NCHRP 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Phase I Report
and
Phase II Report

Prepared by:

Kittelson & Associates, Inc.

In association with:

Northeastern University
Institute of Transportation Engineers
Accessible Design for the Blind

January 2019/August 2020

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PHASE I REPORT

to the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

on

Project 03-133: Traffic Signal Design and Operations Strategies for Non-Motorized Users

Draft 1.0

January 2019

from

Kittelson & Associates, Inc.

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Traffic Signal Design and Operations Strategies for Non-Motorized Users

Task 1 – Literature Review Memorandum

Kittelson & Associates, Inc.

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Accessible Design for the Blind

January 28, 2019

SECTION 1.0 – INTRODUCTION

The purpose of this memorandum is to document current best national and international practices for traffic signal design and operational strategies for non-motorized users including vulnerable road users with disabilities and develop a gap assessment to identify knowledge gaps.

/////Note to the Panel/////

Task 1: Literature Review and Gap Assessment technical memorandum will be a working document during Phase 1 of NCHRP 03-133. As noted in the Amplified Work Plan, an initial draft Task 1 technical memorandum will be submitted as a synthesis of documented and published materials. An updated draft will include information and findings gathered from activities under Task 2: Agency Engagement.

**Version 1.0* August 2018 – The current memorandum primarily focuses on design and operational treatments for non-motorized users at signalized intersections. A description, measure of effectiveness, and general assessment are provided for each treatment. We have been informed that the research team for NCHPR 03-118 (Decision-Making Guide for Traffic Signal Phasing) has compiled references and materials that could benefit this research effort. Initial coordination between projects has begun through TRB staff. Based on initial discussions, topics such as display indications and safety are included in the NCHRP 03-118 Phase 1 report. Upon receipt of the information, the research team will review and update this technical memorandum.*

**Version 2.0* December 2018 – Supplemental information to the literature review is being prepared in an addendum Summary Memo. The Summary Memo will provide additional treatments that have been identified and characterized. Details for some of the treatments will be provided however not all treatments will have complete info. It is envisioned that the outstanding gaps and information for each treatment will be completed in Phase II.*

The memorandum is organized into three sections: national and international practices on treatments, program/policy adopted by agencies, and summary of findings.

SECTION 2.0 – DESIGN AND OPERATIONAL TREATMENTS FOR NON-MOTORIZED USERS AT SIGNALIZED INTERSECTIONS

This section summarizes existing literature on non-motorized treatments at signalized intersections currently used in the U.S. and abroad, distinguishing the treatments by design and operational. The treatments studied in this memo are listed in Table 1. The purpose of this review is not to conduct an exhaustive summary of all treatments, but rather to summarize the state of the research in order to identify research gaps and prioritize treatments for further research in the subsequent tasks. In addition, the research team recognizes that there are other treatments for non-motorized users, but we have tried to include all major treatments and all treatments that would be of interest for future research.

Table 1: List of Treatments Studied (*As of August 2018*)

	Treatment Type	Modes Treated
1	**Actuation versus recall for pedestrians**	Pedestrian
2	**Adaptive walk intervals**	Pedestrian
3	**Bicycle signals and phases**	Bicycle
4	**Detection for bicycles**	Bicycle
5	**Flashing yellow arrow for permitted conflicts with pedestrians and bicycles**	Both
6	**Flashing pedestrian/bicycle indicator for permitted conflicts**	Both
7	**HAWK signals at intersections with minor streets**	Pedestrian
8	**Leading pedestrian interval**	Pedestrian
9	**Leading through interval**	Pedestrian
10	**Minimum green and change interval settings for bicycles**	Bicycle
11	**No turn on red**	Both
12	**Overlapping pedestrian phase with left turn phases**	Pedestrian
13	**Permissive periods for pedestrian actuation**	Pedestrian
14	**Protected left turns**	Both
15	**Red period countdown to promote compliance**	Both
16	**Rest in walk**	Pedestrian
17	**Short cycle length and reservice for the pedestrian/bicycle phase**	Both
18	**Vehicular hold with pedestrian overlaps**	Pedestrian
19	**Walk Countdown**	Pedestrian

SECTION 2.1 – Actuation versus Recall for Pedestrians

Description: The standard form of pedestrian actuation is a pedestrian pushbutton, which when pressed (activated) places a call for pedestrian service with the concurrent phase or a dedicated pedestrian phase. Under pedestrian actuation, the pedestrian typically manually activates a WALK signal. Pedestrian recall, on the other hand, places a continuous call for pedestrian service, without the need for pedestrian actuation, and results in pedestrian phases getting realized every cycle including that phase’s walk and flashing don’t walk (FDW) intervals.

Summary of Findings: Studies show that pedestrian recall reduces pedestrian delay at intersections compared to actuation, which in turn improves pedestrian safety as reducing pedestrian delay tends to improve pedestrian compliance (Pline 2001). Kothuri found greater pedestrian compliance with intersections on recall than pedestrian actuated intersections (Kothuri 2014). For impact on vehicular operations, pedestrian recall may increase vehicular delay particularly at intersections with low to moderate pedestrian volumes (i.e., where there is no pedestrian actuation every cycle).

Passive detection (also known as automatic detection) of pedestrians at intersections automatically identifies the presence of a pedestrian waiting to cross and removes the burden of needing to manually activate a Walk signal. Passive detection has been used to automatically activate the pedestrian signal phase, to monitor and lengthen the amount of crossing time for slower-moving pedestrians, and to increase lighting at midblock crossings. However, difficulty in accurately detecting pedestrian presence and other issues limit the use of this treatment. Studies on the safety impacts of automatic or passive detection of pedestrians show that passive detection may help to reduce pedestrian-vehicle conflicts, reduce the number of late crossings, and reduce the number of pedestrians stranded in the intersection (Hughes et.al. 2001; and Pecheux, Bauer, and McLeod 2009; as cited in PEDSAFE).

Hughes, R., H. Huang, C. V. Zegeer, and M. J. Cynecki (2001). Evaluation of Automated Pedestrian Detection at Signalized Intersections. Publication FHWA-RD-00-097, FHWA, U.S. Department of Transportation.

Kothuri, S. (2014). Exploring Pedestrian Responsive Traffic Signal Timing Strategies In Urban Areas. National Institute for Transportation and Communities.

Pecheux, K., J. Bauer, and P. McLeod (2009). Pedestrian Safety Engineering and ITS-Based Countermeasures Program for Reducing Pedestrian Fatalities, Injury Conflicts, and Other Surrogate Measures Final System Impact Report. Federal Highway Administration, U.S. Department of Transportation.

Pline, J. L. (2001). Traffic Control Devices Handbook, Chapter 13. Institute of Transportation Engineers, Washington, D.C.

