with left turns from a one-way street—to warn of conflicts with crossing pedestrians and bicycles. Several cities—including New York, Charlotte, Portland, and Boston—use FYA in connection with right turns and with left turns from a one-way street. Exhibit 6-29 shows an application in New York City.

A custom flashing sign (see Exhibit 6-30) called a flashing right-hook warning is used at one intersection approach in Portland that has a history of crashes between bicycles and right-turning vehicles. Because of the downhill, bicycles tend to approach at high speed, making it harder for drivers to detect an approaching bicycle.



Source: Andersen (2015).

Exhibit 6-30. A flashing sign warning turning vehicles to yield to bikes, Portland.

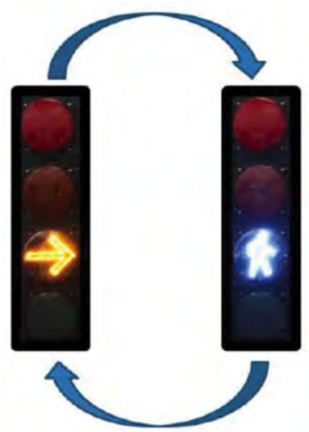
(a) Static warning sign **(b) Flashing warning sign** **(c) Close-up of flashing sign**

Exhibit 6-31. Static and flashing pedestrian-bicycle crossing warnings in the Netherlands. "Let op" means "Watch out."

A flashing right-hook warning is also used at one intersection approach in Amsterdam. Its graphics are based on a commonly used static pedestrian/bicycle crossing warning sign. Exhibit 6-31 shows the static sign and the flashing sign, which both display the image of a cross-walk with a large, red exclamation sign. This video shows the flashing sign in operation: https://www.youtube.com/watch?v=FJQEiNNSegw (Furth, 2019a).

Amsterdam uses a flashing yellow light at a few intersections to warn left-turning motorists of crossing pedestrians and bicycles. The light, substantially larger than a yellow ball used at traffic signals, is oriented diagonally, positioned to catch the attention of a driver whose vehicle has begun to turn left. Exhibit 6-32 shows the flashing warning light. This video shows the flashing sign in operation: https://youtu.be/A1JmWMIjsg0 (Furth, 2019b). This kind of signal is not

Exhibit 6-32. Flashing yellow warning light, Amsterdam.



Source: Boot et al. (2015).

Exhibit 6-33. Flashing pedestrian indicator proposed by Florida State University researchers.

currently allowed in the U.S. because of confusion from displaying a flashing yellow ball (even if it is outside a signal head) at the same time as a solid green.

University researchers in the U.S. have proposed different forms of flashing pedestrian/bicycle crossing warnings and tested them in a laboratory setting. The warning developed and tested at Florida State University (Boot et al., 2015) is shown in Exhibit 6-33—a yellow arrow alternates every 0.5 s with a white walking man. The concept is to alternate a common symbol of warning with a symbol indicating the object of the warning. While it is questionable whether this configuration would be granted approval by FHWA due to confusion over the flashing white man (it normally indicates the Walk interval, but the flashing warning would run throughout the pedestrian phase, including the FDW interval), the concept may have promise.

At the University of Wisconsin, research by Noyce et al. (2017) found that the flashing sign shown in Exhibit 6-34 was the most promising design among alternatives tested to alert drivers who were making permitted left turns to potential conflicts with pedestrians and bicycles. It is a modified version of the MUTCD's R10-15 sign, which flashes only during permissive left-turn periods.

6.9.1.4 Operating Context

Flashing crossing warnings are used where permitted right turns or left turns conflict with crossing bicycles or pedestrians. They can be used at intersections both with and without exclusive turn lanes.

6.9.2 Applications and Expected Outcomes

6.9.2.1 National and International Use

Of the various flashing crossing warnings shown, only FYA is used routinely. Many U.S. cities use this treatment. In New York, it is a standard treatment where permitted outside turns (right turns or left turns from a one-way street) cross a bike lane, and it is used at more than 100 intersection approaches. FYA is also frequently used where there are only conflicting pedestrians. The other warning signs shown earlier are used at only one or a few intersection approaches or have been used only in laboratory experiments.

6.9.2.2 Benefits and Impacts

The flashing warning sign used in Portland (see Exhibit 6-30) was found to reduce right-turn conflicts from 18 to 6 per 24 hours of daytime operation. The reduction in serious conflicts

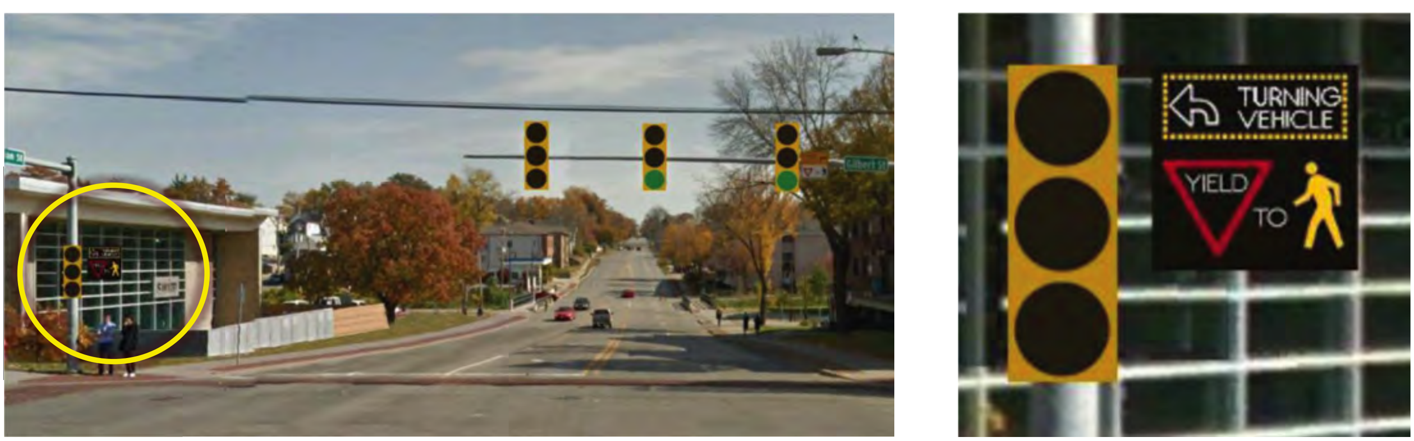


Exhibit 6-34. Flashing pedestrian-crossing warning design by Noyce et al. (2017).

(i.e., conflicts that required substantial braking or course adjustments by one or both vehicles) was even more pronounced (Andersen, 2015).

Florida State University's laboratory study of its proposed warning device found that at intersections with the device, drivers showed greater caution and searched more thoroughly for pedestrians. Using a questionnaire, they also found that it increased participants' recognition of their obligation to yield when turning from 68% (without the flashing sign) to 87% (with the sign) in one test, and from 79% to 94% in another. At the same time, there was a large increase in stopping for pedestrians when pedestrians were not present, an undesirable outcome.

In the University of Wisconsin's study of its proposed warning device, 74% of respondents fully understood the intended message of the signal shown in Exhibit 6-34 (Noyce et al., 2018). Three other alternatives tested resulted in worse understanding.

At Oregon State University, a laboratory study using a driving simulator found that driver-yielding behavior improved significantly when FYA was used instead of a steady green ball at locations with high volumes of permissive right turns from exclusive right-turn lanes (Hurwitz et al., 2018; Jashami et al., 2019). They found that the probability of responding correctly was 0.95 when a driver encountered an FYA versus 0.74 when the signal display was circular green.

FYA is used extensively across the country in connection with permitted left turns, where turning motorists are obligated to yield to opposing traffic as well as crossing pedestrians and bicycles. While studies have shown that FYA reduces crashes with opposing motor vehicles, Van Houten et al. (2012) found that the safety benefit to pedestrians is insignificant.

FYA is part of the delayed-turn treatment described in this guidebook, for which researchers found a significant reduction in conflict rate (see Section 6.6). However, it is not possible to assess how much of that reduction stems from using an FYA as opposed to other features of the treatment—that is, a leading, protected interval and the addition of a turn lane.

6.9.3 Considerations

6.9.3.1 Accessibility Considerations

Not applicable for this treatment.

6.9.3.2 Relationships to Relevant Treatments

FYA is combined with delayed turn (see Section 6.6) in New York City and Charlotte and is sometimes combined with LPI (see Section 6.5) as well.

6.9.4 Implementation Support

6.9.4.1 Equipment Needs and Features

FYAs are a standard signal display that may have to be added. Portland's and Amsterdam's flashing warning signs are custom signs, powered from the controller cabinet and controlled there so as to be active only during the relevant phase.

6.9.4.2 Phasing and Timing

Flashing crossing warnings, including FYA, should be active at any time in the cycle in which pedestrians or bicycles are expected to be in conflict with a turning movement. Where a conflict is only expected during a pedestrian phase, it is advisable to continue the flashing sign from when the pedestrian phase goes to solid Don't Walk until the end of the concurrent vehicle phase, since pedestrians may still be clearing during the early part of the solid Don't Walk interval.

6.9.4.3 Signage and Striping

Not applicable for this treatment.

6.9.4.4 Geometric Elements

Not applicable for this treatment.

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CHAPTER 7

Treatments that Reduce Pedestrian and Bicycle Delays

This chapter describes six treatments aimed at reducing delay for pedestrians and bicycles and accommodating slower pedestrians, grouped by their primary function:

Primary Function	Section	Treatment Name
Reduce effective red time	7.1	Short Cycle Length
	7.2	Reservice
Increase effective green time for pedestrians and bicycles	7.3	Maximizing Walk Interval Length
	7.4	Pedestrian Clearance Settings for Better Serving Slower Pedestrians
Limit impact to other road users while serving pedestrians	7.5	Pedestrian Recall versus Actuation
	7.6	Pedestrian Hybrid Beacons

Additional treatments for reducing delay are found in Chapter 9 (treatments focused solely on cyclist delay) and Chapter 10 (treatments for multistage crossings).

The first pair of treatments, **Short Cycle Length (Section 7.1)** and **Reservice (Section 7.2),** aims to reduce delay by shortening pedestrians' and bicycles' effective red time. "Effective red time" is that part of the signal cycle in which a user group (pedestrians or bicycles) is not intended to begin crossing.

In general, delay for all users is minimized when cycle lengths are as short as possible—that is, just long enough to provide capacity for all movements plus additional slack to account for variability. There is one large exception to this rule, however, which is vehicular traffic along a coordinated arterial. For those vehicles, cycle length matters little if vehicles arrive during a green period as part of a "green wave." To a large extent, traffic signal timing in the U.S. has focused on arterial coordination, which is easier to provide with long cycles. However, long cycles result in long delays for pedestrians, bicyclists, and others (e.g., transit riders, cross-street traffic, and left-turning vehicles) who are not part of the green wave. In many situations, sacrificing coordination for shorter cycles can lead to little or no additional delay for vehicles, while substantially reducing delay for pedestrians and bicyclists.

"Reservice" means serving a movement—in this case, a pedestrian or bicycle crossing—twice (or more) in a cycle, and it has roughly the same effect on delay as halving the cycle length. Section 7.2 also shows how reservice can be applied to vehicular left turns as a way of mitigating a change from permitted to protected-only left turns (a treatment described in Section 6.1).

The next pair of treatments aims to increase the time that pedestrians can use within a signal cycle. One is **Maximizing Walk Interval Length (Section 7.3).** Longer Walk intervals both reduce pedestrian delay and make crossings accessible to pedestrians with lower walking speeds. National and local standards specify a minimum Walk interval length (usually 7 s), and all too often, signal timing uses that minimum standard even when a longer Walk interval would fit within the signal cycle without constraining other traffic movements.

Pedestrian Clearance Settings for Better Serving Slower Pedestrians (Section 7.4) puts a focus on the final intervals of a pedestrian phase: Flashing Don't Walk (FDW) and the pedestrian phase end buffer. It shows how setting these intervals' lengths to maximize usability can enable a pedestrian phase to have a longer Walk interval and/or support pedestrians with lower walking speeds.

The final pair of treatments deals with balancing traffic control's flexibility, or demand responsiveness, with its impact on users. **Pedestrian Recall versus Actuation (Section 7.5)** addresses the long-standing issue of when pedestrian signals should be pushbutton actuated versus on recall (i.e., automatic). Analysis methods used in traditional practice have typically underestimated the delay impact to pedestrians and overestimated the impact to vehicles. In many cases, the vehicle delay impact of having pedestrian phases on recall is negligible, indicating pedestrian recall may be warranted even where pedestrian demand is low.

Pedestrian Hybrid Beacons (Section 7.6) are an alternative to full traffic signals whose demand responsiveness can enable them to serve both pedestrians and vehicles well, with pedestrians served only moments after arriving and vehicles stopped only when needed for a crossing pedestrian.

7.1 Short Cycle Length

7.1.1 Basic Description

7.1.1.1 Alternative Names

None.

7.1.1.2 Description and Objective

The length of a signal cycle is the time from the moment a particular phase ends until that phase is served and ends again. Cycle length may be fixed—as it is with pretimed control and with coordinated-actuated control—or variable, as it is when a signal is running free. For a given set of vehicular and pedestrian demands, there is a minimum cycle length below which capacity will be exceeded due to the capacity loss that occurs when the controller switches phases. A cycle length for a particular situation can be considered short if it is close to that minimum. At a compact intersection with moderate traffic and no turning phases, cycle length can sometimes be as short as 40 s; at more complex intersections with protected turning phases, longer pedestrian crossings, and greater levels of traffic, the minimum cycle length could be 90 s or longer.

Shorter cycle lengths reduce delay for pedestrians and bicycles (and usually for transit) because they involve shorter red periods. They reduce crowding on crossing islands and other queuing areas because fewer people cross per cycle. In addition, short cycle lengths have the potential to make roads safer for walking and cycling because they can reduce speeding opportunities, as explained later.

7.1.1.3 Variations

Cycle lengths can either be fixed—as they are with coordinated and pretimed control—or variable, as they are with fully actuated control.

Fully actuated control, also called running free operation, tends to lead to short cycles because each phase's green is only extended while traffic is still flowing, given minimum and maximum green constraints. This allows the intersection to cycle as quickly as possible for the current level of traffic, automatically lengthening cycles when traffic is heavy and shortening them when traffic is light.

With coordinated and pretimed control, a common cycle length is applied to all the intersections in a corridor or grid for a given coordination period (e.g., a.m. peak). In general, the cycle length is based on the needs of the most demanding intersection during the most demanding 15-minute interval in the coordination period. Therefore, shorter cycle lengths can be achieved by having short coordination zones made up of only one to four intersections as well as short coordination periods. Simple forms of adaptive control constantly monitor traffic volumes and adjust cycle lengths every 10 or 15 minutes.

Where a corridor has a long coordination cycle, less demanding intersections may be able to double cycle, meaning they operate with half of the corridor's prevailing cycle length; this yields the local benefits of a short cycle length without disrupting arterial coordination.

7.1.1.4 Operating Context

Short cycle lengths are of interest at every signalized intersection used by pedestrians or bicycles. More specifically:

- Where a single, complex intersection demands a substantially larger cycle length than the intersections around it, consider taking it out of coordination—either to run free or to run with its own fixed cycle—so that the intersections around it can operate with shorter cycles.
- Where the spacing between two intersections is long enough for queuing with little risk of spillback (around 600 ft, depending on traffic volume and cycle length), coordination zones can be broken to create short coordination zones, with each given the cycle length its most demanding intersection needs.
- Where the current signal operation uses a small number of coordination periods in a day (e.g., a.m. peak, midday, p.m. peak, and nighttime), breaking the day into more coordination periods can allow many hours of operation with shorter cycles.
- Where a corridor has a long cycle length, simple intersections (i.e., intersections with fewer phases and less cross traffic) can be considered for double cycling.
- Where there are one-way grids, such intersections are especially amenable to short cycles, since one-way streets do not require turn phases. For example, downtown Portland, OR, uses cycles of 56 s during off-peak and 60 s during peak periods; the city would use still shorter periods if not for the long clearance time needed by street-running light rail (P. Koonce, personal communication, August 2019). These short cycles contribute to a pedestrian- and bicycle-friendly environment.

7.1.2 Applications and Expected Outcomes

7.1.2.1 National and International Use

Many cities have, by policy, a maximum cycle length and an objective to keep cycle lengths as short as possible. In U.S. cities, a common maximum is 120 s; however, while this is far shorter than the 240 s cycles allowed in some suburban jurisdictions, 120 s is not always considered a short cycle. NYC DOT employs 90-second cycles across Manhattan to limit pedestrian delay, with few exceptions (D. Nguyen, personal communication, August 16, 2019). Cambridge, MA, uses 90-second cycles during peak hours and 75-second cycles during off-peak hours (P. Baxter, personal communication, 2019).

The policy in Amsterdam, Netherlands, is that cycles should be as short as possible, never exceeding 100 s. One of the city's core principles for increasing compliance is that signal control should be "credible," meaning people should not be given a red signal when there is no conflicting traffic. This leads to preference for fully actuated control at most intersections (S. Linders, personal communication, 2018). At compact intersections—even with pedestrian calls—cycle lengths can be as low as 40 s, and they can be even shorter when there are no pedestrian calls.

U.S. practice tends to be strongly in favor of coordination (versus letting signals run free) with long cycles and long coordination zones. Zurich, Switzerland, times its traffic signals using short coordination zones, usually with only two or three intersections per zone. Through traffic gets a green wave through a few intersections followed by a short waiting time (due to the low cycle lengths), which helps compress the platoon and deter speeding (J. Christen & R. Gygli, personal communication, 2005).

Coordination periods in the U.S. also tend to be long, with agencies often using far fewer time-of-day plans than their controller software can support. This creates an opportunity to lower cycle lengths by dividing up longer periods when one part of the period has considerably less traffic than another.

Fully actuated control is widely used in the U.S., but in many cities, few signals have fully actuated control. By contrast, in Amsterdam and other Dutch cities, most intersections use fully actuated control because it keeps cycles short and is especially suitable for transit signal priority, since it can naturally recover from priority disruptions.

With fully actuated control, cycle lengths can be substantially shorter using "snappy" versus "sluggish" settings. Snappy settings include a short unit extension, short minimum green, non-simultaneous gap-out, upstream detectors for gap-out, and lane-by-lane detection and gap-out (Furth et al., 2009).

7.1.2.2 Benefits and Impacts

For pedestrians, a shorter signal cycle almost always means less delay. Shorter cycles also improve pedestrian safety, as pedestrian compliance tends to be poor when pedestrians experience long red periods, especially if there are periods with no conflicting traffic (Kothuri et al., 2017).

Short cycles usually mean less average delay for vehicles too, as long as the cycle stays long enough to avoid a capacity shortfall. However, with coordinated control, one subset of vehicles—long-distance through traffic—prefers long cycles because they make it possible to create better two-way green waves. As a result, one often sees long green periods in which, for example, the northbound platoon passes through early in the green and the southbound platoon late in the green, with much of the green period being unused in each direction. Meanwhile, cross traffic, left-turning traffic, and transit users (buses cannot stay in the green wave because of stops) have longer delay. Therefore, using shorter cycle lengths to break up long coordination zones and using fully actuated control will mean more delay for long-distance through traffic but less delay for local traffic. In many cases, the net effect is to lower average vehicular delay.

Many simulation studies have found that, for the corridor they studied, breaking up coordination zones and either running free or using short-zone coordination with short cycles reduced average vehicular delay as well as pedestrian delay. For example, Kothuri et al. (2017) found that free operation on a corridor in Portland reduced average pedestrian delay from 45 s to 30 s compared to coordinated control with fixed cycle lengths, and at the same time it reduced average vehicle delay from 26.5 s to 23 s. Ishaque and Noland (2007) found that on a coordinated arterial, shorter cycle lengths substantially lowered pedestrian delay and yielded small delay-reductions for motorists as well.

In some corridors with low pedestrian-demand, designers sometimes face a choice: Either use a long cycle length in which the minor street gets enough time in every cycle to support a pedestrian phase, or use a shorter cycle in which the minor street is given only the time needed to serve vehicles. In the latter case, when there is a pedestrian call, the minor-street phase runs beyond its scheduled time, and the controller then has to transition over the next one or two cycles to return the intersection to coordination. A study of a Utah corridor by Chowdhury et al. (2019) found that although through traffic had less delay in the long cycle alternative, the short cycle alternative yielded lower vehicular delay overall as well as lower pedestrian delay.

Short cycle lengths can also improve the safety of a road by inhibiting speeding. Long cycles tend to have long green periods within which vehicles can speed through several intersections; the faster one drives, the farther one can go before hitting a red light. A study of a Boston corridor compared coordinated control with a 120-second cycle (existing control) to two other control alternatives: fully actuated control and small-zone coordination. In the latter alternative, the corridor was divided into three zones with two or three intersections each. Each zone had its own cycle length; one intersection was in a zone by itself and ran free (Furth et al., 2018). The results, summarized in Exhibit 7-1, showed that both small-zone coordination and running free led to cycle lengths that were more than 30% shorter and yielded large reductions in pedestrian delay. Small-zone coordination also led to a decrease in average vehicular delay. Most importantly, this study measured the number of "speeding opportunities" afforded by the three control alternatives, defined as the number of vehicles arriving at a stop line while the signal is green but with no vehicle less than 5 s ahead of them. Compared to coordinated control, small-zone coordination eliminated more than one-third of speeding opportunities and running free eliminated nearly two-thirds.

7.1.3 Considerations

7.1.3.1 Accessibility Considerations

Not applicable for this treatment.

7.1.3.2 Guidance

NCHRP Report 812: Signal Timing Manual, 2nd Edition (STM2) advises that, when designing coordination plans, practitioners should consider whether intersections with exceptionally long cycle-length requirements would better operate independently from a group, especially if they are distant enough from neighboring intersections to prevent spillback. The National Association of City Transportation Officials (NACTO) *Urban Street Design Guide*, PedSafe, and other guides also recommend shorter cycles due to increased efficiency and the potential for increased compliance by all users.

7.1.3.3 Relationships to Relevant Treatments

Using pedestrian clearance settings for serving slower pedestrians (see Section 7.4) can shorten cycle length by avoiding periods at the end of a phase that are not needed by either vehicles or pedestrians.

Exhibit 7-1. Changes in delay and speeding opportunities compared to coordinated-actuated control.

	Change in average cycle length and average pedestrian delay	Change in vehicular delay	Change in speeding opportunities
Small-zone coordination	-33%	-13%	-37%
Fully actuated control (running free)	-31%	11%	-65%

Source: Derived from Furth et al. (2018).

There can be some tension between the desire to keep cycles short and the desire to protect pedestrians from turning conflicts using such techniques as exclusive pedestrian phases (see Section 6.3) and leading pedestrian intervals (LPIs) (see Section 6.5), which can require longer cycle lengths. However, there often are ways to provide the desired protection with little or no cycle-length impact. For example, in most situations, concurrent-protected phasing (see Section 6.2) requires a far shorter cycle length than exclusive pedestrian phases, while still providing fully protected pedestrian crossings, and delayed turn (see Section 6.6) can provide the same or greater partial protection as an LPI with less cycle-length impact. Changing some aspects of an intersection's corner geometry can shorten the needed LPI (see Section 6.5), and using overlapping pedestrian phases (see Section 6.7) can lessen the cycle-length impact of LPIs.

7.1.3.4 Other Considerations

Studies sometimes find that coordination plans with long cycle lengths reduce emissions because they reduce the number of vehicle stops. However, results like this stem from using a short-term analysis framework that assumes fixed travel patterns and ignores human response. Over time, traffic control that reduces travel time for long-distance through traffic will lead to people making longer trips (e.g., by changing their residence or work place) and increasing vehicle-miles traveled, which will drive up emissions by far more than the savings that come from fewer stops.

7.1.4 Implementation Support

7.1.4.1 Equipment Needs and Features

Fully actuated control requires detectors on all approaches, while coordinated-actuated control requires detectors on non-coordinated phases only. Pretimed control requires no detectors.

7.1.4.2 Phasing and Timing

The minimum necessary cycle length for achieving a target degree of saturation is given by Equation 7-1, derived from the 2016 *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis*:

$$C_{min} = \frac{\sum L_{ci}}{1 - \left(\sum \frac{v_{ci}}{s_{ci}}\right) \Big/ X_{target}} \qquad (7\text{-}1)$$

where

X_{target} = the target degree of saturation (typically in the range 0.85 to 0.95);
C_{min} = the minimum cycle length necessary to avoid exceeding that target—both sums are over the critical movements only;
L_{ci} = the lost time associated with critical phase *i;*
v_{ci} = the volume flow rate of critical phase *i*; and
s_{ci} = the saturation flow rate of critical phase *i.*

When a pedestrian crossing is critical, its entire phase time should be treated as lost time and its saturation flow rate as infinite.

As the cycle-length formula shows, an increase in a critical movement's lost time generally leads to a far greater increase in necessary cycle length. For example, if the denominator in Equation 7-1 is 0.25, a 4 s increase in critical lost time (as might be caused by an LPI applied to a critical movement) would increase the necessary cycle length by 16 s.

Some controllers have special features that can reduce phase lengths and sometimes reduce cycle lengths. Sobie et al. (2016) describe the "split extension" feature, which allows a coordinated phase to terminate early if there are no active vehicles on the approach. This reduces delay for vehicles and for pedestrians waiting to cross. Many forms of adaptive control also adjust cycle length automatically.

7.1.4.3 Signage and Striping

Not applicable for this treatment.

7.1.4.4 Geometric Elements

The reduction of crossing lengths will allow for shorter cycle lengths when the pedestrian phase is critical.

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7.2 Reservice

7.2.1 Basic Description

7.2.1.1 Alternative Names

None.

7.2.1.2 Description and Objective

Reservice refers to serving a traffic movement two or more times within a signal cycle. Reservice can be applied to bicycle and pedestrian crossings to reduce their delay as well as to right- and left-turn movements to limit their delay when they are converted to protected-only phasing, with the goal of improving the safety of a bicycle/pedestrian crossing. Exhibit 7-2 shows an intersection in Amsterdam where bicycles and pedestrians are sometimes given two crossing phases in the east–west direction in a cycle.

7.2.1.3 Variations

If every phase is served twice per cycle within a coordinated system, this is called double cycling (see Section 7.1 on short cycle lengths). The local intersection has two cycles within one "system cycle."

When a channelized right turn conflicts with no traffic movement other than its pedestrian/bicycle crossing, it may be possible to control that pair of movements as its own intersection (i.e., running free). This will allow the right turn and its crossing movements to be served multiple times per cycle.

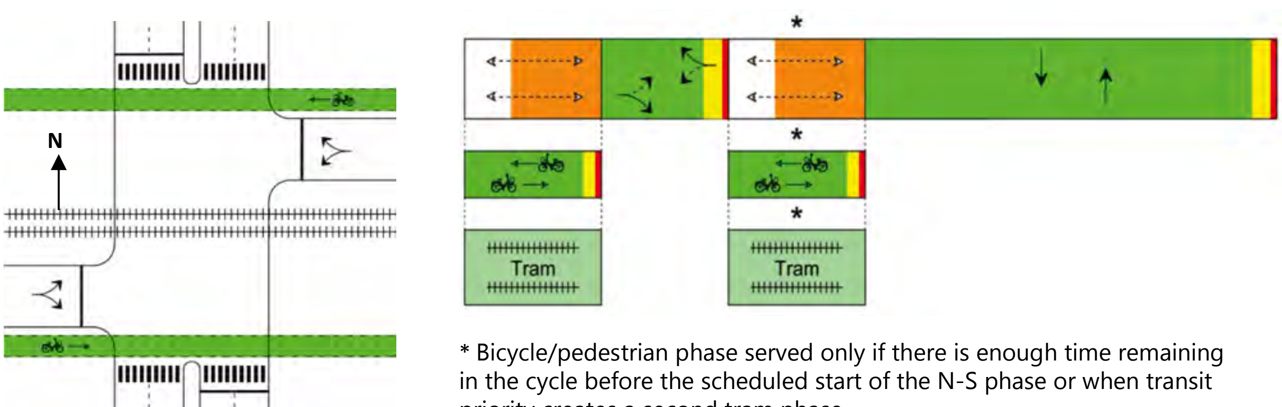
Reservice can also be applied to minor vehicular movements, including left turns and right turns. It can be a way to mitigate longer delays that occur due to making left turns protected-only or applying no turn on red.