SECTION 2.2 – Adaptive Walk Intervals

Description: Adaptive walk intervals is a form of adaptive traffic signal control in which the length of the walk interval is adjusted cycle-by-cycle based on a prediction of the needed green time of the parent phase (Furth and Halawini, 2016). This tactic tries to prevent the situation in which a pedestrian phase is terminated while its concurrent vehicular phase (i.e., parent phase) continues running for an extended duration where the pedestrian phase could have remained in the Walk interval longer without constraining the signal cycle. This treatment is generally more applicable for concurrent vehicular phases with variable green time, but somewhat predictable, and whose minimum pedestrian green requirements is lower than the green duration required for vehicular phases. For concurrent vehicular phases that are coordinated, and therefore typically have a fixed green termination time within a cycle, or for pre-timed intersections, Rest in Green treatment (explained below in details) can be used to increase the length of the Walk interval.

Summary of Findings: A simulation study by Furth and Halawani (2016) tested adaptive walk intervals, permissive windows, and pedestrian recall at two intersections. To predict adaptive walk intervals, each cycle, a prediction of needed green in the next cycle is made using data on the green time of previous cycles over the last 15 minutes or so. The longer the predicted needed green time in the upcoming cycle, the longer the walk interval. Results showed that for one site, a crossing of a wide arterial with coordinated-actuated phasing with random vehicle arrivals on the cross street, adaptive control led to pedestrian delay reductions of seven to 21 seconds, depending on level of pedestrian demand, with no measurable impact on vehicular delay. The negligible delay impact was due to the progression pattern on the coordinated street. For the other test site, an intersection with fully actuated control was assumed. On three legs of the intersection, arrivals were random, and arrivals on the other leg were influenced by an upstream coordinated intersection. Results indicated that adaptive control led to pedestrian delay reductions of three to nine seconds, with vehicular delay increases between zero and 2.5 seconds. For scenarios with low pedestrian demand, the best performing strategy was adaptive walk intervals combined with full permissive windows.

Furth, P. and Halawani, A. (2016). Adaptive Walk Intervals. Transportation Research Record: Journal of the Transportation Research Board, 2586, pp.83-89

SECTION 2.3 – Bicycle Signals and Phases

Description: Bicycle signals include separate signal heads that indicate bicycle phasing, whether protected or concurrent with other vehicular phases. Intersections that include a bicycle signal and bicycle phasing eliminate vehicular-bicycle conflict and can help improve safety particularly at intersections with high volumes of turning vehicular traffic. Adding a bicycle signal allows a protected phase to be added to the traffic signal cycle for bicycle movement (King 2016).

Summary of Findings: Relatively little research has been conducted on the safety impacts of bicycle signals. Studies, referenced below, show that signal timing does impact safety, as does having a protected intersection and treatments to move bicyclists safely through intersections. No research specific to Bicycle Signal Heads was found.

A BIKESAFE study on Bicycle Countermeasures selection found that bicycle signals in Davis, CA, increased bicyclist safety at intersections (BIKESAFE 2006). When comparing the crash reports at a signalized intersection from the two years before the bicycle signal installation and the two years after, the number of bicycle and vehicle crashes decreased from 16 crashes to two, neither of which involved bicyclists. Another study from Thompson, Paulsen, Monsere, and Figliozzi looking at bicycle compliance under various bike treatments found that compliance at bicycle signals was about 90 percent and comparable to traditional signals (Thompson 2013).

King, N. (2016). Implementation of bicycle signals for a two way cycle track on a one way street within a fixed time coordinated network. Retrieved from https://www.cite7.org/wpdm-package/2016-kelowna-compendium/;https://trid.trb.org/view/1434799.

Pedestrian and Bicycle Information Center (2006.) BIKESAFE: Bicycle Countermeasure Selection System. Publication No. FHWA-SA-05-006, Federal Highway Administration, Washington, DC.

Thompson, Sam R.; Paulsen, Kirk; Monsere, Christopher M.; and Figliozzi, Miguel A. (2013). A Study of Bicycle Signal Compliance Employing Video Footage. Civil and Environmental Engineering Faculty Publications and Presentations.

SECTION 2.4 – Detection for Bicycles

Description: Bicycle detection includes technologies such as inductive loop detection systems at or in advance of stop bars that allow signals to passively detect the presence of bicyclists. These are sometimes combined with blue lights near bicycle signals that provide feedback to bicyclists indicating that they have been detected. The purpose of this treatment when combined with the feedback light is to reduce risky behaviors conducted by bicyclists, such as signal noncompliance, which may be more likely to occur when bicyclists are unsure whether their presence has been detected by a traffic signal and reduce bicycle delay by ensuring bicycle phases will be activated when there is a bicycle presence. Passive detection may also be used to extend the red clearance time (or extend green time) for cyclists entering a wide intersection just before the change interval so that adequate clearance time is provided.

Summary of Findings: Little is known about the safety benefits of this treatment due to a lack of research on this topic; however, current research suggests that bicyclist comprehension of the pavement markings likely plays a key role in the treatment's effectiveness. The MUTCD standard 9C-7 bicycle detector marking was developed as part of this treatment in order to indicate to bicyclists where they need to be positioned to be detected by the traffic signal. Past research has found that many bicyclists do not understand what the 9C-7 marking means and therefore do not activate it, thereby reducing its potential effectiveness as a treatment (Boot et al., 2012 and Bussey, 2013).

In response to these findings, research conducted by Boudart et al. (2016) sought to determine whether bicyclists understand both the pavement marking and blue light feedback device and whether bicyclists' behavior changes when they are aware that they have been detected by the signal. The authors found that 60 percent of bicyclist intercept survey respondents correctly identified the existing 9C-7 marking and nearly 75 percent understood the meaning of the blue light detector feedback device. The survey results indicated a 30 percent increase of user comprehension when descriptive text was added to the 9C-7 marking. The authors also observed statistically significant increase in bicyclists waiting on the new bicycle detector signal after a descriptive bicycle detector marking was installed at a re-constructed intersection. There was not enough data to determine whether or not the treatment resulted in a statistically significant reduction in red light running among bicyclists. The results of this study are based on data from only two intersections in Portland, Oregon. Additional studies of this treatment's effectiveness in reducing bicyclist signal noncompliance are needed.

The Portland Bureau of Transportation performed a literature review and found that advanced bicycle detection (using an automated/passive system) reduces bicycle delay but did not associate safety impacts with automated detection (PBOT 2010).

Boot, W., N. Charness, C. Stothart, M. Fox, A. Mitchum, H. Lupton and R. Landbeck. (2012). Final Report: Aging Road User, Bicyclist, and Pedestrian Safety: Effective Bicycle Signs and Preventing Left-Turn Crashes (Technical Report No. BDK83 977-15). Florida Department of Transportation.

Boudart, J., P.E., Foster, N., A.I.C.P., Koonce, P., P.E., Maus, J., & Okimoto, L. (2016). Improving bicycle detection pavement marking symbols to increase comprehension at traffic signals. Institute of Transportation Engineers. ITE Journal, 87(3), 29-34. Retrieved from http://libproxy.lib.unc.edu/login?url=http://search.proquest.com/docview/1874399910?accountid=142.

Bussey, Stefan W. (2013). The Effect of the Bicycle Detector Symbol and R10-22 Sign on Cyclist Queuing Position at Signalized Intersections. Civil and Environmental Engineering Undergraduate Honors Theses, Portland State University.

City of Portland Bicycle Plan for 2030. Portland Bureau of Transportation (2010).

Federal Highway Administration. Manual of Uniform Traffic Control Devices, 2009.

SECTION 2.5 – Flashing Yellow Arrow

Description: A flashing yellow arrow (FYA) is displayed when a phase involves a permitted conflict with crossing pedestrians or bicycles. While application of FYA for permitted left turns from two-way streets – a situation in which the primary conflict of interest is with opposing through traffic – is well-known, FYA can also be used for permitted right turns and for permitted left turns from a one-way street that only have a permitted conflict with crossing pedestrians and / or bicycles.

Summary of Findings: Kothuri et al. (2018) used the conflict method technique to assess the frequency and severity of conflicts under several treatments that are aimed to improve the safety of crossing cyclists. One of the tested treatments was FYA for a left turn from a one-way avenue with a left side protected bike lane. Before and after results were obtained for 6th Avenue (the street with the left-side protected bike lane and FYA treatment) at 23rd Street in New York City. In the before situation, there was a four seconds Leading Pedestrian Interval (LPI) followed by a green ball for 6th Avenue concurrent with the bicycle phase. In the after situation, there was seven seconds Leading Through interval, during which bikes had a green and a green through arrow was displayed to 6th Avenue, after which the 6th Avenue display for vehicles changed to a green ball plus FYA (which the bicycle phase continued).

Based on analysis of video for 11 hours on weekday before and after, and normalizing to the number of bikes, Table 2 provides a comparison of results. The most salient measures of safety, near misses and collisions if no evasive action was taken, both showed a dramatic decline. On the other hand, the number of instances in which a bike rode around the car (presumably because a car was standing in the bike crossing waiting for pedestrians in the crosswalk) increased; however, this is more an irritation than a matter of safety and may be related to differences in pedestrian volumes.

Table 2: Conflict Results Comparison with and without Flashing Yellow Arrow for Turn Conflicts (Source: Kothuri et al., 2018)

	Before	After
Bikes	1,952	1,300
Per 1000 bikes:		
Near misses	4	0
Collisions if no evasive action taken	75	35
Bike rode around car	32	41

The effect of FYA applied for left turns from a two-way street on the safety of left-turning vehicles and on all users (not just non-motorized users) has been studied by several researchers. *Srinivasan et al. (2011, 2012)* summarize their findings as Crash Modification Factors (CMFs) shown in the table below. Results show that, for example, when a protected and permissive left turn phase without an FYA is changed to a protected and permissive phase with an FYA, the total number of crashes is expected to decrease by about eight percent. However, for the same type of intersections in which left-turning vehicles from a two-way road has a permitted conflict with oncoming vehicles as well as with left-side crossing pedestrians and bikes, *Van Houten et al. (2012)* found that the safety benefit of such FYAs to pedestrians is insignificant.

Table 3: Crash Modification Factors for Flashing Yellow Arrow (All Crashes)

Treatment	CMF for All Crashes
Changing left turn phasing from at least one permissive approach to flashing yellow arrow (FYA)	0.753
Changing left turn phasing from protected to flashing yellow arrow (FYA)	1.338
Changing left turn phasing from protected-permissive to flashing yellow arrow (FYA)	0.922

Kothuri, S., A. Kading, A. Schrope, K. White, E. Smaglik, C. Aguilar, and W. Gil. “Addressing Bicycle-Vehicle Conficts with Alternate Signal Control Strategies.” Final report NITC-RR-897. Portland: National Institute for Transportation and Communities, April, 2018.

Srinivasan, R., Baek, J., Smith, S., Sundstrom, C., Carter, D., Lyon, C., Persaud, B., Gross, F., Eccles, K., Hamidi, A., and Lefler, N., "NCHRP Report 705: Evaluation of Safety Strategies at Signalized Intersections.", Washington, D.C., Transportation Research Board, National Research Council, (2011)

Srinivasan, R.; Lyon, C.; Persaud, B.; Baek, J.; Gross, F.; Smith, S.; Sundstrom, C. A. "Crash Modification Factors for Changing Left Turn Phasing." Presented at the Transportation Research Board 91st Annual Meeting, Paper No. 12-2521, January 22-26, 2012, Washington, DC

Van Houten, R., LaPlante, J. and Gustafson, T. (2012). Evaluating Pedestrian Safety Improvements. Report RC-1585, Michigan Department of Transportation, pp.98-101.

SECTION 2.6 – Flashing Pedestrian/Bicycle Indicator for Crossing Warnings

Description: A flashing is displayed to a phase that involves turns that have a permitted conflict with crossing pedestrians or bicycles. This treatment aims to alert turning drivers to the potential presence of crossing pedestrians and/or bicycles, to alert them to scan for potential conflicts in the crossing before turning, and to encourage yielding behavior. An example of this treatment, called *Flashing Right Hook Warning*, is used in some cities in the Netherlands, and illustrated in Figure 1. In the below example, a curved right turn arrow is displayed with a bicycle crossing, and a large red exclamation point within the crossing, with words meaning "Look Out". This is a special signal head, mounted either on its own pole or attached to the side of a signal pole close to the start of the conflicting crossing and angled to aim at a driver who is partway through a right turn.

Figure 1: Flashing Right Hook Warning in Amsterdam ("Let Op" means "Look Out")

Another variation of this treatment is called "*Flashing Yellow Ball"*, also employed in certain Dutch cities for left turn conflicts with crossing pedestrians and bicycles, displaying a large yellow ball, as shown in Figure 2. It is a special signal head, mounted near the start of the crossing opposite the left turn and angled to aim at a motorist when roughly halfway through a left turn. It flashes 0.5 seconds on and 0.5 seconds off while the permitted left turn phase is running.

Figure 2: Flashing Yellow Ball (Flashing Crossing Warning) in Amsterdam

Summary of Findings: Florida State University researchers developed a concept called as *Flashing Pedestrian Indicator* that uses a flashing yellow arrow, except that the yellow arrow alternates with a white walking man (the symbol used to indicate WALK), alternating 0.5 seconds yellow arrow and 0.5 second walking man, as shown below.

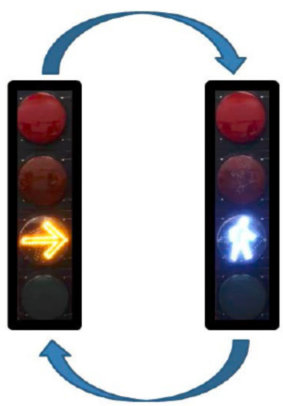


Figure 3: Flashing Pedestrian Indicator proposed by Boot et al. (Florida State University)

In this study, Boot et al., (2015) studied how FPIs are understood by drivers in a laboratory setting at Florida State University. They found that flashing pedestrian indicators resulted in greater caution and search for pedestrians. In their study, some respondents reacted over-cautiously, slowing down when going through and even when no pedestrian was present, which could negatively affect traffic capacity; however, as motorists become accustomed to it, it was indicated that the effect on capacity may disappear.