7.2.1.4 Operating Context

Pedestrian or bicycle reservice might be appropriate:

- Where the cycle length is long and the crossing considered for reservice does not require a long phase, such as a bicycle crossing or a short pedestrian crossing; and
- At channelized right turns with signal-protected crossings. This context typically involves multistage crossings (see Sections 6.4 and 10.1).

Reservice can also be applied to left-turn and right-turn phases to mitigate the large delay increases to those turning movements caused by making them fully protected. This strategy might be appropriate if the corridor has a long signal cycle.



* Bicycle/pedestrian phase served only if there is enough time remaining in the cycle before the scheduled start of the N-S phase or when transit priority creates a second tram phase.

(a) Intersection layout **(b) Phasing plan**

Source: Derived from Furth (2019).

Exhibit 7-2. Bicycle and pedestrian reservice at the intersection of Sarphatistraat and Weesperplein, Amsterdam. Detail for the north–south phase has been suppressed.

7.2.2 Applications and Expected Outcomes

7.2.2.1 National and International Use

Reservice is a well-known technique, although its application is relatively uncommon. It is sometimes used for transit signal priority; for left turns whose turn bay is too short to store the full left-turn demand of a cycle; and for pedestrians and bicycles as well.

7.2.2.2 Benefits and Impacts

Reservice can substantially reduce delay for affected movements when a cycle length is long since it approximately halves the maximum red time. The impact to other movements cannot be generalized; however, when reservice is provided by taking time from movements with ample excess capacity, the impact to those other movements can be small.

A simulation study of a Boston, MA, intersection with a channelized right turn whose crossing is signalized found that, by serving the channelized right turn and its crossing twice per cycle, average pedestrian delay was reduced by 20 s. With this plan, right turns also get reservice; while they had less total green time, their delay still fell slightly because their red times were shorter. Other traffic movements were unaffected (Furth et al., 2019).

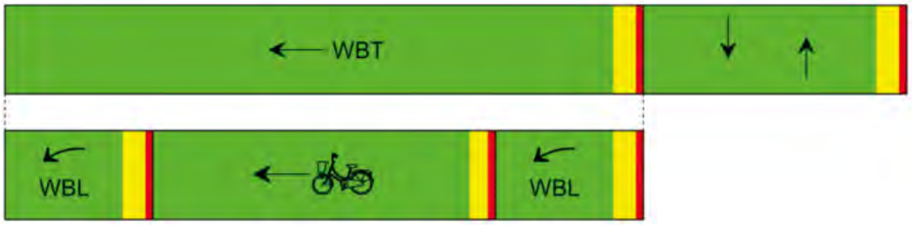
Reservice can also be applied to vehicular phases to mitigate delay increases to left turns or right turns due to making turns fully protected (see Section 6.1) or to prohibiting right turn on red (see Section 6.8). When a protected bicycle lane was installed on West 3rd Street in Long Beach, CA, the phasing plan allowed for left turns to be either leading or lagging, as illustrated in Exhibit 7-3. As implemented, the lagging left could be called only if the leading left had been skipped; however, Furth et al. (2014) found that if both leading and lagging lefts were allowed in the same cycle, delay would be substantially reduced for the left turn (meanwhile, delay for pedestrians and bicycles would increase only a little).

In preparation for this guidebook, a study of Boston's Southwest Corridor bicycle path found that converting northbound left turns at two intersections (Heath Street and Cedar Street) from protected-permitted to protected-only phasing would increase average left-turn delay by 46 s using conventional leading left-turn phasing. Meanwhile, with left-turn reservice, left-turn delay would increase by only 14 s.

7.2.3 Considerations

7.2.3.1 Accessibility Considerations

Without an accessible pedestrian signal (APS), pedestrians who cannot see the Walk indications will not know about the reservice. The APS may help alert other pedestrians to the opportunity as well.



Source: Furth et al. (2014).

Exhibit 7-3. Phasing plan in which a protected left turn across a protected bike lane has both a leading and lagging phase. Based on operations along West 3rd Street, Long Beach, CA.

7.2.3.2 Guidance

Not applicable for this treatment.

7.2.3.3 Relationships to Relevant Treatments

Where crossings of channelized right turns (see Section 6.4) are signalized, reservice for both the crossing and the right turn can substantially reduce delay.

7.2.4 Implementation Support

7.2.4.1 Equipment Needs and Features

Not applicable for this treatment.

7.2.4.2 Phasing and Timing

Reservice can be implemented at coordinated as well as free running intersections. At coordinated intersections with a fixed cycle length, reservice can be conditional on having sufficient time to fit an extra phase, which will depend on when preceding phases terminate.

Where channelized right turns are signalized, reservice can be applied to the right turn and its crossing within a coordinated cycle. If a right turn has no other conflicts, it is also possible to allow the turn and its crossing to run free as their own intersection.

An intersection in Rijswijk, Netherlands, applies reservice using logic that allows a right turn and its crossing to run free for part of a cycle. Where a north–south arterial with a two-way bicycle path on its west side meets on- and off-ramps of the A4 freeway (see Exhibit 7-4), the bicycle path and the southbound right turn conflict only with each other and with the northbound left. During all of the cycle except the northbound left phase, the bicycle path and the southbound right alternate, running freely with phases that can be quite short. As a result, the bike path and right turn are often served two or three times during a cycle (Furth et al., 2014), resulting in very low delay.

7.2.4.3 Signage and Striping

Not applicable for this treatment.

7.2.4.4 Geometric Elements

Not applicable for this treatment.

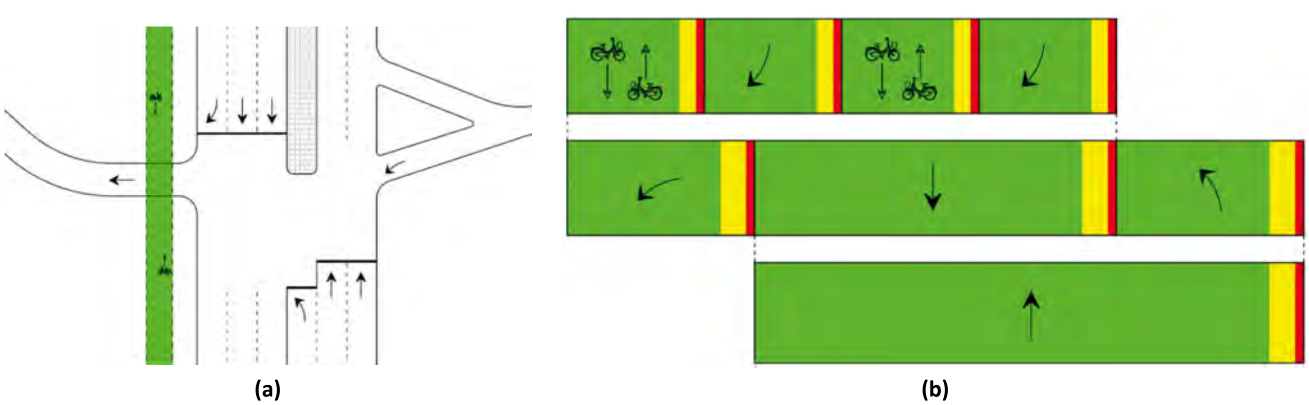


Exhibit 7-4. (a) Layout and (b) phasing plan, in which the bicycle crossing and conflicting right turn alternate freely for part of the cycle. Junction of Prinses Beatrixlaan with A4 freeway ramps, Rijswijk, Netherlands.

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7.3 Maximizing Walk Interval Length

7.3.1 Basic Description

7.3.1.1 Alternative Names

Rest in Walk.

7.3.1.2 Description and Objective

For pedestrian crossings that are concurrent with a parallel vehicular phase, minimum requirements for the pedestrian phase can often be met with time left over before the vehicular phase ends. This set of treatments aims to add this leftover time to the Walk interval, thereby reducing pedestrian delay, increasing compliance, and making the crossing accessible to slower pedestrians without significantly constraining the signal cycle.

7.3.1.3 Variations

Rest in Walk (for coordinated phases). Rest in Walk is a controller setting that maximizes the length of the Walk interval. For signal controllers in the U.S., this setting can be applied only to coordinated phases, whose start times may vary but whose ending time within a signal cycle is generally fixed. With this setting, the concurrent pedestrian signal dwells in the Walk until the "Walk yield point," which is the pre-scheduled end of green ("green yield point") minus the time specified for FDW. This way, if the concurrent vehicular green phase begins earlier than scheduled, the Walk interval will automatically be lengthened correspondingly. Exhibit 7-5 shows how the pedestrian phase runs with and without the Rest in Walk setting.

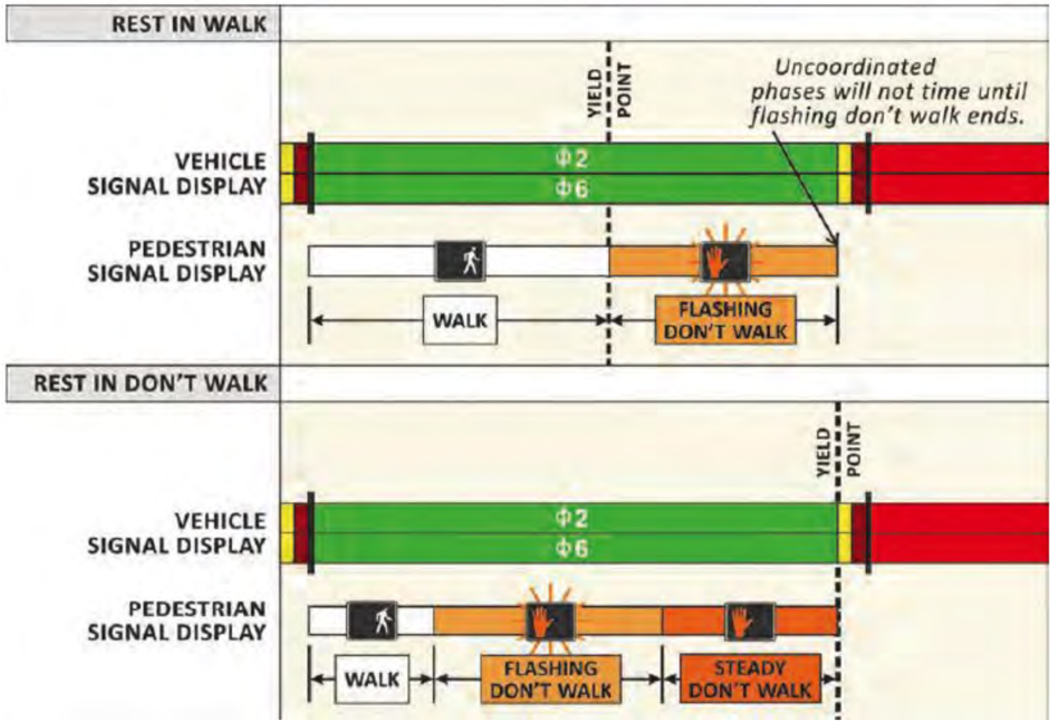
Maximize the Walk (for phases that are not designated as a coordinated phase). For non-coordinated phases, most controllers do not have a Rest in Walk setting, but the same principle can be applied: Calculate the longest Walk interval that will not constrain the concurrent vehicular phase, allowing time for the FDW interval.

If the concurrent vehicular phase is pretimed, the formula is given in Equation 7-2:

$$W = \max\left(\left(Split_{veh} - FDW - t_{buffer}\right), W_{min}\right) \tag{7-2}$$

where

W = the length of the Walk interval based on the Rest in Walk principle;
$Split_{veh}$ = the split duration (i.e., green, yellow, and red clearance) for the concurrent vehicle phase;
FDW = the length of the FDW interval;
t_{buffer} = the length of the pedestrian phase end buffer time; and
W_{min} = the minimum interval allowed by policy (typically 7 s).



Source: STM2.

Exhibit 7-5. Rest in Walk and Rest in Don't Walk modes.

If the concurrent vehicular phase is actuated, the formula is given in Equation 7-3:

$$W = \max\left(\left(MinSplit_{veh} - FDW - t_{buffer}\right), W_{min}\right) \tag{7-3}$$

where

$MinSplit_{veh}$ = the minimum split duration (i.e., minimum green, yellow, and red clearance) for the vehicular phase.

For additional discussion on determining the lengths of FDW and the pedestrian phase end buffer, see Section 7.4.

Example 1: Suppose a pretimed vehicular phase has a split of 35 s that consists of a green interval of 30 s, a yellow interval of 4 s, and a red clearance interval of 1 s. Suppose also that the time needed for FDW is 9 s, and the phase end buffer will coincide with the yellow and red clearance intervals and, therefore, last 5 s. By policy, the minimum Walk interval is 7 s. Following the logic of Rest in Walk, the length of the Walk interval should be 35 – 9 – 5 = 21 s.

Example 2: Suppose the same scenario as Example 1, except the vehicular phase is actuated and has a minimum green interval of 18 s and, therefore, a minimum split of 23 s. In that case, the length of the Walk interval should be 23 – 9 – 5 = 9 s.

Adapting minimum green to demand. The minimum green time for actuated vehicular phases is usually short (e.g., many cities use 6 s for turn phases and 10 s for through phases) in order to give the controller freedom as early as possible to end that phase when a gap is detected and switch to the next phase. For the same reason, the Walk interval length for pedestrian phases concurrent with an actuated vehicular phase is usually set at the minimum value (usually 7 s). However, if vehicular demand is such that the phase routinely runs past its minimum green, then minimum green can be increased with little impact. A suggested rule of thumb is to set the minimum green equal to the 30th percentile green time for the relevant period of the day, then adjust the Walk interval based on Equation 7-3. That way, the minimum green and pedestrian settings will constrain the signal cycle for only 30% of the cycles (and those will be cycles that are well below capacity, with a low risk of creating any significant impact on traffic operations).

Example 3: Suppose the same scenario as Example 2, in which the concurrent vehicular phase has a minimum green of 18 s. Suppose traffic demand is high enough during the p.m. peak that the 30th percentile green interval is 25 s long—in 70% of cycles, the vehicular green runs for at least 25 s. One could then increase the minimum green to 25 s with little impact on signal operations and, following Equation 7-3, the Walk interval could be adjusted to 16 s (7 s longer than before).

Example 4: Take the same scenario as Example 3, but suppose traffic demand is high enough during the p.m. peak that the phase runs to maximum green, which is 30 s, in 80% of cycles. That makes the 30th percentile green time equal to 30 s. Increase the minimum green to 30 s (in effect making the phase fixed time) and, following Equation 7-3, adjust the Walk interval to 21 s.

Adaptive Walk intervals. This treatment, proposed by Furth and Halawani (2016), is similar to adapting minimum green to demand, except that minimum green is set dynamically on a cycle-by-cycle basis to the 30th percentile green time of the last seven cycles, with the Walk interval adjusted accordingly on a cycle-by-cycle basis using Equation 7-3. That way, the length of the Walk interval is adjusted at all times to the largest value it can have without significantly constraining the signal cycle.

7.3.1.4 Operating Context

Maximizing the Walk interval could be considered wherever there are concurrent phases and demand on the concurrent vehicular phase is great enough that the phase's length is governed by vehicular needs rather than pedestrian needs.

The variation that applies depends on how the concurrent vehicular phase is configured:

- Coordinated phases: Use the Rest in Walk setting.
- Pretimed phases that are not a designated coordinated phase: Set the length of the Walk interval based on Equation 7-2.
- Actuated phases, including non-coordinated phases at an intersection with coordinated-actuated control and phases at an intersection with fully actuated control: Set the length of the Walk interval based on Equation 7-3, and consider increasing the minimum green either statically (adapting minimum green to demand) or dynamically (adaptive Walk intervals). Note that the strategy of adapting minimum green requires data on the distribution of green time.

7.3.2 Applications and Expected Outcomes

7.3.2.1 National and International Use

Rest in Walk is widely used in connection with coordinated phases. Many U.S. cities use Rest in Walk by policy with coordinated phases in order to maximize pedestrians' allowable walk time and minimize their delay (Kothuri, 2014).

For pretimed and non-coordinated phases, many cities make it a policy to maximize their Walk interval lengths using Equation 7-2 or 7-3. For example, in Cambridge, MA, most signals are pretimed, but cycle length and splits vary across the day. Designers calculate and apply the Walk interval for each period using Equation 7-2. Any time a Walk phase displays solid Don't Walk while the concurrent vehicular phase is still green is considered a signal timing error that must be corrected.

Still, many cities do not routinely apply Rest in Walk or maximize the Walk interval for non-coordinated phases. Often, a default Walk interval length (usually 7 s) is used even where a longer Walk would fit within a vehicular phase's minimum timing. Sometimes signals apply the same Walk interval length for the entire day when, based on Equations 7-2 and 7-3, it could be longer in periods with longer signal cycles.

This failure to lengthen Walk intervals even when it would not affect vehicular operations at all is not due to antipathy on the part of designers toward pedestrians; rather, it is a shortcoming of signal timing software and of signal controller design. Commonly used signal timing software sets Walk intervals to their minimum value by default, rather than applying Equation 7-2 or 7-3; designers often follow the software's recommendation without checking if longer Walk intervals could be used. And most U.S. signal controllers lack a "Rest in Walk" setting for non-coordinated phases. If they had that setting, maximized Walk intervals would automatically be applied, removing the need for engineers to calculate and set Walk interval lengths for each period of the day.

Adaptive Walk intervals require custom programming and have not yet been applied in the U.S. A form of this logic is used in Amsterdam under the name "variable max green" (S. Linders, personal communication, August 1, 2018).

7.3.2.2 Benefits and Impacts

Maximizing the length of the Walk interval reduces pedestrian delay, improves pedestrian compliance, and makes crossings accessible to slower pedestrians, with no discernable impact on vehicular traffic.

A comparison study found the combination of Rest in Walk and pedestrian recall (see Section 7.5) increased compliance by bicycles and pedestrians from 9% to 70% for one comparison pair and from 31% to 79% for another comparison pair (Mirabella, 2013). The findings are consistent with a second study, which found that pedestrians waiting longer times are more likely to cross illegally (Kothuri et al., 2017).

In a simulation study of two intersections, one coordinated-actuated and one fully actuated, adaptive Walk intervals reduced average pedestrian delay by as much as 15 s, with an impact to vehicular traffic of less than 1 s (Furth & Halawani, 2016). Another advantage of adaptive control is that it adjusts to changes in vehicular demand without requiring manual traffic counts.

7.3.3 Considerations

7.3.3.1 Accessibility Considerations

The *Manual on Uniform Traffic Control Devices* (MUTCD, 2009) recommends that where Rest in Walk is applied, the automatic length of the audible Walk interval for APS should be limited to 7 s, while allowing for the audible Walk to restart if the pushbutton is pressed while the visible Walk interval is still timing:

> MUTCD Section 4E.11 [Standard 5]: The accessible walk indication shall have the same duration as the pedestrian walk signal except when the pedestrian signal is in Rest in Walk.
>
> MUTCD Section 4E.11 [Guidance 6]: If the pedestrian signal is in Rest in Walk, the accessible walk indication should be limited to the first 7 seconds of the walk interval. The accessible walk indication should be recalled by a button press during the walk interval provided that the crossing time remaining is greater than the pedestrian change interval.

7.3.3.2 Guidance

Not applicable for this treatment.

7.3.3.3 Relationships to Relevant Treatments

With most controllers, the Rest in Walk setting automatically applies pedestrian recall (see Section 7.5) to coordinated phases.

7.3.3.4 Other Considerations

At intersections with high right-turn volumes and high pedestrian-volumes, it can sometimes be desirable to end the pedestrian phase before the end of the vehicular phase in order to give right-turning traffic a chance to move.

Intersections whose coordinated phase is subject to frequent preemption for emergency vehicles, railroad vehicles, or other priority vehicles are sometimes exempted from Rest in Walk in order to reduce the likelihood of cutting a pedestrian phase before its clearance has fully timed (Virginia Department of Transportation, 2020).

7.3.4 Implementation Support

7.3.4.1 Equipment Needs and Features

Almost all modern traffic signal controllers have a Rest in Walk setting for coordinated phases.

The lack of a Rest in Walk setting for non-coordinated phases is a deficiency that should be addressed. Because this setting is lacking, Walk intervals must be calculated and set for each period of the day, even for pretimed phases. Providing a Rest in Walk option to non-coordinated phases could be very easy. The only needed user input would be a minimum Walk interval length; the controller already has the other settings needed to apply Equations 7-2 and 7-3.

Adaptive Walk intervals are a form of adaptive control requiring custom logic. However, unlike most forms of adaptive control, it does not require any detection; the only needed input is the duration of recent green intervals.

7.3.4.2 Phasing and Timing

An example of phasing and timing for the Rest in Walk feature was provided earlier in Section 7.3.1.

7.3.4.3 Signage and Striping

Not applicable for this treatment.

7.3.4.4 Geometric Elements

Not applicable for this treatment.

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7.4 Pedestrian Clearance Settings for Better Serving Slower Pedestrians

7.4.1 Basic Description

7.4.1.1 Alternative Names

None.

7.4.1.2 Description and Objective

The objective of this treatment is to go beyond minimum pedestrian clearance standards and maximize a crossing's accessibility to slower pedestrians. Additionally, another objective is to maximize efficiency by avoiding unnecessarily lengthening vehicular phases or otherwise interfering with the signal cycle. It involves the following settings and policies:

- Length of the effective phase end buffer, abbreviated as "effBuffer," a new concept representing the part of the pedestrian phase end buffer that pedestrians can rely on to finish crossings in comfort;
- Pedestrian clearance speeds and the performance measure "lowest pedestrian speed designed";
- Whether a concurrent vehicular yellow can begin while the FDW interval is still timing; and
- Whether concurrent vehicular yellow and red clearance intervals count toward needed pedestrian clearance time.

Effective phase end buffer. The MUTCD (2009) states that the pedestrian phase end buffer (i.e., the time from the end of FDW, which is also the start of solid Don't Walk, until conflicting traffic is released) should be at least 3 s. No maximum is specified; in practice, phase end buffers can last 10 s or longer. From experience, pedestrians know that when FDW ends—which is also when the countdown reaches zero—they have a few more seconds to finish crossing; however, they cannot be expected to know how many more seconds they have at any particular crossing. The effective phase end buffer is defined as the portion of the pedestrian phase end buffer that pedestrians can reasonably rely on to finish their crossing in comfort, and it can therefore count against needed clearance time. This guidebook proposes that the effBuffer be limited to 3 or 4 s—it should be 4 s in cities or regions where pedestrian phase end buffers are almost never shorter than 4 s and 3 s elsewhere.

Pedestrian clearance speeds and the performance measure "lowest pedestrian speed designed." For many years, pedestrian signals were timed using a clearance speed of 4.0 feet per second (ft/s). However, research by Fitzpatrick et al. (2006) found that roughly 20% of young pedestrians and 40% of older pedestrians did not walk this fast (see Exhibit 7-6). Consequently, the MUTCD adopted two lower pedestrian clearance speeds: a primary clearance speed of 3.5 ft/s for pedestrians who begin crossing up to the last moment of the Walk interval, plus a secondary clearance speed of 3.0 ft/s for slower pedestrians who, aware of their limitation, begin crossing only at the onset of the Walk interval.

Primary pedestrian clearance time needed is provided in Equation 7-4:

$$t_{cl,needed} = \frac{D}{s_p} \tag{7-4}$$

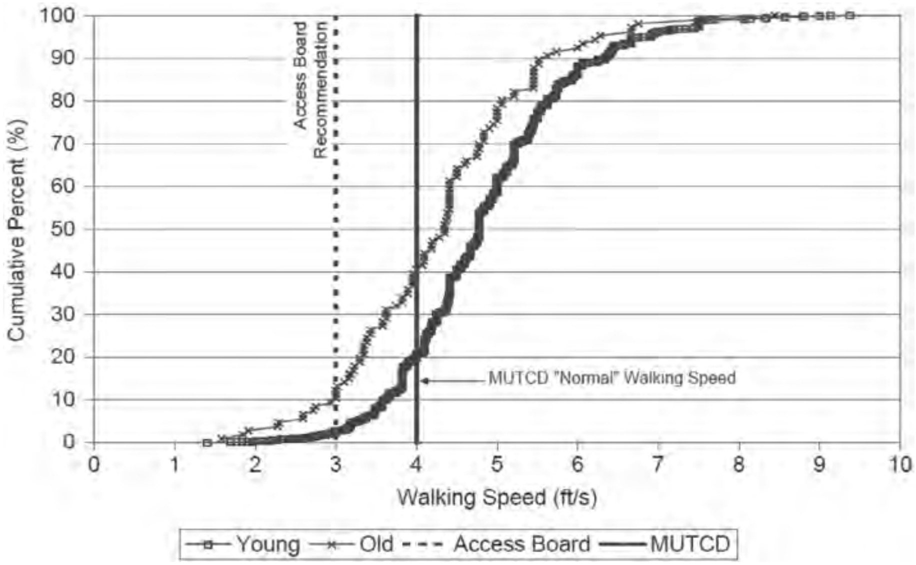

FIGURE 1 Older than 60 (old) and 60 and younger (young) walking speed distribution.

Note: Since publication of this figure, the MUTCD "normal" walking speed has changed to 3.5 ft/s.

Source: Fitzpatrick et al. (2006).

Exhibit 7-6. Walking speed distribution for young (60 years and under) and old (older than 60 years) crossing pedestrians.

where

$t_{cl,needed}$ = primary pedestrian clearance time needed (s);
D = crosswalk length, curb to curb (ft); and
s_p = primary pedestrian clearance speed (ft/s).

For any specified clearance speed, there will still be pedestrians who walk slower. About 8% of younger adults and 26% of older people walk slower than 3.5 ft/s, and about 2% of younger adults and 9% of older people walk slower than 3.0 ft/s. In addition, many children are unable to cross at those clearance speeds. Accommodating slower crossers is an important objective to prevent intersections from becoming barriers to mobility. A performance measure for this aspect of a signalized crossing's accessibility is the lowest pedestrian speed designed, given by Equation 7-5:

$$v_{pa} = max\left(\frac{D}{t_{p,eff} - 2}, \frac{D + D_{pb}}{t_{p,eff}}\right) \tag{7-5}$$

where

v_{pa} = lowest pedestrian speed designed (ft/s);
D = crosswalk length, curb to curb (ft);
D_{pb} = distance from the pushbutton to the departure curb (ft); and
$t_{p,eff}$ = effective pedestrian phase length (s).

Effective pedestrian phase length is given by Equation 7-6:

$$t_{p,eff} = W + FDW + effBuffer \tag{7-6}$$

where

W = length of the Walk interval (s);
FDW = length of the FDW interval (s); and
$effBuffer$ = length of the effective phase end buffer (s).

In Equation 7-5, the first term ensures sufficient time for a pedestrian waiting at the curb and departing within 2 s of the onset of Walk; the second term ensures sufficient time for a pedestrian waiting at the pushbutton and departing at the onset of Walk.

In addition to using v_{pa} as a performance measure, agencies can also specify a target value for v_{pa} and make that target value the secondary clearance speed used to design pedestrian intervals. If design based on the primary speed does not satisfy the secondary clearance requirement, the Walk interval (not the FDW interval) should be lengthened until it is satisfied. The MUTCD (2009) clearance requirement involving a 3.0 ft/s walking speed is roughly the same as specifying a target for v_{pa} of 3.0 ft/s; however, the MUTCD calculation does not limit how much of the pedestrian phase end buffer can count against the needed crossing time. Where the pedestrian pushbutton is closer than 6 ft from the curb, it does not guarantee 2 s for pedestrians to begin their crossing.

The MUTCD advises that where the crossing population includes many older adults, young children, or others with low walking speeds, a slower primary clearance speed might be considered. Accordingly, many cities use a primary clearance speed of 3.0 ft/s at crossings near schools and older adult centers, and some apply it in large areas of the city or even citywide. At the same time, cities should consider establishing a slower secondary clearance speed, or, at a minimum, report the accessibility measure v_{pa} to show how the needs of pedestrians who cannot attain the primary clearance speed are identified and designed for as well.

Example 1: Suppose a crosswalk is 105 ft long, and primary and secondary clearance speeds are 3.5 and 3.0 ft/s, respectively. Primary clearance time needed (Equation 7-4) is 30 s. Suppose pedestrian timing is 4 s of Walk, 26 s of FDW, and 4 s of effective phase end buffer. If the pushbutton is 5 ft from the curb and Equation 7-5 is applied, then $v_{pa} = 3.24$ ft/s, which does not meet the secondary clearance target of 3.0 ft/s. If the Walk interval is lengthened to 7 s, v_{pa} falls to 2.97 ft/s, and the secondary clearance target is met.

Example 2: Suppose a crosswalk length is 60 ft and there is no pushbutton. Many pedestrians in the area are older adults, so the primary clearance speed is 3.0 ft/s, resulting in a primary clearance need of 20 s. Suppose the pedestrian timing is 7 s of Walk, 16 s of FDW, and 4 s of pedestrian phase end buffer. There is no explicit secondary clearance objective, but citizens would like to know whether people unable to walk 3.0 ft/s will also be accounted for in the timings. If Equation 7-5 is applied, $v_{pa} = 2.22$ ft/s.

Whether a concurrent vehicular yellow can begin while the FDW interval is still timing and whether concurrent vehicular yellow and red clearance intervals can count toward needed pedestrian clearance time. The MUTCD is clear that both of these options are allowed; with them, pedestrian clearance and vehicular timing needs can both be met with the least impact on cycle length and/or the best service to pedestrians for a given cycle length. However, state and local policies sometimes restrict these options.

Some agencies make it a policy that vehicular yellow may not begin until FDW ends. This restriction takes away designers' control over the length of the pedestrian phase end buffer. Yellow times typically range from 3 to 5 s and red clearance times range from 0 to 4 s, which can result in pedestrian phase end buffers of up to 9 s. Because no more than 4 s of the phase end buffer can realistically be counted against pedestrian clearance needs, the best balance of service and efficiency results when pedestrian phase end buffers are uniform, lasting 3 or 4 s. That way, pedestrians will know what to expect when the FDW interval and countdown end. It also avoids the inefficiency of a long phase end buffer that does not improve pedestrian service yet constrains the signal cycle, with negative impacts to pedestrians and others.

Likewise, some agencies do not allow yellow or red clearance times to count toward needed pedestrian clearance time, which forces the FDW to be longer. This restriction is similar to lowering the pedestrian clearance speed in that it gives pedestrians more time to cross; however, unlike lowering clearance speed, this restriction adds time to the end of the phase that cannot be counted on to serve pedestrians.

7.4.1.3 Variations

There are no variations to this treatment.

7.4.1.4 Operating Context

This treatment is applicable at every signalized crossing.

7.4.2 Applications and Expected Outcomes

7.4.2.1 National and International Use

The MUTCD has established a national primary pedestrian clearance speed of 3.5 ft/s. Many cities have also followed its suggestion of using 3.0 ft/s where crossings have a lot of children or older adults. In the last few years, NYC DOT has classified nearly the entire city as a "senior zone," and as signals are retimed, it is converting crossings to a primary clearance speed of 3.0 ft/s. At the same time, the city has avoided significant traffic impact by allowing the vehicular yellow time (which in New York typically lasts 3 s) to count toward needed pedestrian clearance.

The MUTCD has also established a national secondary clearance speed of 3.0 ft/s. Cities that have chosen to use 3.0 ft/s as the primary clearance speed have not usually specified a lower secondary clearance speed.

Many U.S. agencies allow yellow time to count toward pedestrian clearance need, consistent with MUTCD guidance; however, many do not. There are also several agencies that, by policy, do not let FDW overlap with the yellow interval. One reason for this restriction is a common limitation of countdown devices: They often can be configured with a zero point at the onset of yellow or at the end of yellow but not in between (see Section 8.1). The combination of this limitation with the requirement that FDW must end when the timer reaches zero effectively forces the FDW interval to end with the start of yellow, unless vehicular red clearance time is at least 3 s or a pedestrian phase overlaps an LPI (see Section 6.7).

In Europe, pedestrian phases are structured differently than in the U.S., with a solid green man period, a flashing green man period in which people may still begin to cross but slow pedestrians are advised not to begin, and then a solid red man clearance time during which conflicting traffic is held (and which continues once traffic is released). These two green intervals together are comparable to our Walk interval, and the pedestrian clearance interval is comparable to our combined FDW interval and phase end buffer.

In the Netherlands, primary pedestrian clearance speed (for those who might begin through the last moment of the flashing green man interval) is 1.2 m/s (3.9 ft/s); secondary clearance speed (for those who start only during the solid green man interval) is 1.0 m/s (3.3 ft/s). The minimum length of the solid green man interval is 4 s; with this requirement, pedestrians who depart within the first 2 s of the pedestrian phase can cross at 3.0 ft/s as long as the crossing is no longer than 70 ft, a length that is rarely exceeded.

7.4.2.2 Benefits and Impacts

Lower pedestrian clearance speeds give pedestrians more time to cross, making crossings accessible to more people but also making the pedestrian phase longer, which can have negative impacts on vehicle capacity as well as on pedestrians. Most prominently, they sometimes force the signal cycle to be longer, which can increase pedestrian delay (see Section 7.1) and make it less feasible for pedestrian phases to be on recall (see Section 7.5).

The two restrictions discussed as part of this treatment—not allowing vehicular yellow to begin until FDW has finished timing and not allowing vehicular yellow and red clearance times to count toward needed pedestrian clearance—have an effect similar to lowering clearance speed. However, they are less efficient because they can result in time at the end of the phase that cannot be counted on to serve pedestrians.

To illustrate, consider a crosswalk that is 70 ft long and has a primary pedestrian clearance speed of 3.5 ft/s, resulting in a needed clearance time of 20 s; with a specified Walk window of 7 s, the time needed to serve pedestrians is 27 s. The concurrent vehicular phase has little traffic; its yellow time is 4 s and red clearance is 2 s. The two potential restrictions create four timing alternatives, with impacts shown in Exhibit 7-7 and summarized as follows:

A. With both restrictions in place, the vehicular change interval (yellow, red clearance) does not begin until the pedestrian phase has completely cleared, resulting in a phase length of 33 s; this is 6 s more than needed to satisfy pedestrian timing objectives directly. Pedestrians benefit from some of that extra time in that a lower crossing speed is adequate. However, they do not benefit from the last 2 s.
B. Letting the yellow begin while FDW is still timing lowers the phase length to 31 s. The unproductive final 2 s of Alternative A are eliminated, with no loss to pedestrian service.
C. Letting 4 s of the pedestrian phase end buffer count toward pedestrian clearance needs shortens FDW by 4 s, and phase length falls to 29 s. The lowest pedestrian speed designed for rises, but it still meets the performance target. Once again, the final 2 s of the phase are of no benefit to pedestrians.
D. Relaxing both restrictions allows the phase length to be 27 s, which is what would have normally been calculated as the time needed to serve pedestrians. It yields the same pedestrian performance as Alternative C but with less impact on the signal cycle. This alternative can be seen as first setting the pedestrian signals based on pedestrian needs and then fitting the vehicular signals around that schedule without further constraining the cycle.

Alternative C, the second-most efficient, is one that agencies may not have considered before now, as guidance documents have not addressed the idea of allowing the early part, but not the latter part, of the pedestrian phase end buffer to count toward needed pedestrian clearance. This alternative is compatible with countdown devices and can be implemented with nothing more than adjusting the FDW setting.

To illustrate impacts when the concurrent vehicular phase is pretimed or coordinated, results for the same example are shown in Exhibit 7-8, with the phase length fixed at 36 s and

Exhibit 7-7. Alternative pedestrian timings for a crossing 70 ft long, with phase timing dominated by pedestrian timing needs.

Alternative	A	B	C	D
Yellow begins while FDW is still timing?	No	Yes	No	Yes
Phase end buffer (up to 4 s) counts toward needed clearance?	No	No	Yes	Yes
Walk interval duration (s)	7	7	7	7
FDW (s)	20	20	16	16
Phase end buffer duration (s)	6	4	6	4
Overall phase duration (s)	33	31	29	27
Lowest pedestrian speed designed, v_{pa} (ft/s)	2.41	2.41	2.80	2.80

Exhibit 7-8. Alternative pedestrian timings for a crossing 70 ft long, with fixed phase length.

Alternative	A	B	C	D
Yellow begins while FDW is still timing?	No	Yes	No	Yes
Phase end buffer (up to 4 s) counts toward needed clearance?	No	No	Yes	Yes
Walk interval duration (s)	10	12	14	16
FDW (s)	20	20	16	16
Phase end buffer duration (s)	6	4	6	4
Overall phase duration (s)	36	36	36	36
Lowest pedestrian speed designed, v_{pa} (ft/s)	2.19	2.06	2.19	2.06

the cycle length at 90 s. As restrictions are relaxed, the Walk interval increases in length from 10 to 16 s, with corresponding reductions in pedestrian delay. For Alternatives B and D, which allow the yellow to begin while FDW is still timing, the lowest pedestrian speed designed is reduced as well.

7.4.3 Considerations

7.4.3.1 Accessibility Considerations

Lower pedestrian design speeds help make crossings accessible to pedestrians with low walking speeds, including older adults and children.

Reporting "lowest pedestrian speed accommodated" as a performance measure can help ensure that signal timing is responsive to the needs of slower pedestrians and can reassure citizens that crossings support people who are unable to walk at the primary clearance speed.

7.4.3.2 Guidance

Not applicable for this treatment.

7.4.3.3 Relationships to Relevant Treatments

Efficient pedestrian clearance settings can enable short cycle lengths (see Section 7.1) and can help maximize Walk interval length (see Section 7.3).

7.4.4 Implementation Support

7.4.4.1 Equipment Needs and Features

While most controllers allow FDW to time during the yellow interval, many countdown devices will not extend partway into a yellow phase—they can be set with a zero point at the start of yellow or the end of yellow but not in between (see Section 8.1). Since countdown timers need to end simultaneously with FDW, this limitation can prevent FDW from ending partway through the yellow, which can have impacts on accessibility, pedestrian delay, and cycle length, as discussed earlier. This limitation is something that countdown device manufacturers should be able to correct.

7.4.4.2 Phasing and Timing

Not applicable for this treatment.

7.4.4.3 Signage and Striping

Not applicable for this treatment.

7.4.4.4 Geometric Elements

Shorter crossings, which might be designed using corner bulb-outs, require less clearance time, making signals more efficient and improving accessibility.

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7.5 Pedestrian Recall versus Actuation

7.5.1 Basic Description

7.5.1.1 Alternative Names

Pedestrian call modes.

7.5.1.2 Description and Objective

At signalized intersections with either fully actuated or coordinated-actuated control, pedestrian phases can be pushbutton actuated or configured on pedestrian recall. With pedestrian actuation, the pedestrian phase is omitted from a cycle unless a pedestrian manually places a call; with pedestrian recall, a call for pedestrian service is placed automatically every cycle. Recall is more convenient and moderately reduces delay because pedestrians arriving during the time scheduled for the Walk interval will be served immediately, whereas with pushbutton actuation, the pedestrian phase will have been skipped unless another pedestrian arrived earlier and pushed the button. Actuation is more efficient for signal operations only if pedestrian demand is low (because with high pedestrian-demand the pedestrian phase will usually be called anyway) and if vehicle demand on the concurrent phase is low enough that, absent a pedestrian call, the phase's green time is not usually long enough to fit a pedestrian phase.

7.5.1.3 Variations

Not applicable for this treatment.

7.5.1.4 Operating Context

Where signals are pretimed, pedestrian phases should be on recall. Pushbuttons may be provided for accessibility, but they should not be needed to call for service (see Section 8.4).

Where signals are coordinated-actuated, Exhibit 7-9 provides suggested guidance, developed for agencies based on the research conducted for this guidebook, to determine whether pedestrian signals should be actuated. The guidance was developed with the aim of balancing pedestrian delay with operations efficiency for vehicles. Pedestrian recall should be considered when

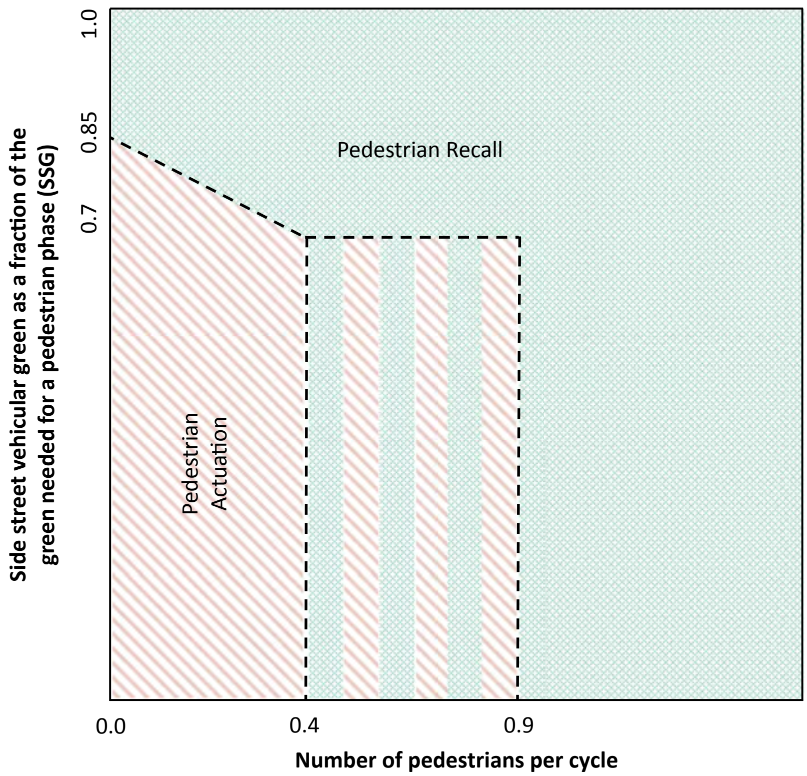

Exhibit 7-9. Criteria for pedestrian recall versus pedestrian actuation with coordinated-actuated control.

pedestrian demand is large enough that there is a call for service in most cycles, as seen on the horizontal axis with total number of pedestrians (for both pedestrian crossings, unless cross streets are on split phase) per cycle. The guidance also considers when the vehicular green on the concurrent vehicle phase is long enough in most cycles that a pedestrian phase would fit without unduly extending the cycle length (as seen on the vertical axis). The second condition—regardless of pedestrian demand—almost always applies to the coordinated phase, which is why coordinated phases should usually have pedestrian recall. This condition also applies to non-coordinated phases with high vehicle demand.

Finally, where signals are fully actuated, pedestrian actuation is the better choice in most cases because it leads to shorter signal cycles, which reduces delay for pedestrians as well as vehicles. The only case for which pedestrian recall might be appropriate is when a vehicular phase's average green is long enough, or its minimum green is nearly long enough, to fit a pedestrian phase.

7.5.2 Applications and Expected Outcomes

7.5.2.1 National and International Use

Pedestrian recall is always used where signals follow pretimed operation, which is common in areas with high pedestrian-traffic, including most downtowns.

Outside of downtowns, the most common control type is coordinated-actuated. In many cities, by policy, the coordinated phase (typically the major street) always has pedestrian recall. However, in many cases the pedestrian phase is still actuated, even when the guaranteed phase length for the coordinated phase is more than enough to fit a pedestrian phase. Crossings associated with a non-coordinated phase are usually actuated, but they may be set to recall where pedestrian demand is high. For example, Boston's policy is to apply pedestrian recall for a crossing if pedestrians are present for at least 50% of the cycles (City of Boston, 2013). When a side street is set to pedestrian recall, a signal's operation usually becomes almost pretimed with coordinated-actuated operation; the only demand-actuated phases are the left-turn phases.

7.5.2.2 Benefits and Impacts

Where the cycle length is fixed—as with coordinated-actuated control—pedestrian recall reduces pedestrian delay (see Section 3.4, which cites an example in which average pedestrian delay is 10 s greater with actuation than with recall). Lower delay improves pedestrian safety because it tends to improve pedestrian compliance (Otis & Machemehl, 1999; Van Houten et al., 2007). In addition, with pedestrian actuation, pedestrians who are not first to arrive at a corner may not push the button, thinking that it has already been pushed, especially if there is not a prominent call indicator. In that case, if the concurrent vehicular phase receives a green display, there is a risk for pedestrians to cross without the protection of the pedestrian signal, which may leave them partway through their crossing when a conflicting movement is released. Pedestrian recall eliminates this type of conflict and therefore improves safety.

For a coordinated phase whose minimum green is long enough to fit a pedestrian phase, there is no delay impact to traffic from having pedestrian recall on the crossing associated with that phase.

For non-coordinated phases, pedestrian recall forces the non-coordinated phase to run long enough for the pedestrian phase, which usually constrains the signal cycle and can increase vehicle delay. The impact of pedestrian recall depends on two factors, the first of which is pedestrian demand. If pedestrian demand is low, recall will constrain most cycles. If demand is high, however, the pedestrian cycle will be called in almost every cycle anyway, in which case recall will have little impact on vehicles. One study conducted using microsimulation recommended that pedestrian signals for side street pedestrians be on recall when there are pedestrian calls in 70% or more of the cycles in a time period and actuated otherwise (Kothuri, 2014).

The other relevant factor is traffic volume on the concurrent vehicle phase. If that volume is low, the phase would have a very short green time unless there was a pedestrian call. However, if it is high then the green time would be long (perhaps long enough to fit a pedestrian phase in most cycles), in which case pedestrian recall would have little or no impact. Historically, this factor has rarely been given due attention in discussions about pedestrian recall versus actuation.

In production of this guidebook, research was conducted using microsimulation of a corridor in Virginia to measure how the impact of pedestrian recall versus actuation varies with both pedestrian demand and concurrent vehicular demand. As expected, it was found that delay to vehicles from a pedestrian recall setting is greatest when pedestrian volume is low; but once pedestrian volume was so great that there was a pedestrian call in most cycles, that delay impact became negligibly small. Likewise, delay to vehicles due to recall was also greatest when the side street volume was very low; but when side street volume increased such that the average side street green time was at least 75% of the green time needed to fit a pedestrian phase, that delay impact became negligible regardless of the pedestrian demand. This research was the basis for the decision rule given earlier in Exhibit 7-9.

7.5.3 Considerations

7.5.3.1 Accessibility Considerations

If a pedestrian phase is on recall then pushbuttons are not needed to call for service, but they can still play a valuable role in making a traffic signal accessible (for more detail, see Section 8.4).

7.5.3.2 Guidance

The NACTO *Urban Street Design Guide* recommends using pretimed signals in urban areas, which results in pedestrian phases being on recall. STM2 indicates that pedestrian recall may be used at locations and/or times with high pedestrian-volumes. Some cities have developed their own guidelines regarding pedestrian recall. For example, Boston recommends pedestrian recall where pedestrians are present for at least 50% of the cycles during peak hours (City of Boston, 2013).

7.5.3.3 Relationships to Relevant Treatments

At intersections with fully actuated control, pedestrian actuation helps contribute to short signal cycles (see Section 7.1).

7.5.3.4 Other Considerations

Not applicable to this treatment.

7.5.4 Implementation Support

7.5.4.1 Equipment Needs and Features

Pedestrian actuation requires pushbuttons, which should be mounted for accessibility and convenience (see Section 8.3).

7.5.4.2 Phasing and Timing

Crossings can be set for recall for certain periods of the day and for pedestrian actuation in other periods. With this strategy, call indicators (see Section 8.2) that activate whenever a call has been registered in the current cycle, whether from the pushbutton or automatically, are helpful for informing arriving pedestrians as to whether they need to push the button for service.

When pedestrian phases are actuated, signal cycles are usually designed assuming the pedestrian phase will be served. In operation, when the pedestrian phase is not called, the concurrent vehicular phase ends earlier than scheduled and yields its remaining time to other phases. Where pedestrian demand is low, another option is to design the signal cycle without reserving time for the pedestrian phase, which can allow the overall cycle length to be lower. In operation, when there is a pedestrian call, the concurrent phase runs longer than scheduled, making the next coordinated phase begin late and getting the intersection out of coordination; further control logic is then invoked to recover over the next cycle or two. This way of timing signals can reduce delay for pedestrians as well as vehicles because of the lower cycle length.

7.5.4.3 Signage and Striping

Not applicable for this treatment.

7.5.4.4 Geometric Elements

Not applicable for this treatment.

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7.6 Pedestrian Hybrid Beacons

7.6.1 Basic Description

7.6.1.1 Alternative Names

HAWK (high-intensity activated crosswalk) signal.

7.6.1.2 Description and Objective

Pedestrian hybrid beacons (PHBs) provide pedestrians with a protected crosswalk without installing a full traffic signal. They include red and yellow aspects but no green aspect, and by default, the beacon is dark. When activated through pedestrian actuation, the yellow light (first flashing, then solid) warns motorists to stop; then a red light is displayed during which pedestrians get a Walk signal (see Exhibit 7-10); then there is a clearance period involving a flashing red (to autos) and first FDW and then solid Don't Walk for a few seconds (to pedestrians, as the pedestrian phase end buffer); and afterward the PHB becomes dark again. Exhibit 7-11 shows a PHB's display sequence.

7.6.1.3 Variations

Not applicable for this treatment.

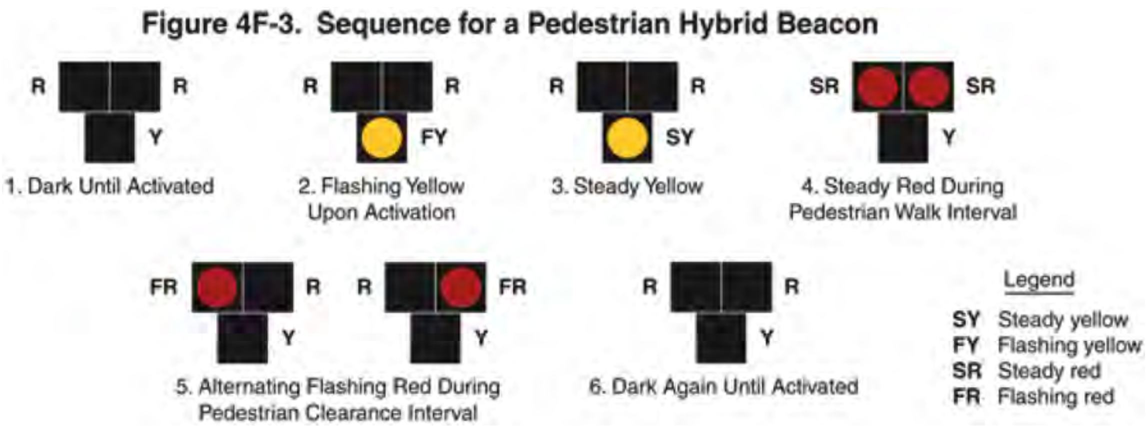
7.6.1.4 Operating Context

PHBs can be applied at unsignalized intersections, midblock crossing locations, and roundabout crossings. At intersections, they are used to protect pedestrians crossing the major street (i.e., the street that is not under Stop or Yield control), with beacons facing the major street approaches. PHBs are often used at intersections whose minor-street demand is too low to warrant a traffic signal, but a safe pedestrian crossing is needed and cannot be achieved with less restrictive measures. PHBs are best suited for:

- Multilane crossings (e.g., four lanes or more), particularly those lacking a median refuge island;

Source: NACTO.

Exhibit 7-10. PHB in Portland providing a protected crossing.



Source: MUTCD (2009), Figure 4F-3.

Exhibit 7-11. Phase sequences for PHBs.

- Crossings of high speed (e.g., 35 mph or more) and high-volume two-lane roadways;
- Locations where local-street bicycle routes (also called bicycle boulevards and neighborhood greenways) cross arterials. PHBs have also been favored at these locations over regular traffic signals because of neighborhood concerns that regular traffic signals might increase traffic on the minor street—typically, bicycles need to use pushbuttons for actuation;
- Bus stops that lack a safe crossing;
- Crossing locations deemed high-risk areas (e.g., schools, shopping centers); and
- Crossings with a large number of vulnerable users (e.g., children, elderly, or disabled).

PHBs can be coordinated with adjacent signalized intersections, or they can operate in isolation. With isolated operation, pedestrians get almost instantaneous service (except for the need to guarantee a minimum "dark" time for mainline between two successive activations), resulting in near-zero delay for pedestrians. Where PHBs are coordinated with adjacent signalized intersections, there is a fixed window for pedestrians each cycle to receive a Walk indication in order to maintain coordination for vehicles. This typically results in longer pedestrian delay.

7.6.2 Applications and Expected Outcomes

7.6.2.1 National and International Use

PHBs were first installed in the 1990s in Arizona as an adaptation of the British "pelican" pedestrian signal. To date, PHBs can be found across America, with the vast majority at intersections. According to a 2019 study conducted by DeLorenzo et al., 41 states have installed PHB devices, seven additional states allow installation of PHBs but have none installed, and one state—Pennsylvania—prohibits PHB installation. (West Virginia did not provide a response in the study.) (DeLorenzo et al., 2019). The lack of PHB implementation for some states is due to concerns with motor vehicle codes that require drivers to stop at dark signals. The same study found that 39 states currently have laws on dark signals, and the other five states require approaching vehicles to proceed with caution. FHWA is careful to call PHBs "beacons" and not "traffic signals."

Some PHBs involve a two-stage crossing, with a separate PHB controlling either side of a divided roadway.

7.6.2.2 Benefits and Impacts

Studies of PHBs generally show decreased crash rates, both for total crashes and pedestrian-related crashes, after an unsignalized crossing was converted to a PHB. A before-and-after study of 21 PHBs in Tucson, AZ, found that total crash rate and pedestrian crash rate were reduced by 35% and 86%, respectively. During the same before-and-after analysis, a control group of 36 signalized intersections saw a 16% reduction in both total crashes and pedestrian-related crashes, and a control group of 102 unsignalized intersections saw a 9% reduction in total crash rate and a 143% increase in pedestrian crash rate, indicating the effectiveness of PHBs in improving pedestrian safety, especially compared to unsignalized crossings (Fitzpatrick & Park, 2010). A study of PHBs with advanced yield or stop markings or signs from 27 sites resulted in a crash modification factor of 0.244 for pedestrian crashes and 0.82 for all crashes compared to unsignalized crossings (Zegeer et al., 2017).

Studies have generally found that the motorist yielding rate at PHBs is only a bit lower than yielding rates at full traffic signals. A study of PHBs at midblock crossings in Lawrence, Kansas, showed a driver-yielding rate ranging from 90% to 95% at PHBs compared to 99% at signalized, midblock crossings (Godavarthy, 2010). A study of 20 PHBs in Arizona and Texas, most of them at intersections, found a yielding rate of 96% (Fitzpatrick & Pratt, 2016).

The same research of PHBs in Arizona and Texas by Fitzpatrick and Pratt indicated that some drivers may not understand all the signal phases. In particular, 5% of drivers stopped and remained stopped during the flashing red phase, not realizing that they may advance after stopping during the flashing red. The study found that only 7% of pedestrians crossed the roadway during the dark indication (Fitzpatrick & Pratt, 2016).

With respect to the impact on drivers, the analysis of two PHB sites found significantly less unnecessary delay compared to a signalized midblock crossing (Godavarthy, 2010). "Unnecessary delay" was defined as time during which the driver was required to stop at the crossing but no pedestrian was present.

PHBs with APS installed at a roundabout to increase accessibility and safety for pedestrians with vision disabilities resulted in an intervention rate (i.e., frequency of someone who is visually impaired stepping out and needing to be stopped to prevent collision) of 0% compared to interventions of 2.4% to 2.8% on two-lane roundabouts with similar crossings without PHB. The intervention rate was 0.8% to 1.4% on single-lane roundabouts without PHB (Schroeder et al., 2011).