Boot, W., N. Charness, N. Roque, K. Baraja, J. Dirghalli, and A. Mitchum. The Flashing Right Turn Signal with Pedestrian Indication: Human Factors Studies to Understand the Potential of a New Signal to Increase Awareness of and Attention to Crossing Pedestrians. Final report BDV30-977-13, Department of Psychology, Florida State University, Dec., 2015.

SECTION 2.7 – High-Intensity Activated Cross Walk Beacon (HAWK) Signals

Description: A High-Intensity Activated Cross Walk Beacon (HAWK), also known as a Pedestrian Hybrid Beacon, is a pedestrian crossing treatment used where minor streets intersect major arterials. The HAWK can be located on the roadside and on mast arms over the roadway. The head contains two horizontally arranged red bulbs above a single yellow bulb. The lights rest in dark when there is no pedestrian actuation. When activated, the first indication for drivers is a few seconds of flashing yellow, followed by a solid yellow. Following the solid yellow, drivers receive a solid red indication and pedestrians receive a “Walk” indication, allowing them to cross while vehicular traffic is stopped. At the start of the “Flash Don’t Walk” interval, the red bulbs on the HAWK beginning alternately in a flash pattern. Drivers are allowed to progress through the intersection after stopping if the pedestrians have cleared the roadway. This limits delay to vehicles; however, it is a variation from normal pedestrian expectations at signals where vehicles are not allowed to progress through a signalized intersection when the “Flash Don’t Walk” indication is shown. At the end of the “Flash Don’t Walk” interval, the pedestrian signal changes to a “Don’t Walk” indication and the HAWK returns to rest in dark. The Pedestrian Hybrid Beacon was included in the 2009 Edition of the MUTCD.

Source: Federal Highway Administration

Summary of Findings: HAWKs have been shown to improve safety at uncontrolled pedestrian crossings on multiple types of roads. Studies have focused on increased driver yielding as the main safety benefit and multiple studies measuring driver yielding compliance show results ranging from 89-98 percent depending on the site (described below in detail). HAWKS have also been studied for their CMFs, and two studies found pedestrian CMFs ranging from 0.45 (55 percent crash reduction) to 0.31 (69 percent crash reduction).

Fitzpatrick found motorist yielding compliance at HAWKs ranged from 94 to 100 percent in the five (5) sites studied (Fitzpatrick et al. 2006). In an FHWA study of 21 sites in Tucson, Fitzpatrick found the use of a HAWK resulted in a statistically significant reduction in total crashes by 19-29 percent and in pedestrian crashes by 65-69 percent (Fitzpatrick et al. 2010).

According to an NCHRP synthesis of pedestrian crossing treatments, “Fewer pedestrian conflicts have also been observed after PHB installation. In a study conducted by the Texas Transportation Institute (TTI), wider crossings were associated with higher yielding rates at sites in Texas, and posted speed did not have an effect on yielding, suggesting that this countermeasure is effective for wider and higher-speed locations. However, results from one study suggest that drivers might use the signal indications—especially when the beacon is in dark mode—to perceive that pedestrians are not present and increase speed. There is also presumably some risk of multiple-threat crash when the flashing red phase is active or if, as some states indicated in survey responses, drivers do not, in fact, stop" (Thomas et.al. 2016).

A 2016 study to develop CMFs for four types of uncontrolled pedestrian crossing treatments found that HAWKs performed best, with a CMF of 0.45 for HAWKs and 0.43 for HAWKs in conjunction with advance stop/yield signs and markings (Zeeger et.al. 2016). Two studies in Michigan that looked at yielding compliance found that adding a HAWK or other device to marked crosswalks achieved the highest compliance (Gates et.al. 2016; Stapleton et.al. 2017). A FHWA report on road user behaviors at HAWKs found that driver compliance averaged 96 percent at over 20 sites (even sites with wide crossings and high speeds), and pedestrians activated the HAWK 91 percent of the time (FHWA 2016). Another study by Fitzpatrick, Brewer, & Avelar (2014) found that across 32 sites, the average yielding rate for HAWKs was 89 percent, and noted that cities where the device was highly used have higher driver yielding rates (Fitzpatrick et.al. 2014). BIKESAFE similarly concluded that bicyclists crossing at HAWKs may benefit from high yielding, and that crashes involving bicyclists may decrease as well (BIKESAFE). It should be noted that the findings included here provide a comparison of HAWK signals to unsignalized intersections. No literature was found that explored the effects of a HAWK signal compared to a signalized intersection.

Fitzpatrick, K., Brewer, M. A., & Avelar, R. (2014). Driver Yielding at Traffic Control Signals, Pedestrian Hybrid Beacons, and Rectangular Rapid-Flashing Beacons in Texas. Transportation Research Record: Journal of the Transportation Research Board, (2463). Retrieved from https://trid.trb.org/View/1289041

Fitzpatrick, K., Turner, S., Brewer, M., Carlson, P., Lalani, N., Ullman, B., Trout, N., Park, E.S., Lord, D., and Whitacre, J. (2006). Improving Pedestrian Safety at Unsignalized Crossings, TCRP/NCHRP Report 112/ 562, Transportation Research Board, Washington, DC.

Fitzpatrick, K. and E.S. Park, Safety Effectiveness of the HAWK Pedestrian Crossing Treatment, Report FHWAHRT-10-042, Office of Safety Research and Development, Federal Highway Administration, McLean, Va., 2010, pp 76.

Gates, T. J., Savolainen, P. T., Stapleton, S., Kirsch, T., & Miraskar, S. (2016). Development of Safety Performance Functions and Other Decision Support Tools to Assess Pedestrian and Bicycle Safety. Retrieved from https://ntl.bts.gov/lib/60000/60400/60477/TRCLC_14_06_Report.pdf

Pedestrian and Bicycle Information Center. (2006.) BIKESAFE: Bicycle Countermeasure Selection System. Publication No. FHWA-SA-05-006, Federal Highway Administration, Washington, DC.

Stapleton, S., Kirsch, T., Gates, T. J., & Savolainen, P. T. (2017). Predicting Yielding Compliance at Midblock Crossing Areas Based on Roadway, Traffic and Crosswalk Characteristics. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board. Retrieved from https://trid.trb.org/View/1438830

Thomas, L., Thirsk, N. J., & Zegeer, C. (2016). NCHRP Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways. Washington, DC: Transportation Research Board of the National Academies of Sciences.

Zegeer, C., R. Srinivasan, B. Lan, D. Carter, S. Smith, C. Sundstrom, N.J. Thirsk, C. Lyon, B. Persaud, J. Zegeer, E. Ferguson, R. Van Houten. 2016. Development of Crash Modification Factors for Uncontrolled Pedestrian Crossing Treatments. Pre-publication draft of NCHRP Research Report 841. Transportation Research Board, Washington, D.C.