The time between pedestrian actuation and the Walk interval given to pedestrians should be carefully considered and minimized. Excessive delay can result in noncompliance by pedestrians, which may result in noncompliance by drivers who arrive at a solid red indication without pedestrians preparing to cross. PHBs that are in isolated operation typically result in very low pedestrian delay because the Walk interval is provided almost instantaneously. Even on coordinated arterials, if the distance to the nearest coordinated signal is large enough to prevent queue spillbacks, PHBs can be configured in isolated mode to reduce pedestrian delay without causing undue delay for vehicles. Where a PHB is operating in coordinated mode on a coordinated arterial with a long cycle length, double cycling can reduce pedestrian delay and increase compliance (see Section 7.2) and will likely have little delay impact on the arterial.

7.6.3 Considerations

7.6.3.1 Accessibility Considerations

Pedestrians who are visually impaired or have low vision tend to initiate crossing when they hear the perpendicular traffic stop and the traffic parallel to the crossing start to move. Since traffic parallel to a PHB crosswalk is not signalized, pedestrians will not hear the expected sound of the parallel traffic. Therefore, it is important to include APS that audibly communicate the pedestrian signal indications.

The MUTCD's recommendations on pedestrian pushbutton location should be followed. Detectable warning surfaces and ADA-accessible curb ramps that apply at signalized crossings apply equally with PHBs.

PHBs are recommended by *NCHRP Research Report 834: Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities: A Guidebook* as one solution to provide access for pedestrians with vision disabilities at multilane roundabout crosswalks (Schroeder et al., 2017).

7.6.3.2 Guidance

MUTCD, Chapter 4F (2009) provides guidance for the application, design, and operation of PHBs. The guidelines provided are based on pedestrian hourly volumes, vehicle hourly volumes, vehicle speed, and the length of the crosswalk.

7.6.3.3 Relationships to Relevant Treatments

Pedestrian countdown (see Section 8.1), call indicators (see Section 8.2), and independently mounted pushbuttons (see Section 8.3) are helpful at PHBs, just as at signalized crossings.

7.6.3.4 Other Considerations

Not applicable for this treatment.

7.6.4 Implementation Support

7.6.4.1 Equipment Needs and Features

PHB installations include a face with two circular red signal indications located side by side, with a circular yellow indication centered below. A second beacon face is either mounted overhead or on the other side of the street. A pair of beacons should be installed for each approach of the major street.

A pedestrian signal head and detection equipment are also needed on both ends of the crosswalk. The detection equipment can be independently mounted or mounted on the pole used to support the beacons, if appropriately located for pedestrian access. If a median is present and two-stage crossing is implemented, an additional pair of pedestrian signal heads and detection equipment are necessary for the median.

7.6.4.2 Phasing and Timing

The display sequence for PHBs is shown in Exhibit 7-11. During Interval 5, also known as the pedestrian clearance interval, the pedestrian display shows FDW for most of the interval, then Don't Walk for the final 3 s as a pedestrian phase end buffer. When the beacon is inactive, the pedestrian indication rests in solid Don't Walk.

The duration of the solid yellow indication can be calculated using the typical procedure for a vehicular change interval. The pedestrian Walk, FDW, and pedestrian phase end buffer should be timed as detailed in Sections 4.2 and 7.4.

7.6.4.3 Signage and Striping

The MUTCD (2009) requires that a crosswalk and stop lines be installed in conjunction with the PHB. Additionally, a Crosswalk Stop on Red sign (R10-23) must also be mounted. Some PHB installations include an educational plaque mounted near the pedestrian detection.

Some PHBs across the country are installed with advanced yield or stop markings and signs. The use of advanced markings increases the distance between the crosswalk and yielding vehicles.

This helps prevent vehicles in one lane from screening pedestrians from drivers in other lanes during the flashing red interval, in which vehicles are allowed to advance.

7.6.4.4 Geometric Elements

Not applicable for this treatment.

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CHAPTER 8

Treatments Offering Added Information and Convenience

This chapter describes treatments aimed at providing pedestrians with information to reduce traveler stress and uncertainty, as well as treatments aimed at improving the physical convenience of crossing a street:

Primary Function	Section	Treatment Name
Information	8.1	Pedestrian Countdown
	8.2	Call Indicators
Convenience and information	8.3	Independently Mounted Pushbuttons
	8.4	Accessible Signals without Pushbutton Actuation

Pedestrian Countdown (Section 8.1). Pedestrian countdowns have become mainstream within the last decade, though they are still not employed everywhere. Section 8.1 discusses, among other things, the practice followed by at least one American city to run the countdown during the Walk interval as well as during FDW, thus providing more information—and more certainty—to crossing pedestrians.

Call Indicators (Section 8.2). This treatment describes call indicators, lights that come on when a call is registered. They can be used with pushbuttons for pedestrians and with passive detection using inductive loops for bicycles. In both cases, the waiting pedestrian or cyclist is reassured that a call has been registered, leading to less stress and greater compliance.

Independently Mounted Pushbuttons (Section 8.3). This section defines independently mounted pushbuttons as mounted on their own pole rather than on a pole supporting other traffic signal equipment. That way, pushbuttons for the two crosswalks that typically meet at a corner can be ideally situated to improve pedestrians' convenience and make it unambiguous as to which pushbutton goes with which crossing. Situating pushbuttons to avoid ambiguity is particularly important for visually impaired pedestrians who rely on audible signals—typically housed in pushbutton units—to know when it is safe to cross.

Accessible Signals without Pushbutton Actuation (Section 8.4). This treatment covers pedestrian signals that provide audible and tactile signals for a pedestrian phase on recall, without creating the expectation that pedestrians must push a button in order to be served. In today's market, accessible signal functions are typically packaged within pushbutton units, creating confusion as to whether pedestrian recall is compatible with accessibility and creating a challenge for how to provide accessibility without misleading pedestrians.

8.1 Pedestrian Countdown

8.1.1 Basic Description

8.1.1.1 Alternative Names

None.

8.1.1.2 Description and Objective

Pedestrian countdowns display the number of seconds remaining until the end of the Flashing Don't Walk (FDW) interval. The countdown typically starts at the beginning of FDW, called the "pedestrian clearance interval" in the *Manual on Uniform Traffic Control Devices* (MUTCD, 2009). Providing this information aims to improve pedestrian compliance and safety and to make the crossing experience less stressful.

8.1.1.3 Variations

While the MUTCD says that the countdown should begin with FDW, some locations begin the countdown at the beginning of the Walk interval.

8.1.1.4 Operating Context

According to the MUTCD, Section 4E.07, all pedestrian signals must have a countdown display if their FDW interval (called "pedestrian change interval" in the MUTCD) is longer than 7 s. There is no prohibition on countdowns that run for 7 s or less. This rule, which took effect with the 2009 edition of the MUTCD, applies to any signal that is new or substantially modified.

8.1.2 Applications and Expected Outcomes

8.1.2.1 National and International Use

The use of pedestrian countdowns is widespread throughout the United States.

At many intersections in Washington, DC, and a few locations elsewhere in the U.S., the countdown runs during the Walk interval as well as the FDW. The District of Columbia is the only jurisdiction to adopt a modified MUTCD guideline allowing countdown timing during the Walk interval (District of Columbia, 2008).

8.1.2.2 Benefits and Impacts

Many studies have found that countdowns reduce pedestrian crashes and conflicts. One study found a crash modification factor (CMF) of 0.75 for pedestrian crashes when traditional Walk/Don't Walk pedestrian signals were replaced with pedestrian countdown signal heads (Markowitz et al., 2006). Another study found CMFs of 0.45 to 0.30 and also found that countdown timers reduced pedestrian–vehicle conflicts by 55%–70% (Van Houten et al., 2012). A recent study of more than 300 intersections in Philadelphia, PA, and Charlotte, NC, found that after countdown signals were installed, total crashes fell by 8% and pedestrian-related crashes fell by 9%. These improvements were statistically significant at 95% and 90% confidence levels, respectively (Srinivasan et al., 2019).

One meta-study found that countdowns led to pedestrian crash rate reductions ranging from 70% (citywide in Detroit, MI) to no statistically significant effect, as cited in PedSafe (Huitema et al., 2014; Markowitz et al., 2006; and Camden et al., 2011). One large Toronto, Ontario, study found that installing pedestrian countdowns resulted in an overall reduction in crashes but with mixed results by age group (Rothman et al., 2017). Another Toronto study found an almost

32% reduction in crashes, with consistent results by age and severity except for a particularly large decrease in crashes involving pedestrians age 65 and older (Kwigizile et al., 2016).

PedSafe's review of the evidence finds mixed results on the impact of pedestrian countdown on Walk signal compliance, with some studies showing a decrease in compliance and some studied sites showing an increase. A decline in compliance as measured by pedestrian departures after the Walk interval ends should not be surprising—with a countdown, people see the remaining time and decide whether to cross based on that and their own walking speed. However, pedestrian countdowns are likely to improve compliance when measured by the number of pedestrians who failed to clear the intersection before conflicting traffic is released. California recently changed its traffic code so that pedestrians are no longer considered non-compliant if they clear the intersection before conflicting traffic is released, even if they did not begin to cross during the Walk interval.

A study in Washington, DC, found there were no statistically significant changes in pedestrian behavior between intersections whose countdown starts with the Walk interval and those whose countdown starts with FDW. They also found that most pedestrians prefer the countdown to start during the Walk interval (Arhin et al., 2011).

8.1.3 Considerations

8.1.3.1 Accessibility Considerations

When a countdown starts with the Walk interval, pedestrians with low vision may have problems distinguishing the countdown numbers from the flashing hand since both are orange and both flash. Displaying the countdown numbers with the walking man indication may cause confusion (Harkey et al., 2007).

At this time, the MUTCD does not allow an audible countdown, although some manufacturers offer that option. According to the MUTCD (2009), Section 4E.11, Paragraph 25: "Standard: Following the audible Walk indication, accessible pedestrian signals shall revert to the pushbutton locator tone (see Section 4E.12) during the pedestrian change interval." The main reason for this is that the continuous sound of the countdown speech may mask vehicular sounds that pedestrians who are visually impaired need to be able to hear.

8.1.3.2 Guidance

Per the MUTCD (2009), Section 4E.07, Standard, all pedestrian signal heads used at crosswalks where the pedestrian change interval is more than 7 s shall include a pedestrian change interval countdown display to inform pedestrians of the number of seconds remaining in the change interval.

8.1.3.3 Relationships to Relevant Treatments

Countdown device limitation can affect pedestrian clearance settings for serving slower pedestrians (see Section 7.4). Countdowns must be configured to reach their zero point at the moment the FDW interval ends. The software that controls countdowns often allows them to be configured with a zero point at the start of yellow or end of yellow, but not in between. As explained in Section 7.4, it can be desirable to have FDW end partway through the yellow interval, but this limitation prevents that. Countdown manufacturers could easily remove this limitation.

8.1.3.4 Other Considerations

Not applicable for this treatment.

Source: MUTCD (2009), Figure 4E-1.

Exhibit 8-1. Typical pedestrian signal indication with Walk countdown.

8.1.4 Implementation Support

8.1.4.1 Equipment Needs and Features

This treatment requires pedestrian signal heads with countdowns. The countdown should be displayed simultaneously with the flashing upraised hand (symbolizing Don't Walk) signal indication for that crosswalk, as shown in Exhibit 8-1.

8.1.4.2 Phasing and Timing

Not applicable for this treatment.

8.1.4.3 Signage and Striping

Not applicable for this treatment.

8.1.4.4 Geometric Elements

Not applicable for this treatment.

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8.2 Call Indicators

8.2.1 Basic Description

8.2.1.1 Alternative Names

Pilot light.

8.2.1.2 Description and Objective

A call indicator is a light that provides real-time feedback to bicycles or pedestrians, confirming that their call for service has been registered (see Exhibit 8-2). Call indicators are generally used in connection with elevator pushbuttons, but in the U.S., they have only recently become common in connection with pedestrians calling for a crossing phase. The purpose of call indicators is to reassure pedestrians and cyclists that their call has been received and that their phase will come up. This helps improve pedestrian comfort and can also lead to an increase in pedestrian and cyclist red-light compliance.

Without a call indicator, pedestrians may not know whether they need to push a button to get service. One example is when another pedestrian has already arrived, yet he or she did not press the button; new arrivals may assume that the button has been pressed. At intersections where the pedestrian phase is on recall for only part of the day, a person accustomed to getting the Walk signal without pushing the button during one period of the day may be surprised when

Exhibit 8-2. Typical American accessible pedestrian signal with the call indicator illuminated.

the same does not happen in another period of the day. Another example is when a pedestrian phase is on recall, but a pushbutton is present as part of an accessible pedestrian signal (APS) (see Section 8.4). In these situations, a call indicator informs pedestrians of their need to push the button and helps ensure that pedestrians receive a crossing phase.

8.2.1.3 Variations

Most call indicators are part of a pushbutton assembly. Call indicators can also be independent of a pushbutton when another means of detection is used, such as cameras or in-pavement loop detectors for detecting bicycles.

8.2.1.4 Operating Context

Call indicators for pedestrian crossings should be considered wherever there is a pedestrian pushbutton.

Likewise, call indicators for bicycle crossings should be considered wherever bicycle phases are actuated (i.e., anywhere a bicycle phase might be skipped if a bicycle is not detected).

8.2.2 Applications and Expected Outcomes

8.2.2.1 National and International Use

In many European countries, call indicators have long been integrated with pedestrian pushbuttons. In the United Kingdom, the standard pedestrian pushbutton includes a large, lighted "Wait" message that illuminates after the button is pressed (see Exhibit 8-3). In the Netherlands, pedestrian pushbuttons have indicator lights either above or surrounding the pushbutton.

In the U.S., call indicators are present wherever APS are used. When pressed, a voice says "Wait" and a small red light illuminates and stays lit until the Walk phase begins. The indicator lights on common APS models are small and dark, so pedestrians may not notice or understand them.

Source: Jim Ellwanger/CC BY-NC 2.0.

Exhibit 8-3. Standard pushbutton in the United Kingdom.

Call indicators for bicycles are unknown in the U.S. outside of Portland, OR. In the Netherlands, they are used at all intersections where a bicycle phase depends on detection (bicycles are typically detected using in-pavement inductive loops, with a pushbutton as backup). The call indicator is part of the pushbutton assembly. It illuminates when a call is registered, whether the bicycle was detected by the pushbutton or by the loop detector. If the loop detector works as intended, bicyclists will see the call detector illuminate before they stop and will know that they do not need to push the button. The following photo shows the bicycle pushbutton assembly (yellow), an illuminated call indicator (red light at the top of the pushbutton assembly), and sealed cuts in the pavement indicating an in-pavement loop detector (see Exhibit 8-4).

Portland has developed a different kind of call indicator for bicycles: a blue LED (light-emitting diode) placed next to the bicycle signal. An example is shown in Exhibit 8-5, in which the indicator is triggered by an in-pavement inductive loop bicycle detector. Because bicycle signals are located on the far side of the intersection, the indicator light is relatively bright. This style of call indicator repurposes the blue "spy" light that controllers offer as an option for enforcement—the spy light illuminates when a signal is red, shining in the opposite direction so that police officers downstream can know when a traffic signal is red. Portland uses this kind of bicycle call indicator at several intersections.

8.2.2.2 Benefits and Impacts

Where there are no call indicators, it is common to see pedestrians anxiously press the pushbutton repeatedly. Call indicators reduce this behavior, which supports the idea that they increase pedestrian comfort.

Where pedestrians fail to push the button because they did not know it was necessary—perhaps because they think other pedestrians have already pushed it or because they are used to the phase coming up automatically—they may cross anyway when the concurrent phase's green begins, creating the danger of being caught within the intersection if the phase ends earlier

Source: Peter Furth.

Exhibit 8-4. Bicycle pushbutton assembly, illuminated call indicator, and in-pavement loop detectors in the Netherlands.

Source: Jonathan Maus/*BikePortland*.

Exhibit 8-5. Bicycle call indicator using blue LED in Portland.

than needed for pedestrians to clear. Van Houten et al. (2006) found that call indicators help avoid this unsafe situation by increasing both button usage and signal compliance. Call indicators also help reduce extraneous button pressing, which may improve the lifespan of the buttons.

Portland has made some effort to educate cyclists about their blue indicator lights. Boudart et al. (2016) found that nearly 75% of cyclists understood their meaning. Additionally, a before-and-after study found that bicycle red-light compliance improved significantly at all nine of the locations studied (Alviani, 2014).

8.2.3 Considerations

8.2.3.1 Accessibility Considerations

For signals to be accessible, per the MUTCD (2009), each pushbutton actuation should be accompanied by the speech message, "Wait." This provides an audible confirmation that a call has been registered, complementing the visible confirmation of a call indicator light.

8.2.3.2 Guidance

The MUTCD (2009) states that a call indicator installed with a pedestrian pushbutton must not be illuminated until actuated, and once actuated, it must remain illuminated (i.e., the indicator should be "latching") until the Walk signal indication is displayed. Note that when a pedestrian phase is on recall, it is actuated by the system—typically when the pedestrian clearance time ends. Therefore, using an indicator light with a pedestrian phase that is on recall is consistent with this standard if the light goes out during the Walk interval and then re-illuminates after it ends.

The MUTCD does not provide specific guidance for bicycle call indicators.

8.2.3.3 Relationships to Relevant Treatments

Call indicators are helpful for having accessible signals without pushbuttons (see Section 8.4) and in connection with bicycle detection (see Section 9.4).

8.2.4 Implementation Support

8.2.4.1 Equipment Needs and Features

Call indicators are usually part of a pushbutton assembly. The only known exception is Portland's blue-light bicycle call indicators.

Pushbuttons for APS also have call-indicator lights and provide audible call confirmations ("Wait"). In addition, there are MUTCD-compliant pushbuttons that come with call indicators that can be retrofitted into an existing two-wire pushbutton system. These pushbuttons have their own control unit and are programmed to provide the latching call-indicator function. No special controller features are required. The pedestrian button control unit in the cabinet will monitor the pedestrian phase outputs and provide detector input for the pedestrian phases.

Some pushbutton controllers may require custom programming to illuminate a call indicator based on a system actuation in which the pedestrian phase is on recall.

Some pushbuttons on the market allow for an indicator light to be non-latching, meaning it is only lit while the button is depressed. This setting is not currently permitted in the MUTCD for signalized crossings.

8.2.4.2 Phasing and Timing

With call indicators that are lit whenever a call is registered, including a system-initiated call, it becomes easier to consider having a pedestrian phase on recall for only part of the day (e.g., daytime or school hours) because the call indicator lets the public know, at all times, when they need to push the button for service.

8.2.4.3 Signage and Striping

Because Portland's blue-light bicycle call indicators are not part of a pushbutton assembly, the City of Portland has added signage to inform cyclists of the meaning of blue light (see Exhibit 8-6). Some agencies use the MUTCD's Bicycle Detector Pavement Marking to indicate the optimum position for a cyclist to actuate the signal.

Source: Jonathan Maus/*BikePortland*.

Exhibit 8-6. Blue-light bicycle call indicator sign to inform cyclists in Portland.

8.2.4.4 Geometric Elements

Not applicable for this treatment.

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8.3 Independently Mounted Pushbuttons

8.3.1 Basic Description

8.3.1.1 Alternative Names

Not applicable for this treatment.

8.3.1.2 Description and Objective

Independently mounted pushbuttons are mounted on their own pole or a pole supporting only pedestrian signals (see Exhibit 8-7), rather than on a pole supporting other signal

Source: U.S. Access Board (2011b).

Exhibit 8-7. Independent poles with pedestrian displays and pushbuttons only.

equipment. The purpose is to locate pushbuttons for user convenience, to keep pushbuttons far enough apart that users at a corner can tell which button should be pressed to cross which leg, and to help visually impaired pedestrians better associate audible signals with the correct crosswalk.

Independently mounted pushbuttons can be especially valuable where bicyclists use a pushbutton. Bicyclists have less lateral mobility than pedestrians and therefore need a pushbutton that can be reached from their queuing position. If a pushbutton is too close to the curb, a bicyclist may not be able to reach it without the bicycle's front wheel encroaching on the street.

8.3.1.3 Variations

Not applicable for this treatment.

8.3.1.4 Operating Context

Independently mounted pushbuttons can be considered at almost any crossing, particularly at crossings with APS and where bicycles use a pushbutton.

8.3.2 Applications and Expected Outcomes

8.3.2.1 National and International Use

In the Netherlands, it is common for bicycle pushbuttons to be on their own short pole (see Exhibit 8-4) and for pedestrian pushbuttons to be on a pole shared only by a pedestrian/bicycle signal.

In the U.S., pushbuttons are most often located on poles supporting other signal control equipment, which are often not ideally placed for user functionality. Often, pushbuttons for both crossings at a corner are located on the same pole, making it difficult for users to distinguish which pushbutton corresponds with which crossing. Since 2009, the MUTCD has recommended separating pushbuttons in Section 4E.08, especially where APS are installed. Independently mounted pushbuttons are now a standard product, though still not widely used.

On shared-use paths and other locations where cyclists are expected to push a button for service, pushbuttons are often located in such a way that bicyclists cannot reach them without leaving a queuing position (at the ramp) or without encroaching on the roadway if the pushbutton is too close to the curb. The U.S. currently has no standards for pushbutton locations that serve bicyclists.

8.3.2.2 Benefits and Impacts

Independently mounted pushbuttons improve user convenience and decrease confusion about which button to press. They can increase the number of users who use the pushbutton, increase accessibility by allowing pushbuttons to be closer to the curb ramp, and decrease unneeded pedestrian phases caused by users pressing the wrong button or all buttons. A reduction in required pedestrian timing may be possible with a relocated pushbutton if the existing pushbutton is more than 6 ft from the edge of the curb.

APS with pushbuttons located close to the curb ramp greatly reduce errors made by visually impaired pedestrians in identifying the correct time to enter a given crosswalk. On corners with independently mounted pushbuttons aligned with the ramp and approximately 3 ft from the curb, the error rate (percent of trials with the pedestrian raising their hand when it was not a Walk signal) was about a third the error rate of all other trials (Harkey et al., 2007).

8.3.3 Considerations

8.3.3.1 Accessibility Considerations

Independently mounted pushbuttons can increase accessibility in several ways. They can reduce the distance from pushbutton to curb ramp, shortening the effective crossing distance for those who wait by the pushbutton for an audible or vibrotactile signal. They can also make it easier for pushbuttons to have the separation needed for visually impaired pedestrians to match an audible signal with the right crosswalk. Guidance from the U.S. Access Board (2001) on pushbutton location (see Exhibit 8-8) states that if there are two accessible pushbuttons at a corner, they should be at least 10 ft apart. And while these guidelines allow pushbuttons to be as much as 5 ft offset from the edge of the curb ramp, a lateral offset that large is inconvenient to all. If pushbuttons require pedestrians who are visually impaired to deviate from their course of travel to reach the button, they lose some of the orientation gained as they approached the intersection.

Intersections where signals are pretimed can still have pushbuttons as part of APS. Those pushbuttons must be located in accordance with guidance on APS, which can require installation of new poles. This issue is particularly common at downtown locations with wide sidewalks and pretimed pedestrian phases, which were not designed with pushbuttons in mind; when they are retrofitted for APS, new poles are often needed.

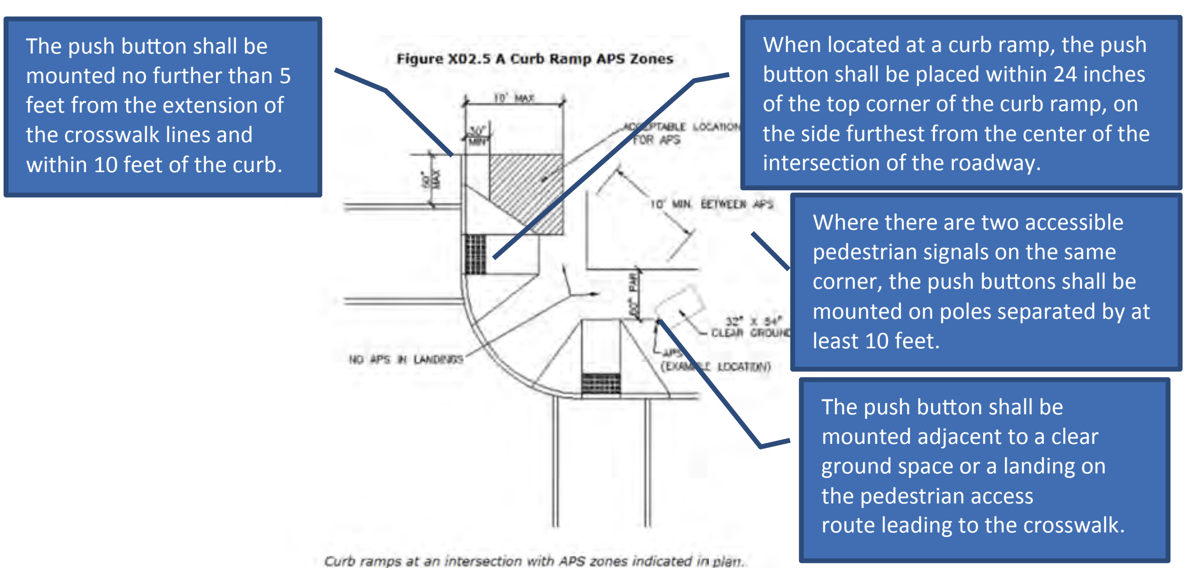
If there is not enough room at an intersection to place the pushbuttons 10 ft or more apart, they may be placed together on the same pole (U.S. Access Board, 2001). If APS are closer than 10 ft apart, the audible messages must include the street name, and there must be an additional pushbutton information message providing the street name.

8.3.3.2 Guidance

Not applicable for this treatment.

8.3.3.3 Relationships to Relevant Treatments

Not applicable for this treatment.



Source: U.S. Access Board (2001).

Exhibit 8-8. Curb ramps at an intersection with APS zones.

8.3.3.4 Other Considerations

Not applicable for this treatment.

8.3.4 Implementation Support

8.3.4.1 Equipment Needs and Features

Pedestrian pushbuttons can be placed on short "stub" poles. For example, Florida Department of Transportation (DOT) (2015) recommends a 4-in. outer diameter aluminum pipe about 5.5 ft tall for a pedestrian pushbutton post.

Putting pedestrian signal heads on their own pole with the pedestrian pushbutton can be an even better solution because it optimally locates both the pushbutton and the pedestrian display (see Exhibit 8-9).

8.3.4.2 Phasing and Timing

Not applicable for this treatment.

8.3.4.3 Signage and Striping

MUTCD signing requirements for pedestrian pushbuttons in general apply to independently mounted pushbuttons.

8.3.4.4 Geometric Elements

The MUTCD (2009) has guidelines regarding pushbutton placement, including the recommendation that pushbuttons at a corner serving two crosswalks be placed at least 10 ft apart, and it provides useful graphics about pushbutton installation with various curb ramp configurations. Another resource on APS pushbutton location and curb ramps is Chapter 6 of the *Special Report: Accessible Public Rights-of-Way Planning and Design for Alterations* at https://www.access-board.gov/prowag/planning-and-design-for-alterations/ (U.S. Access Board, 2007).

Where pushbuttons are intended for bicycle use, they should be offset from the edge of the ramp enough that they are not an obstruction but close enough that bicyclists can reach them without going out of their way. They should be located where a bicyclist can reach the button and wait without encroaching on the road or standing on a steep ramp.

Source: U.S. Access Board (2011a).

Exhibit 8-9. Independently mounted pushbutton pole example.

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8.4 Accessible Signals without Pushbutton Actuation

8.4.1 Basic Description

8.4.1.1 Alternative Names

None.

8.4.1.2 Description and Objective

For crossings with pedestrian recall, pretimed control, and non-intrusive detection, pedestrians do not need to push a button to call the pedestrian signal; however, visually impaired pedestrians still need information about the pedestrian phase. APS can provide feedback to pedestrians without requiring that pedestrian phases be actuated.

8.4.1.3 Variations

There are no variations to this treatment.

8.4.1.4 Operating Context

Accessible signals without pushbutton actuation should be used wherever pedestrian recall or pretimed control is the preferred operating mode and should be used in connection with non-intrusive pedestrian detection, especially when a high number of visually impaired or elderly pedestrians is expected. Designers should be aware that guidelines and local mandates for installing APS—which typically include pushbuttons as an essential element—do not mandate that crossings be pushbutton actuated.