SECTION 2.8 – Leading Pedestrian Interval (LPI)

***Description*: Leading pedestrian interval (LPI, also known as pedestrian head start), is when a walk signal indication is shown to pedestrians a few seconds earlier than a green signal being shown to the adjacent parallel vehicular movement. Figure 4, using a simplified ring diagram, shows how concurrent pedestrian and vehicular phases are aligned in an LPI setting *(1)*.**

Figure 5 is also a schematic illustration of an LPI *(1)*. Duration of an LPI is usually set to 3 to 7 seconds. In fact, in order for an LPI to serve its purpose it should be at least 3 seconds to allow pedestrians to cross at least one lane of traffic.

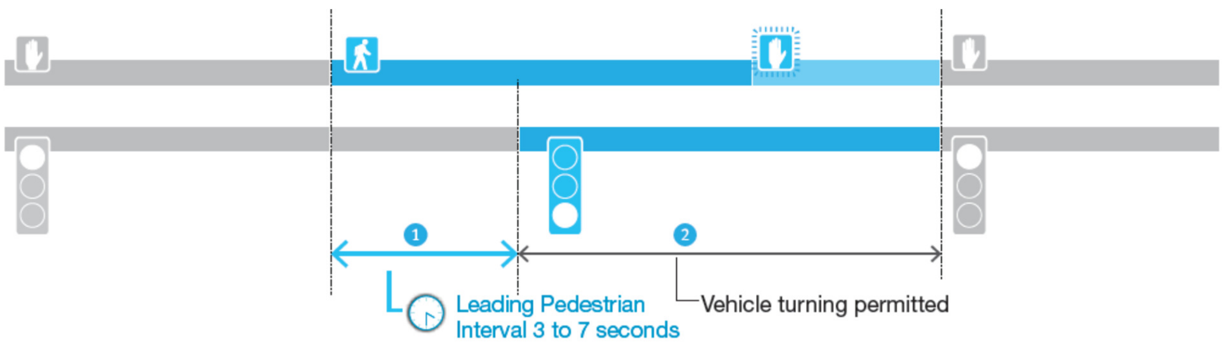
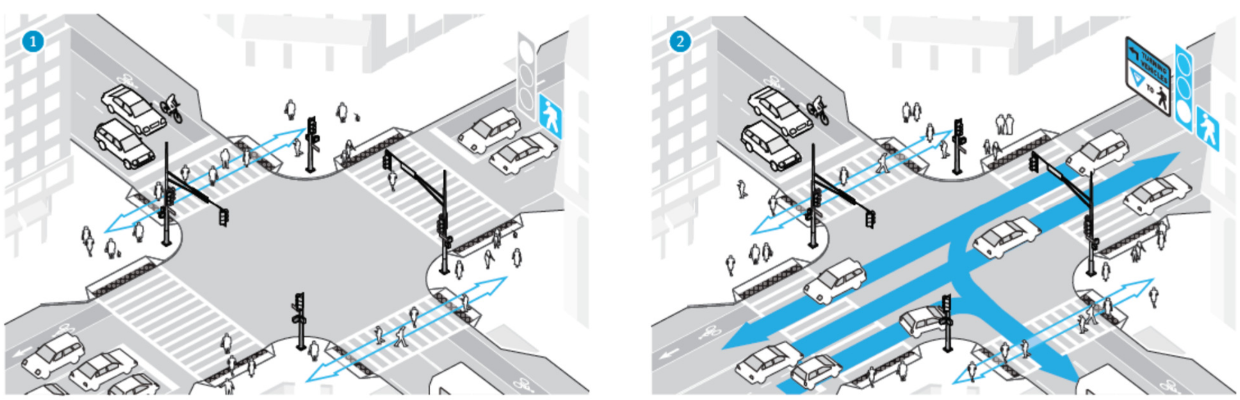


Figure 4: Pedestrian phase and its parallel vehicular phase during and after LPI *(1)*



(b) **During LPI**

(a) **After LPI: Vehicle movement with turn conflicts permitted**

Figure 5: Pedestrian and parallel vehicular movements involved in an LPI *(1)*

Summary of Findings: Up to today, many researchers and practitioners have utilized LPI and studied its impacts, especially on pedestrian safety. By introducing a three seconds LPI at three urban intersections, Houten et al. showed that LPI reduces the event of pedestrians yielding the right of way to turning vehicles. For crash analysis, New York State Department of Transportation compared 26 intersections which had LPI with a group of similar intersections. Up to ten years of crash data for those intersections were studied; the analysis showed a 28 percent reduction in pedestrian-turning vehicle crashes. Furthermore, to account for the severity of crashes, results were adjusted which concluded to a 64 percent reduction in pedestrian-turning vehicle crashes *(7)*.

Fayish et al. conducted a before and after with comparison group study to evaluate the safety effectiveness of LPI implementation. Results of their study showed a significant reduction of approximately 60 percent in pedestrian-vehicle crashes at treated intersections *(12)*. As a result of their study, currently FHWA assigns a Crash Modification Factor (CMF) of 0.413 for intersections with LPI to be used in *Highway Safety Manual* (HSM) methodology *(16)*. In summary, result of all studies on LPI indicates that, for most signalized intersections with concurrent crossing, LPI is a useful measure to enhance pedestrian safety.

For the effects of LPI on pedestrians with disabilities, existing research suggests that newly-installed LPIs should provide accessible pedestrian signals to notify visually-impaired pedestrians of the LPI because without an accessible pedestrian signal, visually-impaired pedestrians who rely on the sound of starting traffic to know when the green begins may miss the LPI and begin to cross with the vehicular movement when motorists are less likely to yield to them *(1, 8)*.

City of Boston (2013). Boston Complete Streets Design Guidelines.

Houten, R., Retting, R., Farmer, C. and Houten, J. (2000). Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections. Transportation Research Record: Journal of the Transportation Research Board, 1734, pp.86-92.

King, M. (2000). Calming New York City Intersections. In: TRB Circular E-C019: Urban Street Symposium. Washington, D.C.: TRB, National Research Council.