8.4.2 Applications and Expected Outcomes

8.4.2.1 National and International Use

Many U.S. cities use APS in connection with crossings that are pretimed or on recall. NYC DOT is installing 150 APS intersections per year, nearly all of them at pretimed locations (D. Nguyen, personal communication, August 16, 2019). In New York, the average cost per unit (including installation) is approximately $1,000, and each four-leg intersection has eight units.

8.4.2.2 Benefits and Impacts

APS offer improved accessibility for individuals who are visually impaired at signals where the pedestrian phase is pretimed or on recall. An audible and vibrotactile Walk indication is provided whenever the Walk signal is displayed. The pushbutton locator tone helps pedestrians who are visually impaired find the crosswalk and proper starting location and use the other features of the pushbutton. A tactile arrow aligned with the direction of travel on the crosswalk allows a pedestrian who is visually impaired or who is deaf-blind to confirm which crosswalk the audible and tactile signals correspond to. Research has found that APS improve crossing performance for visually impaired pedestrians since the devices allow more accurate judgments of the onset of the Walk interval, improving safety for visually impaired pedestrians and also reducing their delay (Harkey et al., 2007).

Holding in the pushbutton for more than 1 s (an extended button press) may provide additional information, such as a speech message with intersection names, additional intersection geometry information, a louder signal during the next pedestrian phase, or longer pedestrian timing.

8.4.3 Considerations

8.4.3.1 Accessibility Considerations

APS help people who are visually impaired and people who have low vision and/or hearing impairments know when the Walk signal is being displayed. These signals use sound, tactile arrows, and vibrotactile feedback to communicate with pedestrians (see Exhibit 8-10). While most APS pushbuttons are designed to serve a dual function as both standard pedestrian pushbuttons and APS, they can be used for their accessible features only, or similar units that lack the pedestrian actuation function can be provided.

8.4.3.2 Guidance

Many U.S. cities—including New York, Portland, San Francisco, CA, and Seattle, WA—have policies to install APS when requested by a member of the public and when the location meets other requirements. These requirements typically mandate that the location is already signalized.

Source: San Francisco Municipal Transportation Agency.

Exhibit 8-10. Accessible pedestrian signal example.

Minnesota, Maryland, San Francisco, and many municipalities install APS at all reconstructed or newly signalized intersections.

The MUTCD (2009) provides guidance on APS, including a requirement that APS clearly indicate which pedestrian crossing is served by each device. Guidance on pushbutton location is provided in Section 8.3 and in the MUTCD, Sections 4E.09–4E.11.

8.4.3.3 Relationships to Relevant Treatments

When installing APS, practitioners should consider independently mounted pushbutton placement (see Section 8.3).

All APS currently on the market in the U.S. provide a latching call indicator or pilot light (see Section 8.2), which allows sighted pedestrians to observe that a call has already been placed. The call indicator can be programmed to illuminate when the system places a call for the pedestrian phase (as it does once every cycle) to let sighted pedestrians know that they do not need to push the button.

8.4.3.4 Other Considerations

Not applicable for this treatment.

8.4.4 Implementation Support

8.4.4.1 Equipment Need and Features

Standard APS equipment may be used with a button that does not provide pedestrian detection; instead, the button can simply provide additional information for pedestrians with disabilities. The call indicator (pilot light or actuation indicator) should be programmed to illuminate automatically each cycle based on the pedestrian phase's call status.

APS may be set to provide the audible and vibrotactile Walk indication whenever the visual Walk indication is displayed (i.e., not only in cycles when its pushbutton is pressed). This provides audible Walk information to all users and has been shown to increase the efficiency of the signal timing. The MUTCD (2009) allows APS to be programmed to provide audible features only when actuated by the pushbutton; however, this requires pedestrians who are visually impaired to find and use the pushbutton, which can be difficult at some intersections where there are often many pedestrians.

8.4.4.2 Phasing and Timing

Not applicable for this treatment.

8.4.4.3 Signage and Striping

Signs are sometimes used to communicate that pushing the button is not required to call for a Walk signal.

8.4.4.4 Geometric Elements

Not applicable for this treatment.

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CHAPTER 9

Treatments Addressing Special Bicycle Needs

This chapter describes six treatments that address needs specific to bicyclists:

Primary Function	Section	Treatment Name
Improve bicycle safety by providing sufficient clearance time	9.1	Minimum Green and Change Interval Settings for Bicycle Clearance
Reduce bicycle delay by providing enhanced progression	9.2	Signal Progression for Bicycles
	9.3	Two-Stage Left-Turn Progression for Bicycles
Offer signal timing techniques made possible by bicycle detection	9.4	Bicycle Detection
Provide information to increase cyclist compliance	9.5	Bicycle Wait Countdown
Reduce bicycle delay	9.6	Easing Bicycle Right Turn on Red Restrictions

Minimum Green and Change Interval Settings for Bicycle Clearance (Section 9.1) addresses critical timing settings for vehicular phases to ensure that cyclists have sufficient clearance time at the end of a phase. It also addresses timing settings for bicycle-specific phases.

Signal Progression for Bicycles (Section 9.2) provides signal timing guidance for providing green waves for bicycles, which enables bicycles to arrive on green at successive intersections, thereby reducing bicycle delay and stops.

Two-Stage Left-Turn Progression for Bicycles (Section 9.3) addresses the traffic signal timing aspect of two-stage left turns with the aim of minimizing delay for left-turning cyclists. While two-stage left turns are a safe mode of turning and are the only practical way of making left turns from protected bike lanes, delay can be large if a cyclist has to wait a long time after the first crossing stage for the phase serving the next stage.

Bicycle Detection (Section 9.4) describes technologies that can be used to detect bicycles and refers to timing techniques that become possible with bicycle detection.

Bicycle Wait Countdown (Section 9.5) aims to improve cyclists' red-light compliance by counting down the time until the start of green for bicycle phases, optionally displaying the word "Wait" while the countdown is active.

Easing Bicycle Right Turn on Red Restrictions (Section 9.6) aims to reduce cyclist delay and promote equity by legalizing the widespread practice of bicycles turning right on red without stopping (while still yielding to pedestrians and cross traffic).

9.1 Minimum Green and Change Interval Settings for Bicycle Clearance

9.1.1 Basic Description

9.1.1.1 Alternative Names

Bike minimum green; bicycle red clearance interval; bicycle yellow change interval; green extension for bike clearance.

9.1.1.2 Description and Objective

The objective is to ensure that bicyclists crossing a street have sufficient time to clear the intersection. For bicycles departing from a standing start at the onset of green, this need can be met by using a sufficiently long minimum green interval, called bike minimum green, combined with the bicycle yellow change interval and bicycle red clearance interval. For bicycles departing near the end of the green on a rolling start, this need can be met by using a sufficiently long red clearance interval, called bike red clearance interval. It has also been proposed, though almost never applied, that the clearance need for rolling starts could be met using green extension for bike clearance.

For bicycle crossings governed by bicycle signals, this section also covers timing for the bicycle yellow clearance interval.

9.1.1.3 Variations

Not applicable for this treatment.

9.1.1.4 Operating Context

Bike minimum green should be considered for all signal phases used by bicycles, including left-turn phases. As a practical matter, attention is needed only for actuated phases when cross streets are wide and have a short minimum green, since pretimed and coordinated phases typically have more green time than needed for bicycle clearance.

Bike red clearance should be considered for all signal phases used by bicycles. As a practical matter, it is of concern only with long crossings, where the clearance time—which is set based on considerations of vehicle safety—may not be enough for bike clearance.

Bicycle yellow interval timing applies wherever there are bike signals, whether for exclusive bicycle phases or for bike phases that run concurrently with a parallel vehicular or pedestrian phase.

9.1.2 Applications and Expected Outcomes

9.1.2.1 National and International Use

In the Netherlands, Germany, and several other European countries, bike minimum green and bike red clearance have been routine and required parts of signal timing practice for several decades.

In the United States, bike minimum green is recommended in the *California Manual on Uniform Traffic Control Devices* (CA MUTCD) (State of California, 2014), and it is used in many (but not all) cities in that state. Some U.S. cities outside California also use bike minimum green. However, it has not yet become part of mainstream practice.

Bicycle detectors have been used in some locations in California to apply bicycle minimum green only when a bike is detected by using the stop-line detector in the bike lane that is already present for call detection.

Bike red clearance is rarely applied in the U.S. While the practice is recommended in the National Association of City Transportation Officials (NACTO) bikeway design guide, it is not mentioned in the AASHTO *Guide for the Development of Bicycle Facilities* nor *NCHRP Report 812: Signal Timing Manual*, 2nd Edition (STM2). There is a common belief that long crossings would demand very long red clearance times, which would be impractical and unsafe to implement from the viewpoint of vehicle operations. A contributing factor is that the standard red clearance formula used in the U.S. makes conservative assumptions that lead to considerably more red clearance time than clearance time formulas used in Europe.

Bicycle Crossing Time from a Standing Start. A bicycle's needed crossing time from a standing start is given by Equation 9-1:

$$BXT_{standing} = \frac{D+L}{v} + StartupOffset \tag{9-1}$$

where

$BXT_{standing}$ = bicycle crossing time from a standing start (s);
D = crossing distance (ft) from the queuing position used by bicycles to the end of the most distant travel lane;
L = bicycle length (ft), usually taken as 6 ft;
v = final bicycle speed (ft/s); and
$StartupOffset$ = startup offset (s), incorporating reaction time and acceleration delay.

Startup offset represents the extra time needed compared to if acceleration were instantaneous, and thus incorporates both reaction time and acceleration delay.

To provide sufficient clearance time for the vast majority of cyclists, one can use either a near-average speed combined with a high-percentile startup offset, or a near-average startup offset combined with a low-percentile speed. Shladover et al. (2011) studied six California intersections and found that median and 15th-percentile speeds were approximately 12 mph and 8.5 mph, respectively, and that median and 90th-percentile startup offsets were approximately 3.5 s and 5.5 s, respectively. The CA MUTCD recommends default values of v = 10 mph (14.7 ft/s) and $StartupOffset$ = 6 s. If, instead, a speed of 8.5 mph (12.5 ft/s) is combined with a less extreme startup offset of 4.5 s, calculated crossing times differ by less than 0.5 s for crossing distances within the range 75–160 ft. The AASHTO manual's crossing time equation has a different form but essentially reduces to the CA MUTCD equation.

Running grade is usually ignored because crossings are typically level; however, where there is a significant upgrade or the road being crossed has a sharp crown, another second or two may be needed. Where the street being crossed has fast and heavy traffic, cyclists may wait further back—particularly where there is poor visibility toward cross traffic—increasing crossing time (Shladover et al., 2009; Shladover et al., 2011).

Bike Minimum Green. Two formulas that may be considered for bicycle minimum green are given in Equations 9-2 and 9-3:

$$BikeMinGreen = BXT_{standing} - Y - RClear \tag{9-2}$$

$$BikeMinGreen = BXT_{standing} - Y - RClear + PET - t_{entry} \tag{9-3}$$

where

$BikeMinGreen$ = bike minimum green (s);
Y = yellow time (s);
$RClear$ = red clearance time (s);
PET = post-encroachment time (s); and
t_{entry} = time needed for the first vehicle released in the next phase to reach the conflict zone (s).

Equation 9-2, used both by the AASHTO guide and the CA MUTCD, aims to ensure that the design bicyclist has reached the end of the most distant travel lane before conflicting traffic is released. STM2, which provides the same guidance regarding bike minimum green as the CA MUTCD, has a table showing the total minimum phase length needed (minimum green plus yellow plus red clearance) as a function of crossing length (see Exhibit 6-7 in STM2).

Equation 9-3 demands a shorter minimum green because it accounts for time needed by the first vehicle released in the following phase to enter the conflict zone, a standard consideration in German and Dutch practice. McGee et al. (2012) found that the average entry time was 4.1 s, including an average reaction time of 1.1 s. For design, suggested default values are $PET = 1.0$ s and $t_{entry} = 2.8$ s. The latter is based on a near-worst-case scenario in which the bike crossing is only 15 ft from the lead car, the lead vehicle's acceleration is 9.2 ft/s^2 (which is 40% greater than the average acceleration from a start found by Long [2000] for passenger cars), and reaction time is 1.0 s. With these default values, bike minimum green will be 1.8 s shorter using Equation 9-3 versus Equation 9-2.

Bicycle minimum green is constraining only when it is greater than the minimum green that would have been applied based on auto needs. To illustrate, consider two crossings: one has a length of 80 ft, yellow time of 3 s, and red clearance time of 2 s, while the other has a length of 120 ft, yellow time of 3 s, and red clearance time of 3 s. Using CA MUTCD default values, bike minimum green would be 6.9 and 8.6 s, respectively. Most agencies use 6 s as the least minimum green for through phases (though many agencies use 10 s), so bike minimum green presents a very minor constraint on signal operations.

Bike Red Clearance. The three formulas in Equations 9-4 through 9-6 may be considered for bike red clearance:

$$BikeRClear = \frac{D+L}{v} \tag{9-4}$$

$$BikeRClear = \frac{D+L}{v} + \left(t_{reaction} + \frac{v}{2d}\right) - Y \tag{9-5}$$

$$BikeRClear = \frac{D+L}{v} + \left(t_{reaction} + \frac{v}{2d}\right) - Y + PET - t_{entry} \tag{9-6}$$

where

$BikeRClear$ = bike red clearance time (s);
$t_{reaction}$ = reaction time for a cyclist reacting to a signal turning yellow (s); and
d = bike deceleration rate at a traffic signal (ft/s^2).

Suggested default values are:

$L = 6$ ft;
$v = 12.5$ ft/s (8.5 mph);

$t_{reaction}$ = 1.0 s;
d = 10 ft/s^2 (as suggested in Ontario's bicycle traffic signals manual);
PET = 1.0 s; and
t_{entry} = 2.8 s.

Equation 9-4 is the clearance time formula typically used for vehicles. It aims to ensure that no conflicting vehicle is released until a bicycle entering the intersection at the last moment of yellow has cleared the most distant travel lane. This formula can lead to rather long bicycle red clearance times; for example, for crossings of 80 ft and 120 ft, the needed clearance times would be 6.9 s and 10.1 s, respectively.

Equation 9-5 allows some of the yellow time to count toward bicycle clearance, based on the idea that at the onset of yellow, cyclists who *can* stop (because they are far enough upstream of the stop line) *should* stop, consistent with the most common legal meaning of yellow. NACTO recommends using this concept when determining bike clearance time need, as does Ontario's bicycle traffic signals manual (Province of Ontario, 2018). The time from the start of yellow to the moment the last cyclist who could not stop enters the intersection is $\left(t_{reaction} + \frac{v}{2d}\right)$. When using the suggested default values, this is 1.6 s; the balance of the yellow can be used toward needed crossing time. (Faster bikes may enter later in the yellow but need less red clearance time because of their greater speed.) Using this formula reduces needed clearance by 1.4 s if yellow time is 3 s, and by 2.4 s if yellow time is 4 s.

Equation 9.6 takes the additional step of accounting for the time needed for the first car released in the following phase to reach the conflict zone, while still allowing a post-encroachment margin (as discussed earlier). Using the suggested default values, the equation further reduces needed clearance by 1.8 s.

An additional reduction in needed clearance can be gained by treating the entry point to the intersection for bicycles to be the curb line of the intersecting street rather than the stop line. This can be appropriate where cyclists routinely stop at that curb line rather than at the stop line. (One advantage of the protected intersection layout is that it places the bicycle stop line in this advanced position, reducing needed bicycle clearance.)

Together, reductions in needed bicycle red clearance gained by more precisely accounting for cyclists' clearance need can be substantial. If the yellow time is 3 s and the stop line is set back 18 ft from the intersecting curb line, those reductions would amount to 4.6 s. For an 80 ft crossing, needed bicycle clearance falls from 6.9 to only 2.3 s; for a 120 ft crossing, it falls from 10.1 to 5.5 s.

Bicycle red clearance affects a signal's operation only when it exceeds the red clearance time needed by autos; that difference can be called *extra clearance time.* Clearance time needed for vehicles is determined by local policy, but a common policy is to equate it to crossing length plus vehicle length (usually taken as 15 ft) divided by the speed limit (in miles per hour). With that policy and a speed limit of 30 mph, red clearance time needed by vehicles is 2.2 s for an 80 ft crossing and 3.1 s for a 120 ft crossing. Continuing the earlier examples, the extra red clearance time needed for bicycles would be 0.1 s for the 80 ft crossing and 2.4 s for the 120 ft crossing.

Making Extra Phase Time for Bikes Bike-Actuated. The extra minimum green or red clearance needed to enable bikes to clear an intersection can be provided every cycle or only in cycles in which a bicycle is detected at specific times. In the latter case, minimum green can be provided if a bicycle is detected during the red interval, and red clearance can be provided if a bicycle is detected during the last few seconds of green or the first few seconds of yellow. The extra minimum green or red clearance needed to enable bikes to clear an intersection can be provided every cycle; alternatively, minimum green can be provided only in cycles in which a bicycle is detected during the red interval and red clearance can be provided in the last few seconds of green or the first few seconds of yellow. If the extra time needed for bikes is large, bike actuation can allow signal cycles to be more efficient.

Except where bikes are in an exclusive path, bike actuation requires selective detection (i.e., the ability to detect a bike as distinct from a motor vehicle). As described later in Section 9.4, there is at least one commercial system using video detection and offering this capability. A few cities use bike detection to trigger longer minimum green intervals.

Green Extension for Bike Clearance. To provide safe clearance for bikes arriving on a stale green, the AASHTO bike guide suggests extending the green rather than providing a longer red clearance time. The advantage of this method is that it leaves the red clearance interval unchanged. However, it can only be applied with bike detection; moreover, it cannot use a stop-line detector and instead requires a special upstream detector, located so that a cyclist who has not quite reached the detector at the onset of yellow has enough distance to stop before entering the intersection.

Bike Yellow. For bike signals, the appropriate length of the yellow interval can be determined using the standard yellow time formula but with performance parameters that pertain to bikes, as stated in Equation 9-7:

$$Y = t_{reaction} + \frac{v}{2d} \tag{9-7}$$

Because the length of the yellow interval is for enforcement, including self-enforcement (i.e., giving cyclists feedback on whether they correctly decided whether to stop at the onset of yellow), its calculation should use a high-percentile speed. Using $v = 14$ mph (20.5 ft/s) and $d = 10$ ft/s^2 yields a bike yellow time of 2.0 s. At the same time, a short bicycle yellow applied to a bike phase that runs concurrently with a vehicular phase leaves more time for bicycle red clearance. This is one of the primary reasons that Amsterdam, Netherlands, recently reduced the yellow time for its bicycle signals from 3 to 2 s citywide (S. Linders, personal communication, August 1, 2018).

9.1.2.2 Benefits and Impacts

Bicyclists will benefit from safer and less stressful crossings; benefits will be particularly strong for those who ride slowly, such as children, older adults, tourists, and people new to cycling. Benefits depend on the number of cyclists, so crossings used by high volumes of cyclists or slower cycling populations should be prioritized.

Impacts to traffic depend on whether bike clearance settings are applied in all cycles or only in those for which bikes have been detected during the red interval (for bike minimum green) or during the last few seconds of green or first few seconds of yellow (for bike red clearance). With detector-based actuation, the impacts of both bike minimum green and bike red clearance will be trivially small except where bike volume is high, in which case the benefits will be large.

Without detector-based actuation, the impact to traffic of applying bike minimum green to through phases will usually be negligible. This is because vehicle green times required for the through phases are typically already longer than the bike minimum green (for most crossings, bike minimum green is 10 s or less). The impact of applying it to minor-street through movements could be greater, especially with long crossings and low left-turn volumes. However, even at very long crossings, there will usually be no impact in peak periods because traffic volume is usually large enough that vehicle green times run longer than bike minimum green. During low-traffic periods, the impact will be very small because there is plenty of excess capacity, therefore increasing a side street's green duration—for example, from 6 to 10 s—will have a negligible effect on average delay. Using microsimulation, Shladover et al. (2009) found that along the very wide El Camino Real corridor in Palo Alto and Mountain View, CA, with 26 signalized intersections, increasing minimum green times on the side streets from 7 to 11 s to provide a bicycle minimum green had negligible impacts on travel times and queue lengths.

For left-turn phases that bikes share with vehicles, it is common to use a minimum green of 4 or 6 s, in which case the impact of imposing a bike minimum green can be greater. Still, the impact is expected to be small because large impacts can only occur when an intersection is operating near capacity, and during those periods, left-turn volume typically dictates a green interval that is longer than bike minimum green.

In the U.S., the impact to traffic of providing bike red clearance time has generally been considered so onerous that the concept has been entirely omitted from national manuals. However, as described earlier, more precisely accounting for bike clearance can reduce the extra red clearance time.

One impact is in the realm of safety; for small increases in clearance time, there may be small improvements in safety. Schattler et al. (2003) found that while adding red clearance time to three intersections did not significantly change the number of related crashes, the number of late exits (i.e., vehicles not clearing an intersection until the next phase has started) significantly declined.

However, for large increases in red clearance time, there is widespread concern that it may lead to a large increase in red-light running, with strong, negative safety impacts.

The other impact is in efficiency. By introducing additional lost time into the signal cycle, longer red clearance times decrease capacity, increase vehicle delay, and—at intersections that are near capacity—may require a longer cycle length. However, the impact will often be small. Where a wide street is crossed by a side street that is not wide, only the side street would need additional clearance; and if the intersection is part of a coordinated system in which it is not critical, the capacity and delay impacts could be negligible.

For crossings whose phase length is governed by pedestrian-crossing needs, using efficient pedestrian clearance settings (see Section 7.4) can make it possible to provide bike red clearance without adding lost time by ending the vehicular green earlier while leaving the pedestrian timing unchanged.

Impacts can be limited by policy. For example, in Toronto, Ontario, providing bike red clearance is part of traffic signal policy, but extra red clearance time is limited to 1 s (Ontario, 2018; Toronto Transportation Services, 2015). And if bike red clearance is bike-actuated, impacts will most likely be negligible.

9.1.3 Considerations

9.1.3.1 Accessibility Considerations

Minimum green and red clearance settings that ensure sufficient clearance time for bikes are particularly relevant for slower bicyclists, including children, older adults, and tourists. At crossings used by slower bicycling populations, it may be advisable to measure bike speeds and startup offsets for calculating clearance needs.

9.1.3.2 Guidance

The AASHTO bike guide and STM2 provide guidance on minimum green and yellow change interval settings for bicycle clearance.

9.1.3.3 Relationships to Relevant Treatments

Bicycle detection (see Section 9.4) can improve the efficiency of this treatment, particularly for providing bike red clearance at long crossings. It is critical that the detector sense bicycles reliably. Accuracy in filtering out actuations from motor vehicles (e.g., a right-turning vehicle that encroaches on a bike lane) is not as critical, but inaccuracies will lower the treatment's efficiency.

Using efficient pedestrian clearance settings (see Section 7.4) lowers the impact of increasing bike red clearance when pedestrians are served concurrently with bikes.

9.1.3.4 Other Considerations

Bicycle crossing time can be affected by the slope of the approach roadways (which affects bicycle crossing speed); the grade to be overcome during the crossing, including grades due to a sharp crown in the surface of the road being crossed; and the ability of the cyclists to see cross traffic from their starting position. Also, where cross traffic is fast, cyclists often wait further back, increasing their crossing time (Shladover et al., 2009; Shladover et al., 2011).

9.1.4 Implementation Support

9.1.4.1 Equipment Needs and Features

No equipment adjustments are needed to change minimum green or red clearance settings in every cycle.

Some controllers have a built-in feature to enter a detector-actuated bicycle minimum green. When a bicycle call is detected, the controller will increase the minimum green in the next cycle to the bicycle minimum green. If that feature is not present, it can usually be added. Likewise, controllers will need to be programmed to apply detector-actuated bicycle red clearance.

To apply detector-actuation for either treatment, the only detector needed is a standard stop-line call detector, unless it is actuated too frequently by motor vehicles. If that cannot be corrected by adjusting the detector's sensitivity—for example, because the stop-line detector is in a shared travel lane rather than a bike lane or because right-turning vehicles routinely overrun the detector—then detector-actuated application may require a detector capable of distinguishing bikes from motor vehicles, such as a camera-based detector.

9.1.4.2 Phasing and Timing

Not applicable for this treatment.

9.1.4.3 Signage and Striping

Not applicable for this treatment.

9.1.4.4 Geometric Elements

Geometric changes that shorten bike crossings reduce clearance time needs. Examples include advanced stop lines for bikes, corner bulb-outs, road diets (on the street being crossed), and protected intersection layouts.

Intersection layouts that guide cyclists to make two-stage left turns eliminate the need for incorporating bicycle clearance needs into left-turn phase timing.

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9.2 Signal Progression for Bicycles

9.2.1 Basic Description

9.2.1.1 Alternative Names

Green wave for bicycles.

9.2.1.2 Description and Objective

Traffic signals can be coordinated so that bicycles arrive at successive signals during a green phase and therefore pass through without delay. This is accomplished by choosing signal offsets that closely match bicycle speed.

A signal offset for a given intersection is how much later its green begins than the green of a reference intersection, which is usually the first intersection in the series and can be numbered Intersection 1. To determine offsets on a one-way street, a progression speed is first chosen, then offsets for each successive intersection ($j = 2, 3, \ldots$) are determined using the formula in Equation 9-8:

$$offset_{1j} = \frac{d_{1j}}{v_{progression}} \tag{9-8}$$

where

$offset_{1j}$ = offset of signal j relative to signal 1 (the signal at Intersection 1) (s);
d_{1j} = distance from signal 1 to signal j (ft); and
$v_{progression}$ = progression speed (ft/s).

For example, if signals are 360 ft apart and the progression speed is 18 ft/s (12.3 mph), then beginning with an offset of 0 s at the first intersection, offsets for successive intersections are 20 s, 40 s, 60 s, etc.

On two-way streets, one-way coordination can be applied to a favored direction, which can switch by time of day; the other direction usually gets poor progression as a result (e.g., bicycles can typically get through only a few intersections before they get a red). Alternatively, signals can be timed for two-way coordination. Offsets for two-way coordination cannot be determined by formula (except for special cases); they are instead determined using signal timing software. The quality of two-way progression depends on intersection spacing and cycle length.

An ideal signal progression speed for bicycles is about 2 mph faster than average bicycle speed, or 12 to 13.5 mph (roughly 17.5 to 20 ft/s) on level ground. This avoids inhibiting faster bicycles and promotes signal compliance, while still enabling slower bicycles to stay in the green wave for a considerable distance. Grades should also be considered when determining ideal progression speed for bicycles.

9.2.1.3 Variations

Coordination can be one-way or two-way, as described earlier.

Small-zone coordination is a coordination scheme affecting only a few intersections, usually focused on a critical intersection at which bikes get only a short green period. Neighboring signals are timed so that bicycles released from an upstream signal arrive at the critical intersection just in time for its green, and bicycles released from the critical intersection can pass through downstream intersections without stopping.

Corridor- or grid-level coordination involves timing signals so that bicycles have a green wave along a corridor or along all the streets in a grid.

9.2.1.4 Operating Context

Main bicycle routes along streets with closely spaced traffic signals are good candidates for corridor-level coordination. Grid-level coordination can be applied where there is a grid of closely spaced intersections, such as in some downtowns.

Small-zone coordination can be a good treatment if an important bicycle route passes through a critical intersection with a long cycle length and a short green phase for bicycles that is near other traffic signals on the same route.

There is little benefit to implementing coordination where signal spacing is more than 1,200 ft apart since bicycle platoons disperse due to bicyclists' varying speeds.

9.2.2 Applications and Expected Outcomes

9.2.2.1 National and International Use

Both Copenhagen, Denmark, and Amsterdam, Netherlands, have green waves for bicycles on major bicycle routes. Copenhagen has bicycle green waves on several streets, of which the best known is Nørrebrogade. This is a very heavily used bicycle route on a historic, narrow road that has been prioritized for bikes—through-auto traffic is prevented by closing several blocks to autos, allowing bicycles and buses only. Signals are timed for one-way coordination (inbound in the morning, outbound in the evening) with a progression speed of 20 km/h (12.5 mph) (Colville-Andersen, 2014).