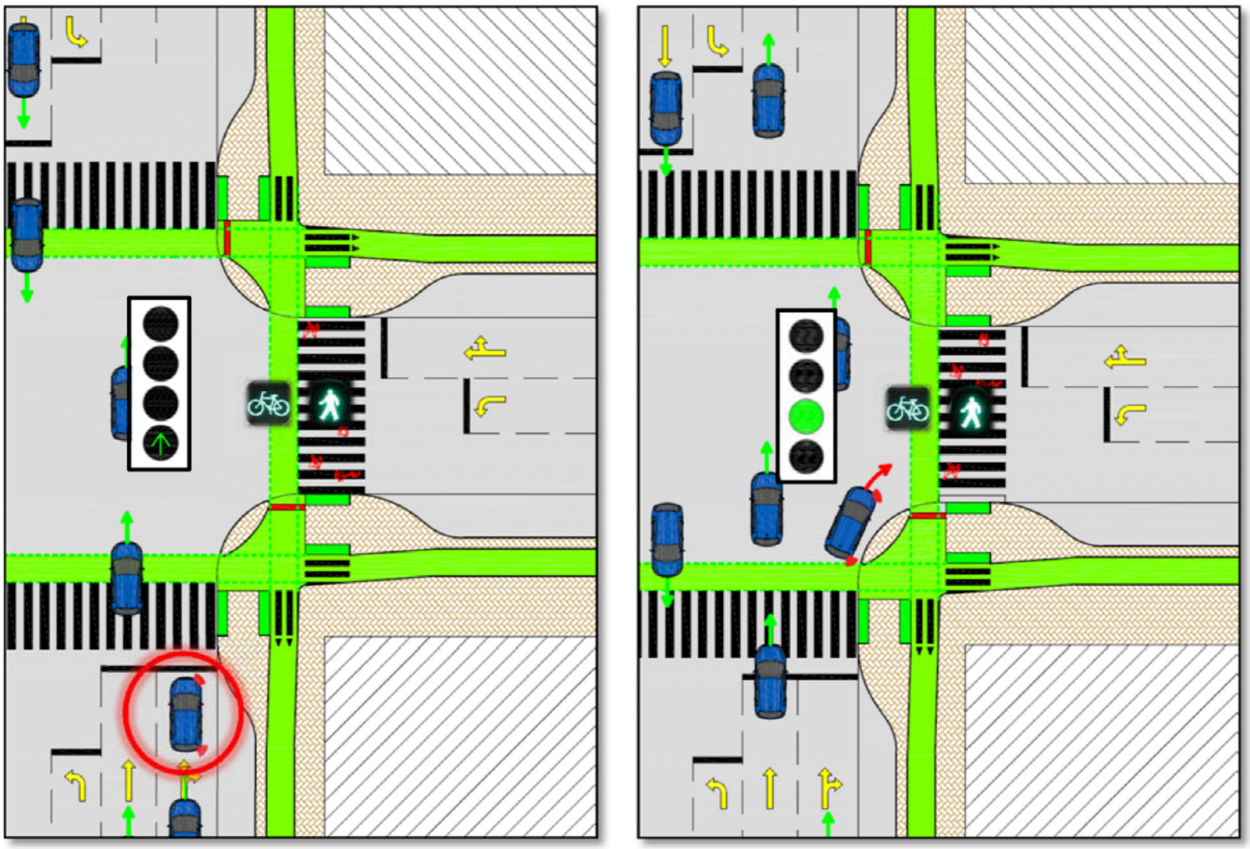
Fayish, A. and Gross, F. (2010). Safety Effectiveness of Leading Pedestrian Intervals Evaluated by a Before–After Study with Comparison Groups. Transportation Research Record: Journal of the Transportation Research Board, 2198(1), pp.15-22.

Cmfclearinghouse.org (2018). CMF Clearinghouse >> CMF / CRF Details. [online] Available at: http://www.cmfclearinghouse.org [Accessed 29 Jun. 2018].

Alexandria Department of Transportation and Environmental Services (2015). Alexandria Complete Streets Design Guidelines. Alexandria.

SECTION 2.9 – Leading Through Interval

Description: A leading through interval (LTI) is a period of time at the start of a phase in which only through-going vehicles are allowed to proceed, together with bikes and pedestrians. As applied in Montreal, the indication to vehicular traffic is a through green arrow. At the end of the LTI, a green ball replaces the green arrow, allowing turning movements to proceed, while bike and pedestrian phases continue (see Figure 6 and Figure 7).



(a) LTI (b) after LTI

Figure 6: Pedestrian, bike, and vehicular movements involved in an LTI

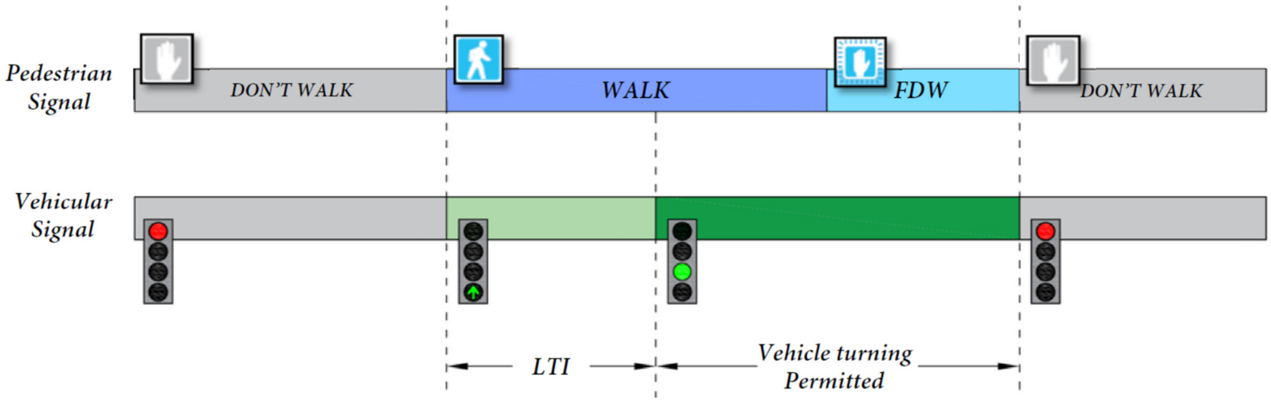


Figure 7: Relationship between pedestrian phase and parallel vehicular phase during and after LTI

There are implementation variations in the U.S. In New York City, LTI is known as Split Leading Bicycle Interval (Split LBI) and is applied on one-way avenues with a left-side bicycle lane where the indication to vehicular traffic during the leading interval is a green ball together with a red left arrow. Where the cross street is one-way and therefore right turns are prohibited, Split LBI functions as a Leading Through Interval. At intersections with a two-way cross street, the leading interval under Split LBI holds turns to one side while allowing them to other side, and so, strictly speaking, it is not a Leading Through Interval (though it is still a Partially Protected Crossing). LTI can be applied whether turning traffic has its own turn lane or shares a lane with through traffic. When turns use a shared through-turn lane, then by stopping turning cars, an LTI can block through traffic as well.

LTI is similar to an LPI in that both of them hold turning traffic for a few seconds while pedestrians, and perhaps bicycles, get a head start. However, because an LTI allows through traffic to proceed, it has less impact on traffic capacity than LPI. As a result, from a vehicular capacity perspective, one can afford to make an LTI last longer than an LPI (e.g., Montreal typically uses seven to nine seconds of LTI (Montreal DOT Guide DT 2001) (LTI interval with Peter Furth); New York City's LTI lasts seven to ten seconds (New York City DOT, Don't Cut Corners, 2016)). However, where the turns are from a shared through-turn lane, through-going motorists can be frustrated if they see a green signal but cannot proceed because a turning vehicle ahead of them is stopped. For this situation, if turn volumes are high and turning vehicles don't have an exclusive lane, LPI can be preferred over LTI. LTI can also be combined with a Flashing Yellow Arrow, displayed during the part of the phase in which turn conflicts are permitted.

Summary of Findings: Kothuri et al. (2018) (the same study that also looked at Flashing Yellow Arrow) used traffic conflict analysis, based on video, to gauge the impact of LTI and other treatments on cyclists' safety. One intersection, 6th Avenue at 23rd Street in New York City, was observed for 11 hours each before and after implementing an LTI. For the before scenario, the 6th Avenue phase began with a short LPI (which some bicycles used), followed by a (much longer) interval with permitted left-turn conflicts from the adjacent lane shared by left turning and through vehicles. For the after scenario, the 6th Avenue phase began with a seven seconds leading interval without left turn conflicts, followed by the remainder of the 6th Avenue phase in which left-turn conflicts were permitted from a newly created left turn lane (the left side parking lane was converted into an exclusive left turn lane, with bikes remaining on the outside of the turn lane, against the curb). Table 1 shows a before-after comparison 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 after introduction of the LTI together with an exclusive left turn lane. There was a small increase in the frequency of bikes who had to ride around a car (something that occurs usually because a car began its turn, but then stopped for crossing pedestrians).

Table 4: Traffic Conflict Measures Before and After Implementation of a Leading Through Interval for 6th Avenue @ 23rd Street, New York. (Data source: Kothuri et al. (2018) with our analysis of that data)

	Before: Permitted Turn Conflict Throughout the Bicycle Phase	After: Leading Protected Interval (7 s) Followed by Permitted Turn Conflict
Bikes	1,952	1,300
Per 1000 bikes:		
Near misses	4	0
Collisions if no evasive action taken	75	35
Bike rode around car	32	41

It should be important to note that a conclusion of that study uses wording that may lead to misunderstanding of the findings: "With the split LBI treatment, there is little to no risk for bicyclists during the leading interval. However, the risk for bicyclists is shifted towards the stale green portion of the phase." Some might interpret this as the authors found that a lessening of risk in the early part of the phase was accompanied by an increase in risk in the latter part of the phase (which might imply that there is no net safety benefit). However, this study has no findings, or even discussion, of increased risk during the latter part of the phase. The authors are only pointing out that where LTI is implemented, cyclists will still face risk from turning conflicts after the leading interval has ended.

Regarding delay impacts, LTI is not expected to affect delay for any movements other than the turns that are held during the leading interval, if turns are from an exclusive lane. If turns are from a shared through-turn lane, then additional delay to through traffic should be expected, increasing with the volume of turning traffic. In the same study, Kothuri et al. (2018) used simulation to measure delay impacts of a five second LTI 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 – the traffic movement directly affected by a five second hold – was small, less than a second. This small impact is probably because Right Turn on Red was allowed during all red periods except the LTI, leading to very little queuing in the right turn lane.

Montreal Department of Transportation (2017). Feux pour Piétons à Décompte Numérique. Guide DT2001.

Hamaoui, J. (2018). Leading Through Interval. Interview with Peter Furth.

New York City Department of Transportation (2016). Don't Cut Corners - Left Turn Pedestrian & Bicyclist Crash Study. New York.

Kothuri, S. et al. (2018). Addressing Bicycle-Vehicle Conflicts with Alternate Signal Control Strategies. Portland (OR): National Institute for Transportation and Communities (NITC), pp.16, 23, 25-26, 29-30.

SECTION 2.10 – Minimum Green and Change Interval Settings for Bicycles

Description: The operating characteristics of bicycles are substantially different than that of automobiles. The ability of bicycles to accelerate and decelerate and the speeds they are able to attain and sustain are contingent on a number of variables such as the fitness and physical condition of the bicycle operator as well as the type and quality of bicycle itself (Curtis, 2015). Therefore, the minimum green and change interval settings should be designed to serve the needs of bicyclists, in particular at signalized intersections where bicycles use vehicular phases (e.g., intersections with bike lanes but without exclusive bike phases)

Summary of Findings: Existing research indicates that based on what is currently understood about bicycles, a limited number of traffic signal timing parameters, including minimum green interval and change interval settings, have been developed to provide some degree of safety and maintain efficiency when bicycles are present. AASHTO Guide for the Development of Bicycle Facilities (2012) states that the computation of standing bicycle crossing time should be used to design the setting for Bicycle Minimum Green (BMG) time when the feature is available in the traffic signal control device. When a BMG feature is not available, the vehicle minimum green time for the appropriate phase should accommodate the bicycle crossing time.

Curtis, E., Comprehensive On-Street Bicycle Facilities: An Approach for Incorporating Traffic Signal Operational Strategies for Bicycles, M.S. Thesis, Georgia Institute of Technology, 2015.

AASHTO. (2012). Guide for the Development of Bicycle Facilities. Washington, DC: American Association of State Highway and Transportation Officials.

SECTION 2.11 – No Turn on Red Signs

Description: “No Turn on Red” signs are used to restrict right turn on red movements. The purpose of this treatment is to eliminate conflicts between turning vehicles and pedestrians/bicyclists crossing during a concurrent walk phase.

Summary of Findings: Existing research indicated that “No Turn on Red” signs may be effective at reducing pedestrian-vehicle conflicts. According to the Harkey et al. (2008), “No Turn on Red” signs were estimated to reduce crashes by about 3 percent with a crash modification factor (CMF) of 0.97.

A recent study conducted by Lin et al. (2016) examined the effectiveness of four signs (“Stop here on Red”, “No Turn on Red”, “Turning Vehicles Yield to Pedestrians”, and “Right on Red Arrow after Stop”) aimed at increasing driver yielding to pedestrians at intersections with restricted right turns. The results showed that “No Turn on Red” signs had the highest rate of compliance of all four treatments studied with the average driver compliance of 70 percent.

An earlier study by Preusser et al. (1982) indicated that permitting a right turn on red increases crashes involving a motor vehicle making a right turn by 43 percent to 107 percent for pedestrians and by 72 percent to 123 percent for bicyclists (with CMF ranging from 1.43 to 2.08). A similar CMF of 1.69 is documented in the Highway Safety Manual, First Edition, for vehicle-bicycle and crashes involving pedestrians (AASHTO 2010).

Harkey, D.L., S. Tsai, L. Thomas, and W.W. Hunter. Pedestrian and Bicycle Crash Analysis Tool (PBCAT): Version 2.0 Application Manual, Report FHWA-HRT-06-089, Office of Safety Research and Development, Federal Highway Administration, McLean, VA., 2006, 241 pp. Software FHWA-HRT-06-091 Available: http://www.pedbikeinfo.org/pbcat_us/

Lin, P.-S., Wang, Z., Guo, R., & Kourtellis, A. (2016). A Pilot Study on Interactions between Drivers and Pedestrian Features at Signalized Intersections. Presented at the 11th Asia Pacific Transportation Development Conference and 29th ICTPA Annual Conference International Chinese Transportation Professionals Association Chinese Institute of Transportation. Chung Hua University, Taiwan American Society of Civil Engineers. Retrieved from https://trid.trb.org/View/140820

Preusser, D. F., Leaf, W. A., DeBartolo, K. B., Blomberg, R. D., and Levy, M. M., "The Effect of Right-Turn-on-Red on Pedestrian and Bicyclist Accidents." Journal of Safety Research, Vol. 13, No. 2, Oxford, N.Y., Pergamon Press, (1982) pp. 45-55.