On Raadhuisstraat, a street in Amsterdam, 11 signals over a span of 650 m (0.4 mi) are timed with a progression speed of 18 km/h (11 mph) (Linders, 2013). They use one-way coordination, with a green wave inbound in the morning and outbound in the evening. This street has a considerable amount of auto traffic, and bikes on this street have a conventional bike lane, with bike demand so great that bikes often spill out into the adjacent travel lane. The green wave not only reduces bicycle delay but also improves safety by effectively limiting motor vehicle speed to 18 km/h, removing the incentive for motor vehicles to pass bicycles.

Copenhagen and Utrecht, Netherlands, have installed pilot projects that provide cyclists with advice on whether to speed up or slow down to make the next green phase. However, such systems cost a lot more than retiming signals, and both Copenhagen and Amsterdam have found that when intersection spacing is not large, cyclists quickly learn what speed will enable them to stay within the green wave (Colville-Andersen, 2014; Linders, 2013).

In the United States, New York City, San Francisco, CA, and Chicago, IL, have retimed streets for bicycle progression. New York's first application is the one-way couplet of Hoyt Street and Bond Street in Brooklyn, New York (see Exhibit 9-1), retimed in December 2018 with a progression speed of 15 mph (Colon, 2019; D. Nguyen, personal communication, 2019). A safety reason for this treatment is that cyclists going downhill (on Hoyt) were reluctant to stop at red signals, and a few red-light runners crashed into vehicles. Timing the signals so that through bicycles arrive on green eliminates most of that safety problem.

In San Francisco, Valencia Street and Folsom Street—both two-lane, two-way streets in a mixed-use context—were retimed for progression at 13 mph. The signal spacing is approximately 600 ft with a signal cycle of 60 s. While ideal one-way progression can be achieved with any progression speed, only one progression speed results in ideal green waves for two-way progression, as shown in Equation 9-9:

$$ideal\ two\text{-}way\ \ progression\ speed = \frac{signal\ spacing}{(cycle\ length)/2} \tag{9-9}$$

For Valencia Street and Folsom Street, that speed is 600/30 = 20 ft/s or 13.5 mph. With this design, bicycles get green waves in both directions. For bikes, this is an ideal solution. To some degree, finding an ideal progression speed that matches cyclists' speeds is lucky—if the cycle length had been 100 s instead or if signal spacing were 360 ft, the ideal progression speed would have been only 8 mph.

Source: Kuntzman (2020).

Exhibit 9-1. Hoyt Street in Brooklyn, timed for a bicycle green wave at 15 mph.

For vehicles as well as bicycles, the "ideal" progression speed is 13.5 mph (calculated using the same formula as Equation 9-9); this means that if signals were timed for a speed better suited to vehicles—for example, 25 or 27 mph—coordination would not be ideal and vehicles would still have to stop frequently, except during light traffic conditions. Instead, they can advance at a slow but steady speed of 13.5 mph. This also meets the desired driving regime for Valencia Street, as it is not meant to support through traffic (nearby parallel arterials have that function). Rather, it supports local traffic circulation with slower speeds. In addition, San Francisco has recently retimed signals for bicycle green waves on seven streets, using a 15 mph progression speed. Six of the seven streets are two-way, and intersection spacing is such that bicycles get green waves in both directions (Stonehill, 2016).

The downtown in Portland, OR, is a one-way grid with square blocks, 260 ft on each side. The signal cycle throughout the downtown is 56 s (60 s in peak hours). In a one-way grid, the progression speed that results in ideal one-way green waves in all four directions is given in Equation 9-10:

$$\textit{ideal progression speed (one-way grid)} = \textit{block circumference} / \textit{signal cycle length} \qquad (9\text{-}10)$$

For Portland's downtown, this is 12.7 mph (and 11.8 mph in peak hours). Portland has timed its downtown signals with this progression speed for decades, well before bicycling was popular. This regime serves bicycles well. This timing regime, known as quarter cycle offsets, offers good service for vehicles too; drivers have to go slowly but, in return, they can drive north, south, east, and west with almost no signal delay.

Portland also has an example of small-zone coordination for bicycles. On NE Broadway, a one-way street, bicycles receive a short green period at North Williams Avenue because the bicycle movement has to split time with a very heavy right-turn movement. To avoid the long bicyclist delay, the intersection is coordinated for bicycle progression with the upstream (NE Victoria Avenue) and downstream (North Vancouver Avenue) intersections. When bicycles are released from Victoria, a bicycle phase at Williams becomes scheduled to begin a few seconds later; it is actuated, so a bike phase at Williams is only called if a bicycle is detected just downstream of Victoria. The same combination of coordinated timing and actuation happens at Vancouver. Bicycles that pass Victoria on a stale green may not catch the green wave at Williams; however, once released at Williams, they will have a green wave through Vancouver. Overall, bicycles stop at most once through this set of three intersections. Littman and Furth (2013) show the phasing plan and a simulation video explaining how the coordination works.

9.2.2.2 Benefits and Impacts

For bicycles, enhanced coordination results in less delay. In addition, crash types associated with red-light running can be expected to go down when coordination enables most bicycles to arrive on green.

Small-zone coordination can be a critical component of safety projects. At intersections where the bicycle green phase is shortened to provide a protected-only turn phase to protect bicycles from turn conflicts, small-zone coordination can reduce bicycle delay and improve compliance, which also improves safety. For example, at Portland's NE Broadway and North Williams Avenue intersection, bicycles had previously crossed Williams with the vehicular phase, which involved a permitted conflict with heavy right-turn flow. It was changed to a concurrent-protected crossing (see Section 6.2), which protects bicycles from the turn conflict but at the same time drastically reduces bicyclists' green time. By providing a small-coordination zone for bikes, the Portland Bureau of Transportation kept the increase in bicycle delay small in spite of that greatly reduced green time, which helped ensure compliance and was critical to improving safety (Littman & Furth, 2013).

Lower progression speeds in combination with short cycle lengths (see Section 7.1) reduce speeding opportunities, thereby reducing extreme speeds, especially during periods of low traffic (Furth et al., 2018). This brings general safety benefits for pedestrians crossing the street (including those crossing away from the traffic signals) and for cyclists.

On one-way streets that are independently timed (i.e., not timed as part of a grid), ideal progression can be achieved for any desired progression speed. While bringing progression speed closer to bicycle speed on such streets will decrease bicycle delay by enabling bicycle progression, it will also increase delay for motor vehicles. Analysis conducted for this guidebook suggests that the delay increase to motor vehicles will typically exceed the delay reduction to bicycles. Exhibit 9-2 shows how bicycle delay and auto delay vary with progression speed on a one-way street whose cycle length is 90 s, with 40 s of green for the street of interest and with signalized intersections 0.1 mi apart. Bicycle speed is assumed to be in a range centered around 11 mph, and target auto speed is taken to be 25 mph.

As progression speed is lowered, delay reduction for bicycles stays small until progression speed gets within approximately 6 mph of bicycle speed (i.e., 17 mph in this example). Meanwhile, auto delay increases considerably when progression speed is reduced below the target speed. Thus, lowering progression speed to reduce bicycle delay on independently timed one-way streets does not appear to be a promising strategy unless a street has been prioritized for bicycling or there are other reasons that favor a reduction in progression speed (e.g., a goal of discouraging auto traffic).

9.2.3 Considerations

9.2.3.1 Accessibility Considerations

Not applicable for this treatment.

9.2.3.2 Guidance

Not applicable for this treatment.

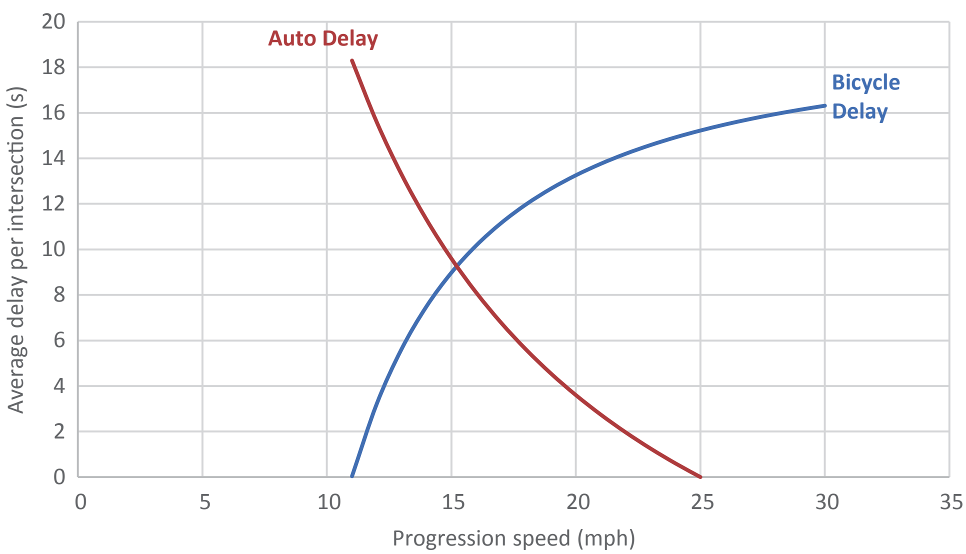

Exhibit 9-2. Through-bicycle and through-auto delays per intersection versus progression speed for an uncongested one-way street with 25 mph target speed.

9.2.3.3 Relationships to Relevant Treatments

Bicycle coordination should be considered in combination with treatments that substantially reduce bicycle green time to eliminate turn conflicts (e.g., protected-concurrent crossings) and reduce bicycle delay.

Combining low progression speeds with shorter cycle lengths reduces speeding opportunities on a street, reducing extreme speeding for vehicles.

9.2.3.4 Other Considerations

Not applicable for this treatment.

9.2.4 Implementation Support

9.2.4.1 Equipment Needs and Features

Not applicable for this treatment.

9.2.4.2 Phasing and Timing

Section 9.2.2.1 discusses signal timing considerations for providing signal progression for bicycles.

9.2.4.3 Signage and Striping

Not applicable for this treatment.

9.2.4.4 Geometric Elements

Not applicable for this treatment.

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9.3 Two-Stage Left-Turn Progression for Bicycles

9.3.1 Basic Description

9.3.1.1 Alternative Names

Pedestrian-style left turn; hook turn; box turn; Copenhagen left.

9.3.1.2 Description and Objective

To turn left at an intersection, bicyclists have the choice of making a vehicle-style turn, which typically involves shared use of a vehicular left-turn lane, or making a pedestrian-style turn, executed as a pair of simple crossings. In Exhibit 9-3, a northbound left (NBL) bicycle would first make Crossing (a) when the northbound movement has the green, wait in the far corner, and then make Crossing (b) when the westbound movement has the green.

Two-stage left turns are common in many European countries and are becoming popular in the United States. NACTO's *Urban Bikeway Design Guide* (2012) has guidance on their geometric design, including how to mark two-stage queuing boxes—also known as bicycle turn boxes—where cyclists wait between simple crossings. This treatment focuses on the signal timing aspects of two-stage left turns. If there is good signal progression between the two phases of a turn, bicycle delay can be moderate; however, without any progression, delay to left-turning cyclists can be very large.

Exhibit 9-4 provides an example with good progression for bicycles turning left from O Street to D Street. By providing a leading left turn for O Street and a lagging left turn for D Street, the through movement for O Street is immediately succeeded by the through movement for D Street. However, this phase sequence results in poor progression for left turns beginning on D Street; this makes it a good solution if left-turn demand from one street dominates, as might occur at a skew angle intersection. Where there is a full set of left-turn phases, it is not possible to provide good progression for all left turns as long as the crossings are unidirectional.

Making bicycle crossings bidirectional gives cyclists a choice in how to make their crossing and creates new opportunities for providing left-turn progression, as explained in the Dutch bikeway design guide (CROW, 2016). In the example shown in Exhibit 9-5, left turns are sequenced (as in Exhibit 9-4) so that the through movements for one street (in this case, the east–west street) are immediately followed by the other street's through movements. With bidirectional crossings (also shown in Exhibit 9-5), this phasing sequence creates good progression for all

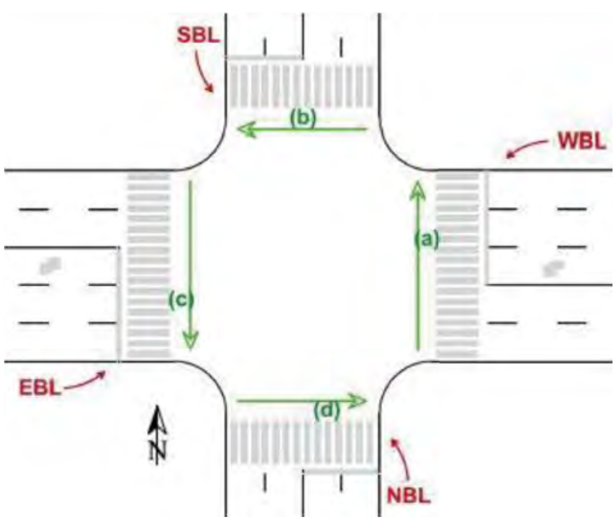

Exhibit 9-3. Unidirectional bicycle crossings for making a two-stage left turn: Cross at (a) then (b) for northbound left (NBL); (b) then (c) for westbound left (WBL); (c) then (d) for southbound left (SBL); and (d) then (a) for eastbound left (EBL).

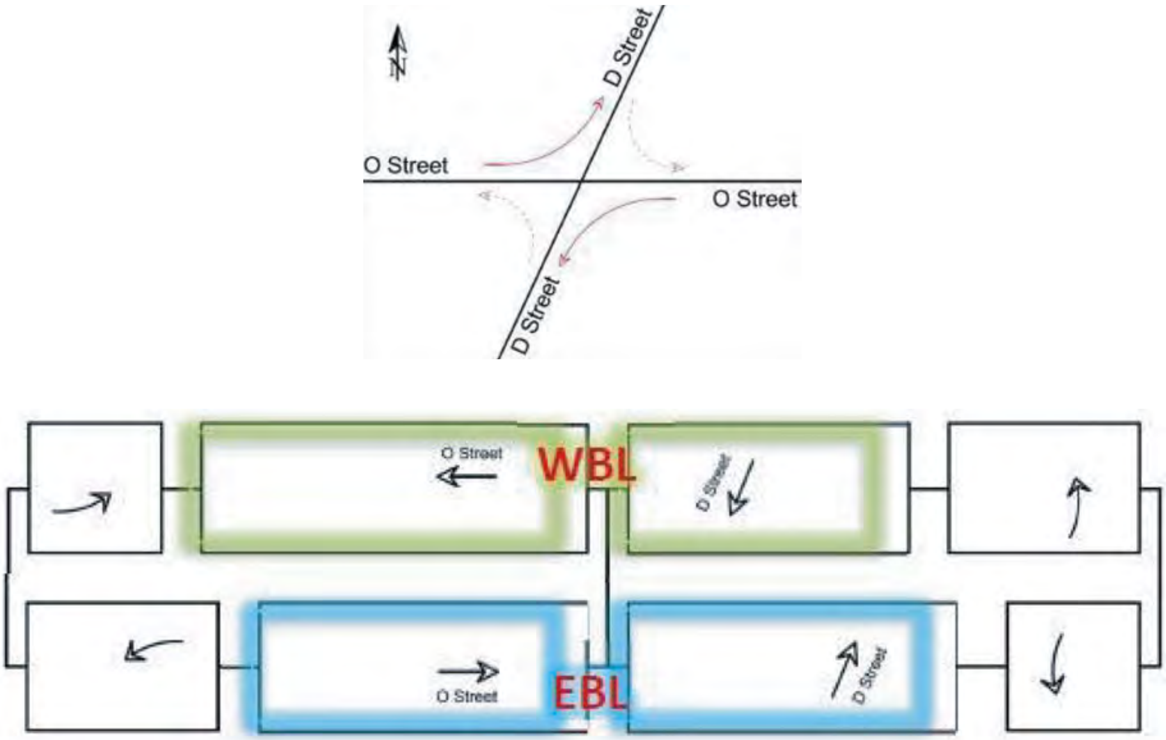

Exhibit 9-4. Lead-lag progression for bicycles traveling from O Street to D Street.

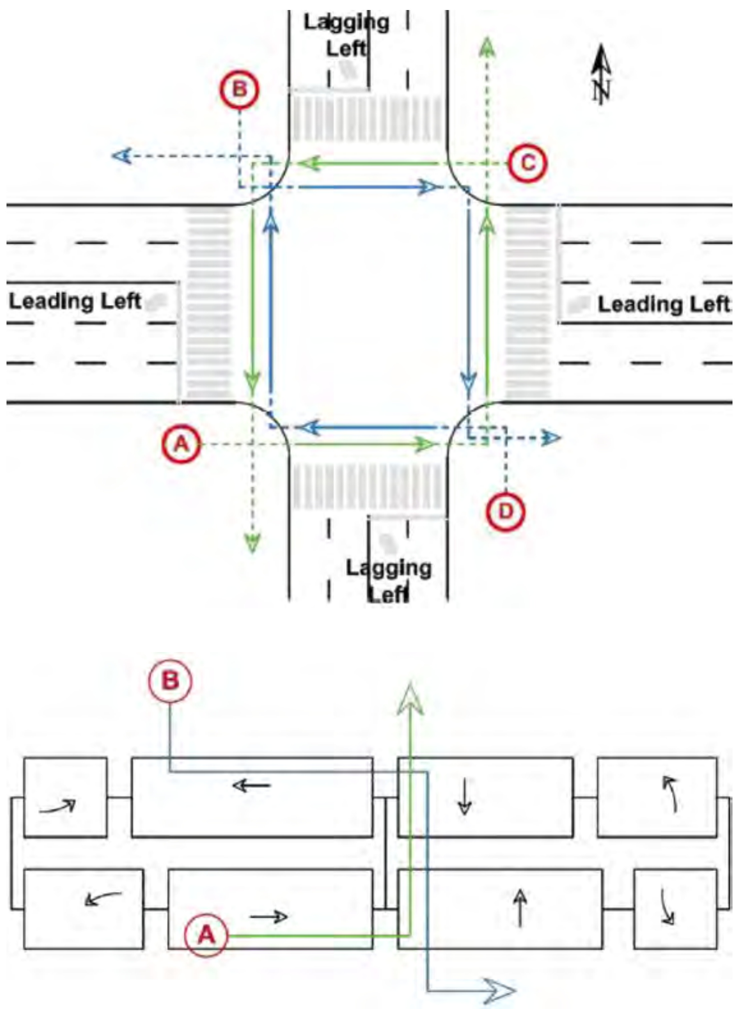

Exhibit 9-5. Bidirectional bicycle crossings, allowing for additional crossing movements.

bicycle left turns, as every left turn becomes possible by first crossing with the east–west street and then finishing with the north–south street. Left-turning bicyclists approaching the intersection at Crossings A and C can make their left turn by traveling counterclockwise (following the green arrows), and those approaching at Crossings B and D can make their left turn by traveling clockwise (following the blue arrows). However, cyclists are not obligated to follow the directions with good progression; they minimize their delay by choosing the first crossing at their arrival corner that gets a green light.

9.3.1.3 Variations

Not applicable for this treatment.

9.3.1.4 Operating Context

This treatment is applicable wherever bicycles make two-stage left turns and the phasing plan includes left-turn phases. It is particularly important where a main bicycle route turns or switches from one side of a street to the other or switches from a bidirectional path on one side of a street to unidirectional paths on the other, forcing a large stream of bicyclists to make two-stage turns.

9.3.2 Applications and Expected Outcomes

9.3.2.1 National and International Use

In Denmark, two-stage left turns are mandatory since vehicular-style left turns are prohibited by law, except between local streets that lack a centerline. In the Netherlands, while there is no such prohibition, road design guidelines require provision for two-stage left turns at traffic signals. Dutch traffic planning emphasizes the need to provide good progression for two-stage turns, and standard intersection analysis includes measuring delay for two-stage left turns. Intersections there often have phasing plans and bidirectional crossings for improving two-stage turn progression.

Wagenbuur (2014) describes an example in ‘s-Hertogenbosch, the Netherlands, in which a bidirectional bike path on one side of a street transitions to unidirectional paths on either side of the street, forcing a large volume of bicyclists to make a two-stage turn. To reduce delay, crossings are bidirectional, giving bicyclists a choice of two routes: one beginning with a northbound crossing and the other beginning with a westbound crossing. A dynamic display has been set up pointing bicyclists to the crossing that will next get a green signal.

9.3.2.2 Benefits and Impacts

To assess the benefit of this treatment, one needs to be able to measure average delay for two-stage turns, something that is still new to American practice (see Section 3.3). Delay for a two-stage turn is not equal to the sum of the average delay of the two crossings that make up the turn—it may be considerably greater or lower, depending on the progression, and it can be far less where bidirectional crossings create two path options for people turning left. The Northeastern University Ped and Bike Crossing Delay Calculator is a freely available tool that can be used to determine average delay for two-stage turns, including those with bidirectional crossings (Furth & Wang, 2015).

By using a phasing sequence that creates good progression for two-stage turns, bicycle delay can be substantially reduced. In one example, Furth et al. (2019) show that with bidirectional crossings and a favorable phasing sequence, two-stage left-turn delay can be comparable to delay for bikes making a single-stage crossing.

Changing phase sequence to improve bicycle turn progression will have no impact on traffic operations at many intersections, while at others it may affect arterial progression and thereby increase auto delay.

9.3.3 Considerations

9.3.3.1 Accessibility Considerations

Not applicable for this treatment.

9.3.3.2 Guidance

Not applicable for this treatment.

9.3.3.3 Relationships to Relevant Treatments

Providing short cycle lengths (see Section 7.1) will help further reduce bicycle delay at two-stage left turns.

Two-stage left turns with good progression can be an alternative to an exclusive diagonal bicycle phase (in which a bike path crosses from one side of the street to another or transitions between a bidirectional path and one-way bike lanes) (see Section 6.3).

9.3.3.4 Other Considerations

Not applicable for this treatment.

9.3.4 Implementation Support

9.3.4.1 Equipment Needs and Features

Not applicable for this treatment.

9.3.4.2 Phasing and Timing

Section 9.3.2.1 provides phasing and timing guidance.

9.3.4.3 Signage and Striping

Both NACTO and the *Manual on Uniform Traffic Control Devices* provide guidance on how to design two-stage turn boxes, with detailed information on pavement markings and striping.

9.3.4.4 Geometrics

Bidirectional crossings must be wider than unidirectional crossings. Queuing areas in the corners of an intersection should be large enough to hold waiting bicyclists, including those waiting to make the second stage of their turn.

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9.4 Bicycle Detection

9.4.1 Basic Description

9.4.1.1 Alternative Names

Bicycle actuation.

9.4.1.2 Description and Objective

In bicycle detection, the presence of bicyclists is made known to the signal controller, which can use that information to activate the signal for phases that serve bikes, including calling for service (see Section 7.5), extending the minimum green interval (see Section 9.1), extending red clearance (see Section 9.1), and extending the green for bicycle clearance (see Section 9.1). The objective is to make traffic signal operations more efficient by running or extending phases for bikes only when needed, rather than in every cycle. A secondary benefit is that bicycle detectors can be used to collect data on bicycle use that can be archived and used for many purposes, including monitoring bicycle-use trends and signal timing design.

For some applications, calling for a phase that bicycles share with autos—that is, picking up both bicycles and autos without distinguishing them, also known as mixed detection—is sufficient. For actuating bicycle-specific phases and extensions, exclusive detection (detecting bicycles only) or selective detection (detecting bicycles from within a mixed traffic stream) is necessary.

9.4.1.3 Variations

A variety of technologies can be used for bicycle detection. Inductive loops, buried in the pavement, detect the presence of metal. Their shape and sensitivity can be tailored to maximize the chance that a bicycle is detected while minimizing false calls from vehicles in an adjacent lane. In a lane shared with autos, they provide only mixed detection, while in a physically separated bike lane, they provide exclusive detection. In conventional bike lanes, their ability to provide exclusive detection depends on whether autos encroach in the bike lane, such as when making right turns. For extending minimum green and red clearance times, occasional encroachment can be tolerated.

Video with image processing can be a powerful method for selective detection. At night, image processing algorithms oriented to autos rely on identifying headlights; different algorithms are needed to identify bicycles.

Bicycles can also be detected using pushbuttons, although this method is inconvenient for bicyclists except when used as a backup for another automatic detection method.

Bicycle detection can be considered near the stop bar or upstream from a given intersection (i.e., in advance). Stop-bar placement or advanced detection is appropriate for calling for service, extending minimum green, or extending red clearance; advanced detection is needed to provide green extension for bike clearance.

9.4.1.4 Operating Context

Call detectors that can detect bicycles are needed wherever the phases that serve bikes are actuated, including both bicycle phases and mixed traffic phases.

Bicycle detectors with exclusive or selective detection can be considered for all intersection approaches used by bicycles in conjunction with the treatments that are based on bicycle clearance (bike minimum green, bike red clearance, and green extension for bike clearance), as described in Section 9.1. While the first two of these treatments can also be applied without detectors, using exclusive or selective detection makes it possible to apply those extensions only in cycles in which a bicycle is present to benefit from it.

9.4.2 Applications and Expected Outcomes

9.4.2.1 National and International Use

Using bicycle-sensitive call detectors for phases shared by bicycles and autos is common in the United States. Where bikes share a lane with motor traffic, a special loop layout resembling a figure eight is used to increase a detector's sensitivity to the relatively small amount of metal in a bicycle. In keeping with an option described in the *Manual on Uniform Traffic Control Devices* (MUTCD) (2009), a small bicycle silhouette with a broken line can be marked on the part of the detector with maximum sensitivity, accompanied by an explanatory sign (as shown in Exhibit 9-6). One weakness of this approach is that the combination of marking and sign is not well understood; another is that the small bike silhouette marking often does not survive winter snow removal operations, and if it is not replaced, the sign becomes meaningless.

Based on public outreach, Portland developed the marking shown in Exhibit 9-7 for use with inductive loops. In this design, the information is provided as part of the marking rather than in an accompanying sign.

For detectors in bike lanes, STM2 recommends setting the detector back a short distance to minimize actuations from vehicles that are turning right.

In the Netherlands, small inductive loops near the stop bar are used to detect bicycles in physically separated bike lanes, with pushbutton backup (see photo in Section 8.2). A call indicator lights up when the bicycle is detected, so bicyclists know that if the loop detector senses them, they do not need to push the pushbutton. Some intersections have an upstream call detector as well so that, during periods of light traffic, a bicyclist detected at the upstream detector may get a green light without having to stop.

In the U.S., Portland has been a leader in developing and applying inductive loop detectors for separated bike lanes. Portland also use pushbuttons (without loops) for bicycle detection, and has used educational campaigns to help cyclists better understand how to be detected.

In the Netherlands, an app called "Schwung" has been developed that enables signal controllers to detect approaching bikes using cyclists' smartphones several seconds before they arrive

Source: MUTCD (2009), Figures 9B-2 and 9C-7.

Exhibit 9-6. MUTCD marking and sign for inductive loop bicycle detectors.

Source: Maus (2016).

Exhibit 9-7. A bicycle loop detector marking developed in Portland.

at an intersection. At the same time, controller logic has been modified to use this information to more quickly change phases in favor of bikes and to extend bike phases (Wagenbuur, 2018).

9.4.2.2 Benefits and Impacts

The effectiveness of inductive loop detectors in shared lanes depends on whether bicycles position themselves where the detector has greatest sensitivity. Research has found that many bicyclists do not understand the meaning of the MUTCD's "9C-7" marking and corresponding sign shown earlier in Exhibit 9-6 (Boot et al., 2013; Bussey, 2013). Making matters worse, the zone of heightened sensitivity in the standard layout of a bike-sensitive loop detector is the middle of a lane, while cyclists tend to ride near the right edge of a lane. Boudart et al. (2016) found that 60% of survey respondents understood the meaning of Portland's marking (shown earlier in Exhibit 9-7), a 30% improvement over locations that did not have the explanation provided as part of the pavement marking.

A literature review done by Portland found that advanced bicycle detection (using an automated, passive system) reduces bicycle delay but was not associated with any safety impact (City of Portland, 2010).

Bicycle detection using active infrared, video image processing, and cell phone app technologies are developing rapidly, but at this time they have not been well documented.

9.4.3 Considerations

9.4.3.1 Accessibility Considerations

Pushbuttons intended for bicyclists should be reachable without requiring that they deviate from their path. Path deviations that require bicyclists to shift laterally are difficult for those with limited strength or balance and for those who are carrying children. Pushbuttons should be set back enough from the curb that the bicycle will not encroach on the conflicting roadway (for more detail, see Section 8.3).

9.4.3.2 Guidance

Not applicable for this treatment.

9.4.3.3 Relationships to Relevant Treatments

Pedestrian recall versus actuation (see Section 7.5) discusses considerations that are also relevant to bicycle phases being actuated.

When implementing bicycle detection, it is desirable to provide call indicators (see Section 8.2) to assure bicyclists that they have been detected, which may improve compliance.

Pushbuttons should be located for safety, convenience, and accessibility (see Section 8.3).

Minimum green and change interval settings (see Section 9.1), including bicycle red clearance, can be applied more efficiently using bicycle detection.

Flashing indicators for permitted conflicts (see Section 6.9) could be dynamic, that is, activated only when a bicycle is detected.

9.4.3.4 Other Considerations

Real-time applications of active infrared detection and video image processing are not well documented or researched. As the technology for these methods advances, there will be more opportunities to include them for bicycle detection at signalized intersections instead of just for bicycle counting purposes.

9.4.4 Implementation Support

9.4.4.1 Equipment Needs and Features

Most modern traffic signal controllers allow for bicycle detection inputs.

9.4.4.2 Phasing and Timing

Not applicable for this treatment.

9.4.4.3 Signage and Striping

Section 9.4.2.1 provides examples of signing and striping for bicycle detection.

9.4.4.4 Geometric Elements

Not applicable for this treatment.

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9.5 Bicycle Wait Countdown

9.5.1 Basic Description

9.5.1.1 Alternative Names

Wait signal; bicycle red countdown.

9.5.1.2 Description and Objective

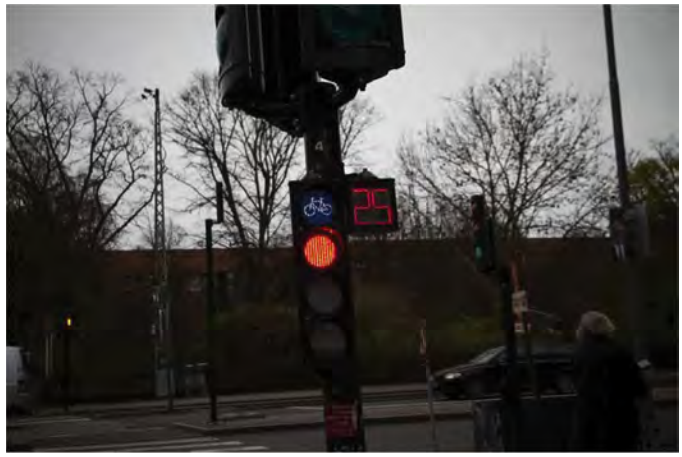
Bicycle wait countdown devices indicate the time remaining in the bicycle red period, often in combination with displaying the word "Wait." They aim to improve cyclist red-light compliance and to reduce the anxiety associated with waiting.

9.5.1.3 Variations

The countdown can have a figurative display, which shows an arc of lights becoming successively shorter (see Exhibit 9-8), or it can have a digital display, which shows the number of seconds remaining in the red period (see Exhibit 9-9). The figurative display is more appropriate with fully actuated control since the time remaining in the red interval is not known.

Source: Peter J. Koonce.

Exhibit 9-8. Wait signals in Amsterdam (left) and Portland (right), with time shown as a shrinking arc. "Wacht" is Dutch for "Wait."



Source: Colville-Andersen (2014).

Exhibit 9-9. Numerical wait countdown in Copenhagen.

9.5.1.4 Operating Context

Bicycle wait countdown signals may be an appropriate treatment for bicycle signals when there is a desire to increase cyclist compliance with the red signals.

9.5.2 Applications and Expected Outcomes

9.5.2.1 National and International Use

Amsterdam introduced wait signals in order to reduce noncompliance with red signals. They are now used at more than 50 intersections in the city. Some use numeric countdowns; others show a shrinking arc. Digital countdowns stop 5 s before bicycle signals turn green so that bicyclists will look to the bicycle signal, not the countdown, for their cue to depart.

In North America, the only known application of this treatment is in Portland (see Exhibit 9-8). At this intersection, the red period varies in length from cycle to cycle, so the “time remaining” indicator remains at the “full” position during the cross street’s green and declines during the cross street’s yellow interval and red clearance interval.

9.5.2.2 Benefits and Impacts

According to Fong et al., a 2003 international scan sponsored by FHWA noted that the use of shrinking-arc wait countdowns in the Netherlands reduced bicycle red-light running by 25% to 30%. Additionally, the same scan revealed that 60% of users thought their waiting time was shorter, and 78% of users found the bicycle wait countdown information helpful.

However, Amsterdam officials report, based on an internal study, that wait countdowns led to no net change in bicycle red-light running. While there was some reduction in bicycles departing early during the red period, it was offset by an increase in bicycles departing late during the red period. Nevertheless, there is a general perception that shrinking-arc wait countdowns improve compliance; therefore, the transportation department often receives requests to install them (S. Linders, personal communication, 2018).

9.5.3 Considerations

9.5.3.1 Accessibility Considerations

Not applicable for this treatment.

9.5.3.2 Guidance

Not applicable for this treatment.

9.5.3.3 Relationships to Relevant Treatments

Not applicable for this treatment.

9.5.3.4 Other Considerations

When a wait countdown device is visible to waiting motorists, there is concern about whether motorists might use this information and what its impact might be. In Amsterdam and Portland, using a shrinking-arc display—or in the case of a numeric display, halting the countdown at "5"—seems to have avoided any such issue.

9.5.4 Implementation Support

9.5.4.1 Equipment Needs and Features

The wait/countdown device should be mounted next to the bicycle signal, so that its meaning and intended audience (i.e., bicyclists) is clear.

A wait/countdown device can be smaller if it is mounted next to a bicycle signal that is on the near side of an intersection, as bicycle signals are in Europe. In North America, where bicycle signals are far-side, a larger device is needed unless the crossing has a supplemental near-side bicycle signal.

Bicycle wait countdown displays are not available in the U.S. market. The one located in Portland was imported from Europe, and its wiring was adapted for American AC (alternating current) voltage and frequency.

9.5.4.2 Phasing and Timing

Not applicable for this treatment.

9.5.4.3 Signage and Striping

Not applicable for this treatment.

9.5.4.4 Geometric Elements

Not applicable for this treatment.

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9.6 Easing Bicycle Right Turn on Red Restrictions

9.6.1 Basic Description

9.6.1.1 Alternative Names

Bicycle turn on red.

9.6.1.2 Description and Objective

This treatment encompasses two provisions that can be applied independently. One is exempting bicycles from no turn on red (NTOR) restrictions; the other is requiring bicyclists to only yield, not stop, when turning right on red. The objectives are to reduce bicycle delay and to promote equity by legalizing safe, common behaviors.

9.6.1.3 Variations

For spot applications, exemptions from an NTOR restriction can be implemented by posting bike exception signs, as in Exhibit 9-10. For systematic application, state law can be changed to exempt bicycles from NTOR restrictions.

In New York City and on the island of Montreal, Québec—the only places in the United States and Canada, respectively, where RTOR is prohibited by default—spot application of an exemption could be applied using signs such as those used in France to allow RTOR and to allow cyclists at the top of a "T" intersection to go through on red, with an obligation to yield to pedestrians (see Exhibit 9-11).

Removing a bicyclist's obligation to stop when turning right on red (while retaining the obligation to yield to pedestrians and to vehicles that have lawfully entered the intersection) can be done through legislation that applies only where bikes are allowed to turn right on red. Such a law could also be applied universally, encompassing a universal NTOR exemption.

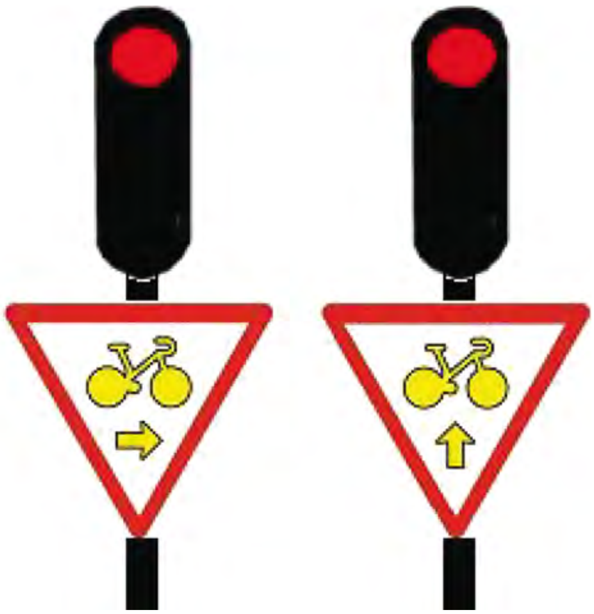
9.6.1.4 Operating Context

Exempting bikes from NTOR restrictions can be considered at any intersection with an NTOR restriction. It can be considered for specific locations by using signs or universally by means of legislation.

Allowing bikes to turn right on red without stopping, but with an obligation to yield, can probably only be implemented statewide, through legislation. It could be limited to intersections

Source: Peter Furth.

Exhibit 9-10. Bicycle exemption from NTOR restriction, Cambridge, MA.



Source: Mieux se Déplacer à Bicyclette.

Exhibit 9-11. Signs in France permitting bikes to turn right on red (*left*) and go through on red but only at the top of a T-intersection (*right*).

where bicycles are already allowed—by existing laws—to turn right on red, or it could be applied universally, in which case it would encompass a universal exemption to NTOR restrictions.

9.6.2 Applications and Expected Outcomes

9.6.2.1 National and International Use

In the U.S., bicyclists routinely violate RTOR restrictions. Yielding, but not necessarily stopping, when turning right on red is also common practice. Since 1982, Idaho law has allowed bicyclists to turn right on red with an obligation to yield but not to stop. Starting in 1982, the obligation to stop was lifted at both Stop signs and at red traffic signals. In 2005, the law was amended to reinstate the obligation to stop at red traffic signals, except for bikes turning right on red. (Recently adopted "Idaho stop" laws in Delaware, Arkansas, Oregon, and Washington State apply only at Stop signs, without any provision regarding RTOR.)

Posting bicycle exemptions to NTOR signage is rare. Cambridge has posted exemptions to NTOR restrictions at a few intersections where the restriction appeared to be hindering cyclists. For example, the intersection in Cambridge shown previously in Exhibit 9-10, at Broadway approaching Galileo Galilei Way, has concurrent-protected crossings (see Section 6.2), with right turns for vehicles allowed only during a short phase that overlaps with a left-turn phase. With the NTOR exemption, bicycles—which approach in a separated bike lane along the right curb—are allowed to turn right during other phases as well, particularly during the through phase. Due to a railroad crossing, the bicycle and vehicle stop lines are set back about 60 ft from the curb of the cross street, which led to more bicyclists than usual stopping for a red light rather than informally turning right on red, as they do at most other intersections (P. Baxter and C. Seiderman, personal communication, September 2018).

In the Netherlands, where RTOR for vehicles is almost unknown and enforcement of bicycle laws is stricter, bicycles may legally turn right at most signalized intersections. The most common mechanism—which applies where both intersection streets have cycle tracks (i.e., separated bike lanes)—is that the stop line for bicycles is at the curb of the cross street, so that bicyclists turning right from one cycle track to another never pass the stop line and therefore are not regulated by the traffic signal. This is known colloquially as "right turn past red" (Wagenbuur, 2012). At intersections lacking this layout, a sign permitting bicyclists to turn right on red is sometimes posted.

9.6.2.2 Benefits and Impacts

Exempting bicycles from RTOR restrictions and allowing them to turn on red without stopping (provided that they yield to pedestrians and other road users who have legally entered the intersection) will reduce bicycle delay. Additionally, easing these restrictions will legalize the behavior of many bicyclists who commonly ignore these restrictions.

It is unlikely that there will be any negative safety impact from easing RTOR restrictions on bicyclists because these restrictions are often violated already. Furthermore, the safety reasons behind most NTOR restrictions from motor vehicle considerations either do not apply to bicycles or apply too weakly to merit a restriction. These reasons include turning onto high-speed roads (which usually have a shoulder or bike lane into which a bicycle can turn safely) and preventing turning vehicles from blocking a crosswalk while waiting to turn on red (this is not a problem for turning bicycles as they usually wait beyond the crosswalk, and their ability to use bike lanes and shoulders means they rarely have to wait). RTOR restrictions prevent vehicle collisions with crossing pedestrians, but pedestrian collisions are far less likely with bicycles compared to motor vehicles because of their smaller size and mass and their better lateral visibility (i.e., no A-pillar obstructing their view).

Easing RTOR restrictions on bicycles is similar to easing restrictions at Stop signs. A study of the safety impact of Idaho's stop law found that the law has been beneficial or had no negative effect (Meggs, 2010).

9.6.3 Considerations

9.6.3.1 Accessibility Considerations

Not applicable for this treatment.

9.6.3.2 Guidance

Not applicable for this treatment.

9.6.3.3 Relationships to Relevant Treatments

Not applicable for this treatment.

9.6.3.4 Other Considerations

Not applicable for this treatment.

9.6.4 Implementation Support

9.6.4.1 Equipment Needs and Features

Not applicable for this treatment.

9.6.4.2 Phasing and Timing

Not applicable for this treatment.

9.6.4.3 Signing and Striping

Not applicable for this treatment.

9.6.4.4 Geometric Elements

Not applicable for this treatment.

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CHAPTER 10

Techniques for Multistage Crossings

This chapter describes treatments that might be applied in connection with multistage crossings and have not been described in previous chapters:

Primary Function	Section	Treatment Name
Provide convenient and accessible crossings	10.1	Multistage Crossings
Reduce pedestrian delay using left-turn overlaps	10.2	Left-Turn Overlap for Pedestrian Half-Crossings
Provide safe crossings for bicycles at multistage crossings	10.3	Single-Pass Bicycle Crossings with Two-Stage Pedestrian Crossings

Multistage Crossings (**Section 10.1**) addresses general themes related to pedestrian crossings, including pedestrian signalization options, accessibility considerations, and the critical importance of pedestrian progression in mitigating pedestrian delay at multistage crossings.

Left-Turn Overlap for Pedestrian Half-Crossings (**Section 10.2**) explains a technique that creates more opportunities for pedestrians to cross to or from a median island by letting them cross during left-turn phases, thereby reducing their delay. The potential to use this treatment depends heavily on whether left-turn phases are actuated versus on recall (see Section 7.5) and whether minimum green is adapted to demand (part of Section 7.3, which discusses maximizing Walk interval length).

Single-Pass Bicycle Crossings with Two-Stage Pedestrian Crossings (**Section 10.3**) is a treatment that acknowledges speed differences between bicycles and pedestrians, as well as their differing storage area requirements, and describes how this can lead to serving them differently at intersections with multistage crossings.

Pertinent Treatments Described in Previous Sections

In Chapter 6, **Channelized Right Turns/Delta Islands** (**Section 6.4**) describes a treatment that creates signalized multistage crossings if the crossings between the sidewalk and delta islands are signalized.

Several techniques described in earlier sections can play an important role in improving multistage crossings:

- **Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds (Section 6.7).**
- **Short Cycle Length (Section 7.1).** Because virtually all pedestrian crossings are two-way, providing good progression in both directions is only possible when a cycle is short. At the same time, using multistage crossings can sometimes make it possible to have a shorter cycle.

- **Reservice (Section 7.2).** This treatment is especially relevant in relation to partial crossings to and from delta islands.
- **Maximizing Walk Interval Length (Section 7.3).**
- **Pedestrian Recall versus Actuation (Section 7.5).** This treatment is especially pertinent in relation to left-turn overlaps.

In addition, measuring pedestrian delay (see Section 3.3) is particularly critical with multistage crossings. The rule that pedestrian delay is roughly proportional to cycle length does not apply with multistage crossings. Pedestrian delay can be far greater than one might expect unless a timing plan ensures good progression. With multistage crossings, it is important to measure pedestrian delay by direction because the delay to pedestrians walking in one direction through a set of partial crossings can be substantially different from the delay to those walking through the same set of partial crossings but in the opposite direction.

10.1 Multistage Crossings

10.1.1 Basic Description

10.1.1.1 Alternative Names

None.

10.1.1.2 Description and Objective

A multistage crossing is a crossing that is physically divided into two or more partial crossings interrupted by crossing islands, also called refuge islands (see Exhibit 10-1).

By breaking a long crossing into parts, multistage crossings can improve pedestrian safety and comfort as well as make crossings more accessible to pedestrians with walking disabilities. Multistage crossings can improve intersection efficiency due to the shorter pedestrian clearance interval requirements, which may lead to shorter signal cycles and greater capacity. In addition, multistage crossings can reduce pedestrian delay if more crossing opportunities and signal progression from

Source: Google Maps.

Exhibit 10-1. Multistage crossing example at the intersection of East Flamingo Road and Boulder Highway in Las Vegas, NV.

one partial crossing to the next are given to pedestrians. An example of this is overlapping pedestrian phases with left-turn phases that are not in conflict with one another (see Section 10.2).

At the same time, multistage crossings can lead to exceedingly long pedestrian and bicycle delays if signal timing does not provide good progression between partial crossings. With poor progression, average pedestrian delay for multistage crossings can be more than double the delay of a single-stage crossing. Pedestrian noncompliance is known to increase with delay, posing a significant safety issue if signal timing causes long waiting times on a crossing island. Furthermore, pedestrians often complain about signal timing that leaves them stranded in the middle of the street. Therefore, a critical objective in the design of multistage crossings, not just for convenience but for safety as well, is to minimize pedestrian delay by providing progression from one partial crossing to the next.

10.1.1.3 Variations

Where an island physically divides a crossing into two parts, different configurations can be used that determine the degree to which the crossing functions as a multistage versus single-stage crossing:

a. **Treat it as a simple, single-stage crossing with no waiting intended in the island.** Passage through the island is treated as part of the crosswalk, and the pedestrian clearance interval is based on crossing the full street. Formally, this is not a multistage crossing, and no signals or detection is provided on the island. The crossing island may be used informally. This treatment is used, for example, in Cambridge, MA, on the northern part of Massachusetts Avenue.
b. **Design the island as a pedestrian refuge, but time signals so that nobody has to wait at the island.** The island includes pedestrian displays facing both directions, accessible pushbuttons for both directions, and truncated domes. However, the pedestrian phases are timed assuming that there is no island, with the pedestrian clearance time calculated for crossing the entire street. This typically results in a short Walk interval and a long Flashing Don't Walk (FDW) interval. With this configuration, no pedestrian who begins crossing during the Walk interval will have to wait on the island, except for very slow pedestrians. This option presents some ambiguity because pedestrians are expected to leave the median island facing a FDW display, a sign that normally means "don't begin crossing." New York City uses this option for crossings of Broadway north of 59th Street.
c. **Design the island as a pedestrian refuge and provide a pedestrian phase long enough for a single-stage crossing, but run the pedestrian signals for half-crossings.** As in Option b, the island is designed as a pedestrian refuge, but in this configuration, the pedestrian clearance intervals are based on the lengths of the half-crossings and are therefore relatively short. To support a single-stage crossing, the Walk interval is long. Pedestrians who begin crossing early in the Walk interval can cross in a single stage, while those who begin later in the Walk interval will only have enough time to reach the island and will have to wait there until the next cycle. This option has less pedestrian delay than Option b since those who begin late in the Walk interval will finish their crossing sooner than if they had waited until the next cycle to start crossing (as they would in Option b). New York City uses this option for crossings of Queens Boulevard.
d. **Design the island as a pedestrian refuge, time pedestrian signals for half-crossings, and do not provide a single-stage crossing.** This is the general case for a multistage crossing, offering the greatest flexibility. However, it also carries the danger that unless signal timing ensures good progression for pedestrians between each crossing, pedestrian delay could be very high.

At intersections with channelized right turns and delta islands (see Section 6.4), crossings across the channelized turns are considered stages of a crossing if they are signalized.

It is possible to have a crossing that is two-stage for pedestrians yet single-stage for bicycles, as discussed in Section 10.3.

An intersection where pedestrians have a strong desire line for a diagonal crossing but have to make it by following two square crossings can be considered a two-stage pedestrian crossing. Techniques for multistage crossings can therefore be applied to serve such desire lines, just as they are applied to two-stage left turns for bicycles (see Section 9.3), which can also be considered a type of multistage crossing.

10.1.1.4 Operating Context

Multistage crossings might be appropriate for intersections:

- With long crossings where providing a single-stage crossing can drastically impact intersection capacity;
- With a crossing that has an existing median large enough to serve as a safe waiting area for pedestrians;
- Where there are channelized right turns and either intersection geometry or a high volume of right-turn traffic makes it unsafe to allow unsignalized partial crossings across the right-turn lane (see Section 6.4); and
- Where pedestrians or bicyclists have an important diagonal desire line that is served by a pair of square crossings.

At the same time, unless signal timing can offer good progression from one partial crossing to the next, it may be more appropriate to avoid multistage crossings or to time the pedestrian signals for single-stage crossings.

10.1.2 Applications and Expected Outcomes

10.1.2.1 National and International Use

Multistage crossings are a standard treatment both in the United States and internationally. They are more common in countries where multilane roads usually have medians (because long, uninterrupted pedestrian crossings are discouraged), such as the Netherlands.

A key difference between Dutch and American practice is that in the Netherlands, minimizing pedestrian delay is an essential part of multistage crossing design, while in typical American practice, pedestrian delay at multistage crossings is rarely measured or minimized. As a result, average pedestrian delay often ends up being extremely long—sometimes exceeding 120 s, which is more than double the 60 s threshold at which pedestrian level of service is "F" (*Highway Capacity Manual*, 2000).

To avoid these long delays and associated safety problems, some U.S. cities seek to avoid multistage crossings or at least time signals to facilitate single-stage crossings. For example, before 2000 many NYC crossings of wide streets with medians were timed for two-stage crossings, but they have all since been retimed so that pedestrians can cross in a single stage.

10.1.2.2 Benefits and Impacts

Benefits and impacts discussed in this section include:

- Safety and accessibility benefits of interrupting a long crossing with a pedestrian island;
- Safety and delay benefits from replacing multistage crossings with single-stage crossings;
- Delay reductions as a result of improved pedestrian progression; and
- Delay reductions and safety improvements gained by facilitating short signal cycles.

Measuring delay impacts requires a method to measure pedestrian delay at multistage crossings. The Northeastern University Ped and Bike Crossing Delay Calculator is a free tool that can be used for this purpose, available at https://peterfurth.sites.northeastern.edu/2014/08/02/delaycalculator/ (Furth et al., 2019). A new *Highway Capacity Manual* (HCM) procedure and computational engine for measuring pedestrian delay at multistage crossings has also been developed (Ryus et al., in press), which will be included in an update of the HCM that was in publication at the time of writing.

Safety and accessibility benefits of interrupting a long crossing with a pedestrian island. A long crossing can be a barrier to slower pedestrians. Interrupting it with a refuge island can enable pedestrians with disabilities to cross a street that they might not otherwise be able to cross. Similarly, long crossings present a hazard to pedestrians who, for any reason, find themselves only partway across the street when the signal is about to change (e.g., adults crossing with small children). A refuge island shortens the crossing distance and improves safety.

Safety and delay benefits from replacing multistage crossings with single-stage crossings. Queens Boulevard is a wide road in New York City, including a six-lane central roadway with a wide median as well as a pair of service roads on the outside. Before 2002, almost all crossings along Queens Boulevard were timed such that pedestrians had to wait approximately 100 s in the median before they could finish their crossing, leading to poor compliance. In 2002, signals were retimed to provide a single-stage crossing, which required a crossing phase of 60 s and increased the cycle length from 120 to 150 s in peak periods. Average pedestrian delay was reduced from 144 s to 53 s. There were 10.0 pedestrian fatalities per year on average over the period 1993–1998, followed by 4.7 per year over the period 1999–2001 as various safety improvements were made. This number fell to 1.5 fatalities per year after a single-stage crossing was implemented (NYC DOT, 2007).

In Brookline, MA, changes in the signal timing in 2007 required pedestrians crossing Beacon Street at Harvard Street to cross in two stages (Beacon Street has a wide median with light rail transit running in the middle). Pedestrian noncompliance was nearly 100% (i.e., scarcely any pedestrian stopped and waited in the middle). Pedestrians were often still in the crosswalk when Beacon Street's green phase began, creating friction with motorists. In response to citizen complaints, the signal was retimed by shifting a few seconds from one phase to another so that pedestrians could have a single-pass crossing. Noncompliance and friction with motorists at the start of the green largely disappeared. Impacts to motorists from the timing change were negligible.

Delay reductions as a result of improved pedestrian progression. With poor progression, pedestrian delay at multistage crossings can be very long; with good progression, it can sometimes be far smaller. Findings reported from various studies include:

- A parkway intersection in Boston, MA, was recently reconfigured with a three-stage crossing whose average pedestrian delay was 123 s. Neither the designer nor the approving agencies knew what the average pedestrian delay was because it had never been calculated. A study found that with small adjustments to the timing plan, good progression could be provided for pedestrians crossing in both directions; average pedestrian delay was reduced to 41 s, and average vehicular delay increased by less than 1 s (Furth et al., 2019). One of the techniques used to create this good progression was a short vehicular-hold interval, in which all vehicular phases are held in red while pedestrian phases overlap (see Section 6.7).
- A study found that pedestrian overlaps with left-turn phases (see Section 10.2) could be used to reduce average pedestrian delay at a two-stage crossing in Brookline from 86 s to 26 s, with only minor changes to vehicular signal timing (Furth et al., 2019).
- Research done for this guidebook found that at an intersection in Evansville, IN, a shared-use path has a two-stage crossing involving a channelized right turn with an average bicycle delay of 66 s. Giving the channelized right turn its own phase and developing signal timing so the shared-use path crossing has good progression would reduce average bicycle delay for this crossing to 14 s. The only impact to traffic would be a small increase in delay to an affected right-turn movement.

Delay reductions and safety improvements gained by facilitating short signal cycles. At a midblock crossing with a wide median, replacing a single long crossing with a pair of short partial crossings can lead to a short cycle length. In such a case, timing the two half-crossings so that they are offset from each other by half a cycle can provide good progression for pedestrians walking in both directions. Furth et al. (2019) provides an example of a midblock crossing in a coordinated system with a single-stage crossing and a cycle length of 100 s. With a two-stage crossing, the cycle length could be only 50 s, reducing average pedestrian delay from 39 s to 30 s while reducing delay for autos as well.

10.1.3 Considerations

10.1.3.1 Accessibility Considerations

While multistage crossings create opportunities to improve pedestrian comfort and reduce individual crossing segments, there are challenges to integrating accessibility features with this treatment, particularly related to guiding pedestrians to the appropriate refuge area. When crossings are designed and operated in multiple stages, each individual segment should be designed as a single crossing with supporting treatments to aid in the crossing.

10.1.3.2 Guidance

Not applicable for this treatment.

10.1.3.3 Relationships to Relevant Treatments

Treatments that might apply at multistage crossings are listed in the introduction to Chapter 10.

10.1.4 Implementation Support

10.1.4.1 Equipment Needs and Features

Except for Option a, described at the start of this section, applying multistage crossings requires that crossing islands be equipped with pedestrian signals facing both directions and corresponding pushbuttons (if the crossing is actuated). Accessible signals are highly desirable.

When the pedestrian phase is actuated, a call for one partial crossing can be programmed to automatically trigger a call for the next partial crossing, which allows pedestrians arriving at the island to be served on the next partial crossing with little or no delay. To implement this feature, each pushbutton must be wired to a different controller port so that the pedestrian's direction of crossing can be determined.

10.1.4.2 Phasing and Timing

Section 10.1.2.2 provides examples of phasing and timing for this treatment.

10.1.4.3 Signage and Striping

Not applicable for this treatment.

10.1.4.4 Geometric Elements

A pedestrian refuge island must be at least 6 ft deep, preferably 8 ft. To serve as a crossing island for bicycles, an island should be at least 10 ft deep. Islands must have a large enough queuing area for a signal cycle with high demand. Where pedestrian or bicycle demand has periodic surges, such as at schools or entertainment venues, pedestrian volumes per hour are misleading; counts are needed by signal cycle, and elements should be sized for a high-demand cycle.

When multistage crossings are used, the signal timing can create a situation where the second-stage crossing receives a Walk indication prior to the first-stage crossing. To avoid having pedestrians who are waiting for the first-stage crossing mistakenly think they can start their crossing when the second-stage Walk is displayed, it is important to consider the placement of the two sets of pedestrian signal heads relative to the pedestrians' line of sight. Additional guidance is provided in the section on left-turn overlap for pedestrian half-crossings (see Section 10.2).

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10.2 Left-Turn Overlap for Pedestrian Half-Crossings

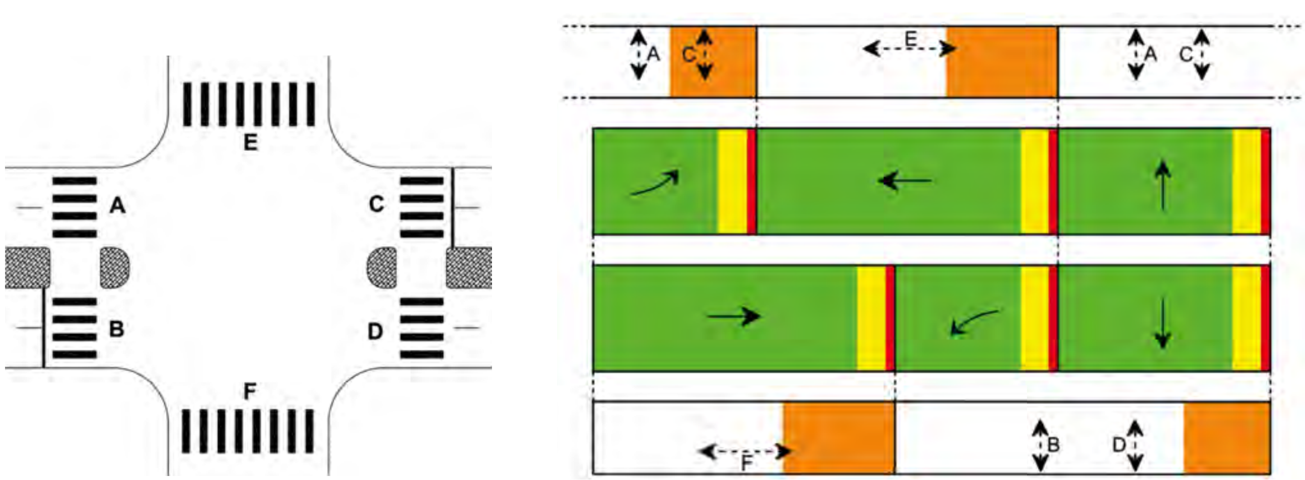
10.2.1 Basic Description

10.2.1.1 Alternative Names

None.

10.2.1.2 Description and Objective

Where a refuge island divides a crossing into half-crossings, some half-crossings can run concurrently with left-turn phases as well as with their concurrent through phases. For example, in Exhibit 10-2, Crosswalks A and D could run concurrently during a phase serving eastbound and westbound left turns. The objective of this treatment is to reduce pedestrian delay through a multistage crossing by enabling pedestrians to cross in a single stage or with improved progression.



(a) Example intersection layout (b) Phasing plan with pedestrian overlaps with left turns

Exhibit 10-2. Half-crossings and the left-turn movements with which they can overlap.

10.2.1.3 Variations

Not applicable for this treatment.

10.2.1.4 Operating Context

Pedestrian overlaps with left-turn phases might be appropriate anywhere with multistage crossings and exclusive left-turn phases. This treatment is especially applicable where pedestrians need more time to make the full crossing than the duration of the concurrent vehicular phase and where left-turn phases are on recall.

10.2.2 Applications and Expected Outcomes

10.2.2.1 National and International Use

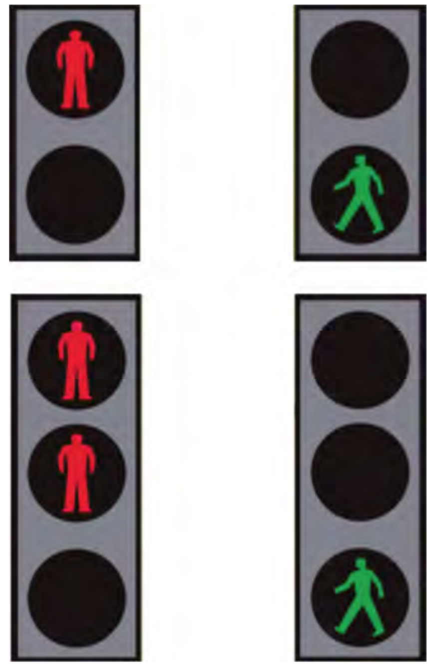
Having a pedestrian half-crossing run during a left-turn phase is a routine traffic control strategy. This tactic is used commonly in the Netherlands; it is less common, but not unusual, in the U.S.

Danish signal design guidance stresses the need to consider the placement and design of the pedestrian signal heads when multistage pedestrian crossings are used and the signal timing produces a situation where the second-stage crossing receives a Walk indication before the first-stage crossing (referred to in Danish guidance as "green behind red"). To avoid having pedestrians who are waiting for the first-stage crossing mistakenly think they can start crossing when the second-stage Walk is displayed, Danish guidance recommends that the pedestrian heads be placed such that the closest pedestrian signal (i.e., on the refuge island) dominates a pedestrian's sight line. For example, this can be done by placing the two signals in a line on the same side of the crosswalk so that they appear close to each other in a pedestrian's field of view. Another method, often used in Copenhagen, is to use three-head pedestrian signals (two Don't Walk over one Walk) for the first-stage crossing to reinforce which signal head a pedestrian should be watching and to provide redundancy in case one Don't Walk signal is non-functioning (see Exhibit 10-3) (Danish Road Directorate, 2018a).

10.2.2.2 Benefits and Impacts

Where there is a two-stage crossing and the length of the concurrent through vehicular phase is not enough for pedestrians to cross, pedestrians may have to wait a long time on the median island. Extending the pedestrian phase for some or all half-crossings by having them overlap with a left-turn phase reduces delay. These longer half-crossing phases often improve pedestrian progression, which can lead to dramatically shorter delay and sometimes enable pedestrians to cross without waiting in the median at all. As an example, Furth et al. (2019), in a simulation experiment of the form of intersection shown in Exhibit 10-2, found that adding left-turn overlaps reduced average pedestrian delay from 86 s to 26 s.

For intersections that are coordinated, left-turn overlaps may force left-turn phases to run to their maximum green more often instead of terminating early, which would reduce delay slightly for left turns and increase it slightly for the coordinated movements. Where left-turn demand is such that left-turn phases are never skipped and usually run to their maximum green, the impact on traffic will be negligible. If pedestrian phases are actuated, impacts to vehicular traffic will occur only in cycles with pedestrian calls. The same study by Furth et al. (2019) showed that adding left-turn overlaps to reduce pedestrian delay only increased intersection vehicle delay by 1 s at the intersection studied.



Source: Danish Road Directorate (2018b).

Exhibit 10-3. Examples of two- and three-head Danish pedestrian signals.

10.2.3 Considerations

10.2.3.1 Accessibility Considerations

Not applicable for this treatment.

10.2.3.2 Guidance

Not applicable for this treatment.

10.2.3.3 Relationships to Relevant Treatments

Where left-turn and cross-street phases are actuated, maximizing the Walk interval length (see Section 7.3) is important for getting the best service for pedestrians.

10.2.3.4 Other Considerations

See Section 10.1 for general considerations regarding multistage crossings.

10.2.4 Implementation Support

10.2.4.1 Equipment Needs and Features

All modern controllers can support serving pedestrian phases during a left-turn overlap.

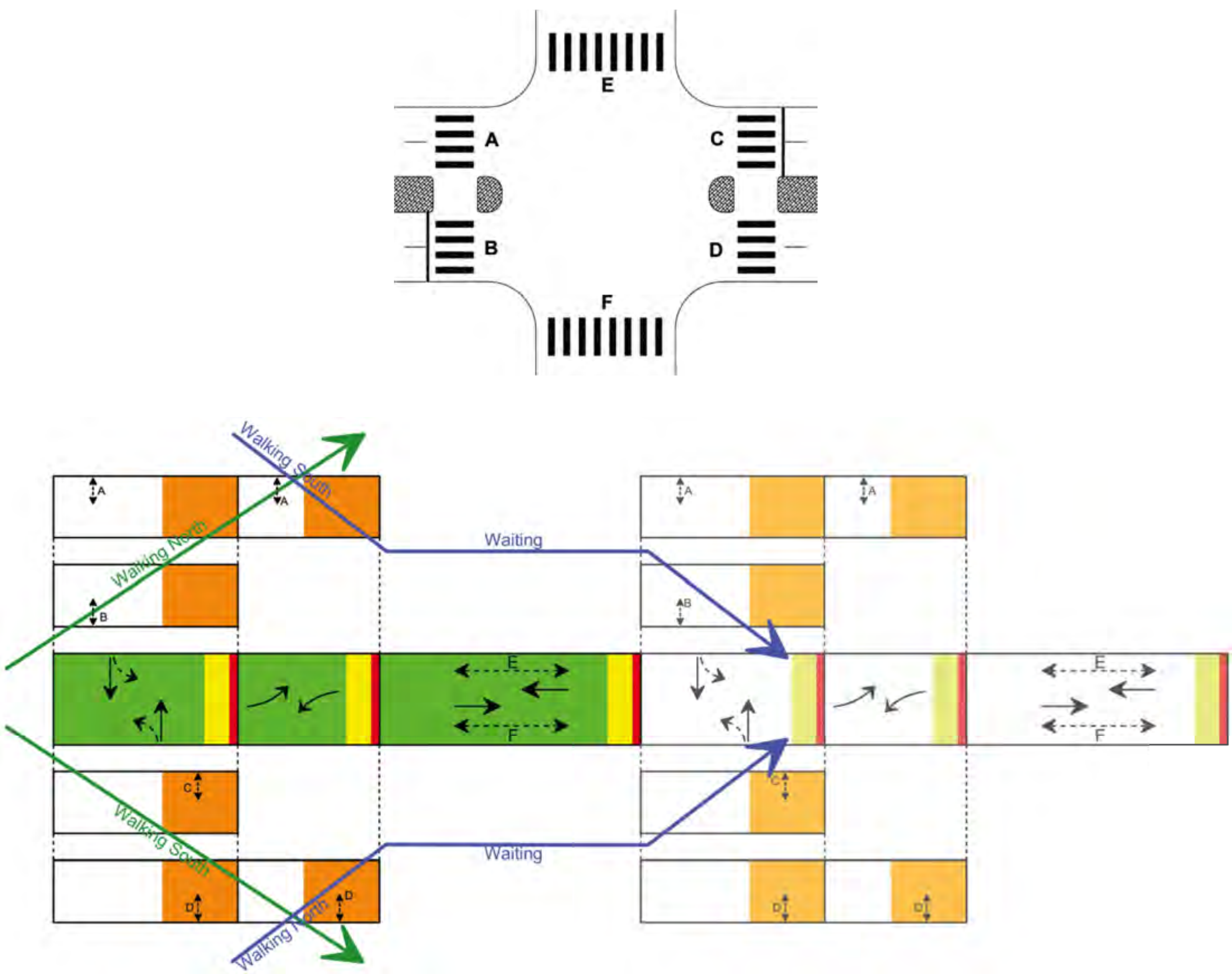
Where left-turn and cross-street phases are actuated, special programming may be needed to ensure that Walk intervals take advantage of the full vehicular intervals. To illustrate using Exhibit 10-2, if the westbound left-turn phase runs longer than its minimum green due to left-turn demand, Crossing B—which overlaps with that left turn—should have a correspondingly longer Walk interval as well. This is not a built-in feature with many controllers, which typically can only be set to give the Walk interval a fixed length; however, with most controller software, the desired outcome can be achieved with custom programming.

10.2.4.2 Phasing and Timing

Different phasing sequences—leading lefts, laggings lefts, and a combination of the two—have different progression implications for pedestrian crossings that use left-turn overlaps.

Exhibit 10-4 shows a phasing plan with leading left turns that might apply to the same intersection layout discussed before and shown below. Crossings A and D overlap the east–west left-turn phase, which means that they extend through both the north–south phase and the left-turn phase that follows. The combined duration of the north–south phase and a left-turn phase is assumed to be enough to make a full north–south crossing.

With this phasing sequence, northbound pedestrians can start Crossing B when the north–south phase begins and continue directly to Crossing A using the left-turn overlap to complete



Source: Furth et al. (2019).

Exhibit 10-4. Phasing plan with leading lefts, which provides ideal progression for Crossings B–A and C–D.

the crossing; similarly, southbound pedestrians can do the same with Crossings C and D. However, pedestrians making movements A–B and D–C cannot make a single-pass crossing; their route involves waiting at the median island. In summary, pedestrians get ideal progression only if they walk on the left side of the street. In the example cited earlier by Furth et al. (2019), pedestrians were walking on the right side. (For reference, without left-turn overlaps, average delay on either side of the street would be 84 s.) An interesting question is whether it would be helpful to provide signs pointing out which side of the street offers better service.

If left-turn phases are lagging instead, as in Exhibit 10-5, it can be observed that people walking on the right side of the street (Crossings A–B and D–C) get a single-pass crossing and better progression than people on the left side. Average delay for crossings A–B and D–C with lagging lefts is the same as the average delay for crossings B–A and C–D with leading lefts.

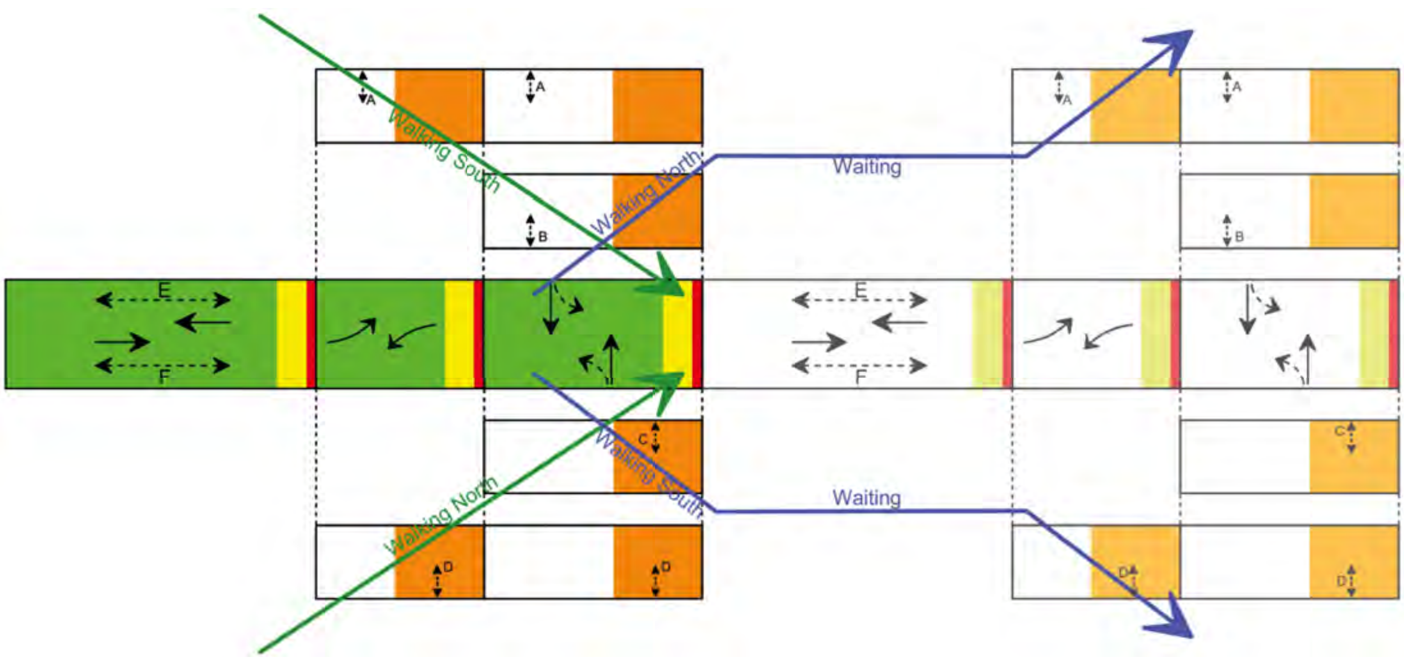
And if one of the left-turn phases leads while the other lags, as in Exhibit 10-6 where the westbound left turn leads and the eastbound left turn lags, both southbound crossings (A–B and C–D) get ideal progression, while northbound crossings do not get desired progression. (If the left turns exchange position, northbound would be the favored direction.) However, with “lead-lag phasing” all four half-crossings—A, B, C, and D—overlap with a left turn, and the longer Walk intervals that result make this the least-delay option. In the example from Furth et al., lead-lag phasing results in the lowest average delay—14 s for pedestrians walking southbound and 38 s for those walking northbound, which averages to 26 s.

10.2.4.3 Signage and Striping

Not applicable for this treatment.

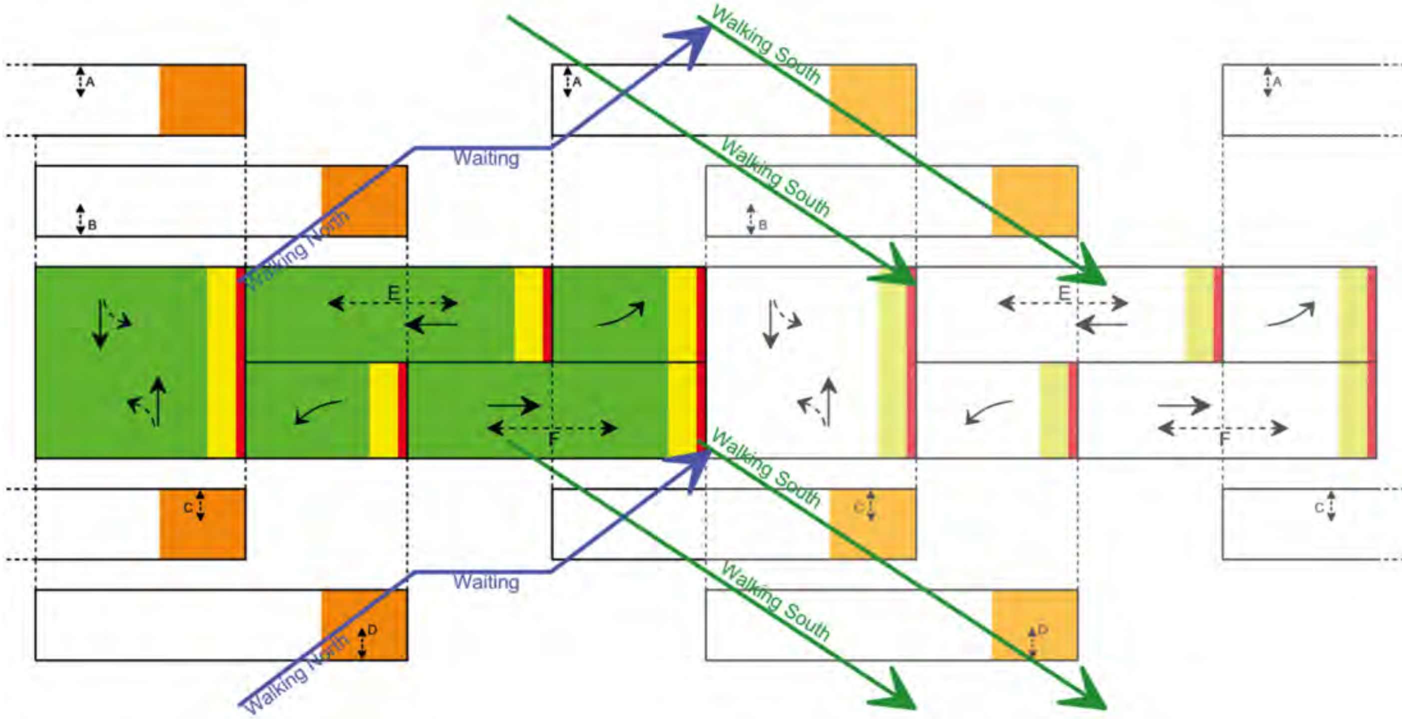
10.2.4.4 Geometric Elements

Section 10.2.2.1 provides an example of Danish guidance for pedestrian signal head placement and design for multistage crossings.



Source: Furth et al. (2019).

Exhibit 10-5. Phasing plan with lagging lefts, providing ideal progression for Crossings A–B and D–C.



Source: Furth et al. (2019).

Exhibit 10-6. Phasing plan with one left leading and one lagging, providing ideal progression and a wide crossing window for Crossings A–B and C–D.

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10.3 Single-Pass Bicycle Crossings with Two-Stage Pedestrian Crossings

10.3.1 Basic Description

10.3.1.1 Alternative Names

None.

10.3.1.2 Description and Objective

At intersections with two-stage crossings where a pedestrian refuge is not large enough to serve as a bicycle queuing area, signal timing can allow bicycles to cross a street in a single pass while pedestrians cross in two stages. For example, pedestrians may be given a Walk signal to advance to a crossing island while bicycles are held at the curb until the time at which they can cross without stopping at the island. One reason is that bicycles need less crossing time than pedestrians; another is that a pedestrian refuge island may not be large enough to serve as a bicycle queuing area.

10.3.1.3 Variations

Not applicable for this treatment.

10.3.1.4 Operating Context

This treatment is appropriate wherever pedestrians have a two-stage crossing and the crossing island is not large enough to serve as a bicycle queuing area.

10.3.2 Applications and Expected Outcomes

10.3.2.1 National and International Use

In the Netherlands, it is not unusual for intersections to be timed for single-pass bicycle crossings while parallel pedestrians cross in two stages. Two examples in Delft are (a) crossing Wateringsevest at Noordeinde and (b) crossing Van Foreestweg at Prinses Beatrixlaan. Both examples use a left-turn overlap for pedestrian half-crossings (see Section 10.2) in which pedestrians start crossing during a left-turn phase, advance to a median island, and wait there while bicycles are held at the curb during this phase. When the left-turn phase ends, pedestrians finish their crossing (their second stage), and bicycles are released to cross the full intersection in a single pass. In both cases, the median island is too small to serve as a bicycle queuing area. (In the second example, the median island is 13 ft, but the high volume of bicycles and mopeds on this route makes it too small to be a bicycle queuing area.)

In the U.S., it is routine for bicycles to follow vehicle signals and make crossings in a single pass that pedestrians make in two stages. In principle, it can be possible to follow the same strategy when bicycles follow bike signals.

10.3.2.2 Benefits and Impacts

Timing bicycle crossings separately from pedestrian crossings in this way allows bicycle and pedestrian phases to be tailored to the users' different speeds, an intersection's available queuing space, and phase overlap opportunities. Bicycle queues are kept off the island where they might otherwise overflow into the street, while pedestrian crossings—by taking advantage of phase overlap possibilities—constrain the signal cycle less than they would if they were single-stage, resulting in shorter cycles.

In Boston, a study examined an intersection with a three-stage crossing whose crossing islands are too small for bicycle queuing, meaning bicyclists have to become pedestrians to cross. In addition, due to poor pedestrian progression, pedestrian delay is very long. Furth et al. (2019) found that a timing plan with a single-pass crossing for bicycles and a well-coordinated multistage crossing for pedestrians would reduce bicycle delay from 123 s to 42 s and reduce pedestrian delay from 123 s to 41 s, while increasing auto delay by less than 1 s and avoiding the need to enlarge the crossing islands to support bikes.

10.3.3 Considerations

10.3.3.1 Accessibility Considerations

Not applicable for this treatment.

10.3.3.2 Guidance

While both the *Manual on Uniform Traffic Control Devices* (MUTCD) (2009) and *(Proposed) Public Rights-of-Way Accessibility Guidelines* (U.S. Access Board, 2011) offer consistent guidance that 6 ft is the minimum depth (i.e., the dimension in line with pedestrian movement) for pedestrian refuge islands, guidance is lacking regarding the minimum size for bicycle refuge islands.

Bicycles are about 6 ft long, but for a bicyclist to stop safely, the island depth should be longer in order to provide bicyclists with a short stopping zone and to provide a small offset between the bike and travel lanes. The AASHTO *Guide for the Development of Bicycle Facilities* (2012) recommends a minimum depth of 10 ft in order to support bicycles with trailers. Further guidance is needed to address both the depth and breadth of bicycle queuing area required to account for bicycle demand and the need to support cargo bicycles, bicycles with trailers, three-wheelers, and other large bicycles.

10.3.3.3 Relationships to Relevant Treatments

Not applicable for this treatment.

10.3.4 Implementation Support

10.3.4.1 Equipment Needs and Features

Not applicable for this treatment.

10.3.4.2 Phasing and Timing

Exhibit 10-7 shows an example intersection in which the bicycle crossing occurs in a single pass during Phase C, while the pedestrian crossing is divided into two stages, A and B. The pedestrian-crossing phases are coordinated to enable good progression walking east (A–B) as well as west (B–A).

10.3.4.3 Signage and Striping

Not applicable for this treatment.

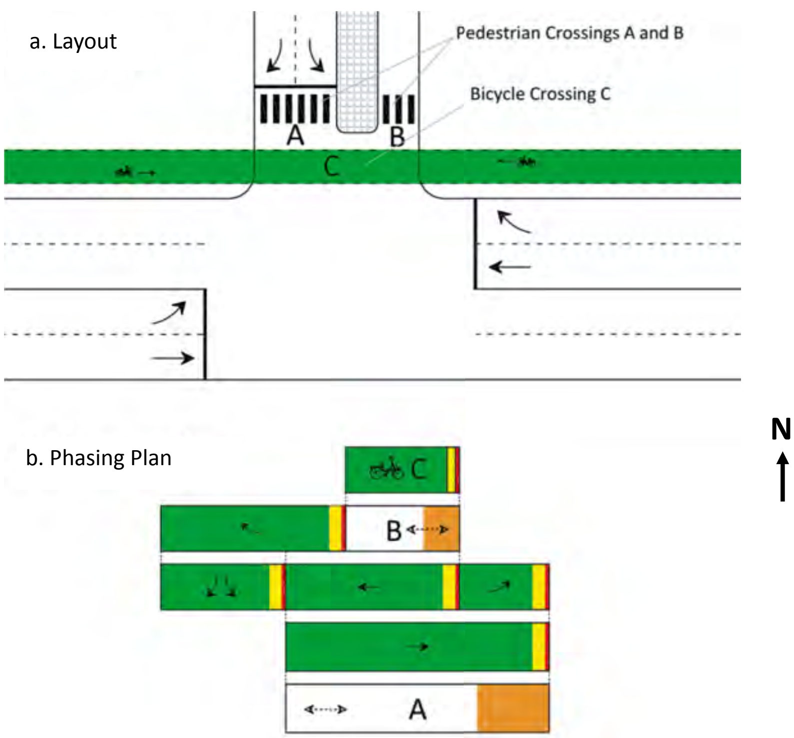

Exhibit 10-7. Intersection with a single-pass crossing for bicycles while pedestrians have a two-stage crossing: (a) layout and (b) phasing plan.

10.3.4.4 Geometric Elements

To serve as a bicycle refuge, a crossing island should be deep enough for a bicycle to stop and still leave an offset to travel lanes (the AASHTO bike guide recommends that a crossing island be at least 10 ft deep). The island should also have a queuing area wide enough to hold the anticipated demand per signal cycle.

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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