American Association of State Highway and Transportation Officials. Highway Safety Manual. Washington, DC, 2010.

SECTION 2.12 – Overlapping Pedestrian Phases with Left Turn Phases

Description: At signalized intersections with multi stage crossings and a safe median refuge (where pedestrians can stop in between), pedestrian crossing phases for some half-crossings can run concurrently with both a concurrent vehicular phase and a left turn phase that pedestrian phases are not in conflict. The goal of this treatment is to increase the length of the WALK interval and improve pedestrian progression on multi stage crossings, which in turn reduce pedestrian delay and improve compliance. However. pedestrian phase overlaps with left turn phases can only be employed when the left turn phase is on recall and has a fixed duration of green time (e.g., set to max recall).

Summary of Findings: There is limited research found in the literature on overlapping pedestrian crossings with left turn phases. Furth and Wang (2015) tested this treatment in a simulation experiment and found that using overlapping pedestrian phases with left turns substantially improve pedestrian progression, leading to considerable reductions in average pedestrian delay for multi stage crossings. In that study, left turn phases were set to max recall. However, the study did not measure the effects of this treatment on motor traffic.

Furth, P.G. and Y.D. Wang. "Delay Estimation and Signal Timing Design Techniques for Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Left Turns." Transportation Research Board 94th Annual Meeting. No. 15-5365. 2015.

SECTION 2.13 – Permissive Periods for Pedestrian Actuation

Description: A permissive window is the range of time in the signal cycle within which a call will trigger that phase being served in the current cycle; calls received after the end of the permissive window will be served in the next cycle (Urbanik et al., 2015). Lengthening the permissive window for a pedestrian phase will allow some calls to be served in the current cycle, rather than in the next cycle, reducing pedestrian delay. It should be noted that in this definition, the start of a cycle is specified as the scheduled termination point of the coordinated phase. A permissive window allows the placement of the pedestrian phase (i.e., when in the cycle it begins) to be flexed to match the time at which pedestrians arrive. For example, if no pedestrian call has been received by the time the cycle reaches the scheduled start of the pedestrian phase, without the permissive window, the pedestrian phase will be skipped, and any call received after this time won't be served until the next cycle. With a permissive window, however, if a call is later received, and it comes in before the end of the permissive window, it will still trigger the pedestrian phase to start, albeit later than its schedule start time. This treatment is typically effective for crossings with moderate to low pedestrian demand (e.g., fewer than two pedestrians per cycle on average), because where pedestrian demand is high, a call will usually have been received before the scheduled start time of the pedestrian phase, eliminating the opportunity to flex the start time in response to late-arriving calls.

Summary of Findings: Kothuri et al. (2013) tested different length permissive windows at a half signal intersection, in which the crosswalk phase stands alone (i.e., is not concurrent with a vehicular phase). It was a full-scale field test in which time between pedestrian actuation and start of the WALK interval was taken as the measure of pedestrian delay. Testing permissive windows with length 19 seconds, 28 seconds, and 35 second, results indicated a significant reduction in average pedestrian delay with longer permissive windows. Results also highlighted that by not accounting for the flexibility afforded by permissive windows, the Highway Capacity Manual's formula overestimates pedestrian delay when permissive windows are used. A later study by Furth and Halawani (2016) showed that when pedestrian volume is low, and a permissive window is present, average pedestrian delay can be estimated using the following formula:

$$d_{ped} = \frac{(C - L_{window})}{2} \times \frac{(C - L_{window})}{C}$$

where d_{ped} is average pedestrian delay, C is cycle length, and L_{window} is the length of the permissive window. Kothuri et al.'s study did not measure impact to vehicular traffic.

Furth and Halawani (2) used a simulation study to examine the impact of maximum permissive windows on both pedestrian and vehicular delay at two intersections with concurrent crossings. In lieu of minimum permissive windows, they tested putting the pedestrian phase into recall. Using a reference case in which there is no recall or permissive window, and testing 12 scenarios (two intersections, two treatments, and three levels of pedestrian demand), the increase in delay to motor vehicles was one second or less in all scenarios. There were significant reductions in pedestrian delay only in the low demand scenario (0.5

pedestrians per cycle on average), with delay reductions of seven to 12 seconds with maximum permissive windows and three to five seconds with recall. In the medium and high pedestrian demand scenarios (two and five pedestrians per cycle, respectively), there was almost no change in pedestrian delay (or vehicle delay) because the operation was essentially the same as in the reference case – with moderate demand, a call is usually received in time to run the pedestrian phase in its normal, scheduled time, whether or not the pedestrian phase has recall or a permissive window.

Urbanik, T. et al. Traffic Signal Timing Manual (2nd ed). NCHRP Report 812, Transportation Research Board, 2015.

Kothuri, S., T. Reynolds, C. Monsere, and P.J. Koonce. Testing Strategies to Reduce Pedestrian Delay at Signalized Intersections: A Pilot Study in Portland, Oregon. Transportation Research Board Annual Meeting Compendium of Papers, 2013.

Furth, P. and Halawani, A. (2016). Adaptive Walk Intervals. Transportation Research Record: Journal of the Transportation Research Board, 2586, pp.83-89.

SECTION 2.14 – Protected Left Turns

Description: Protected left-turn phases at intersections provide a way to separate conflicts between left turning vehicles and opposing through vehicles, pedestrians, and bicyclists. Protected left turns at signalized intersections are displayed using a green arrow instead of a green ball, which is the case for the permissive left turns.

Summary of Findings: Relatively few studies on the pedestrian and bicyclist safety impacts of protected left-turn phasing have been conducted. Overall, existing studies, referenced below, show that protected-permissive left-turn phasing, protected left-turn phasing, and split phasing had a positive effect on motor vehicle and pedestrian safety when compared to permissive left-turn phasing. One recent study found no significant safety effect.

Pratt, Songchitruska, and Bonneson studied pedestrian crossings in the path of a signalized left-turn movement. They found a leading protected-permissive left-turn phase and split phasing were effective in reducing conflict rates between vehicles and pedestrians when compared to signals with a permissive left-turn phase (Pratt, Songchitruska, and Bonneson 2012). Chen, Chen, Ewing, McKnight, Srinivasan, and Roe found that converting a left turn phase from permissive to protected-permissive or protected only decreased the rate of crashes involving pedestrians by 44.9 percent, compared to a decrease of 11.5 percent at comparison sites (2012).

De Pauw, Daniels, Van Herck, and Wets studied signalized intersections with left-turn signals in Flanders, Belgium. They found that converting left-turn phasing from permitted to protected had favorable effects for multiple groups, including a 43 percent reduction in bicyclist injuries The total number of injury crashes decreased by 46 percent, which was attributed to a decrease in left-turn crashes. The total number of serious injury and fatal crashes decreased by 66 percent. The number of injured pedestrians was too low to draw meaningful conclusions (De Pauw, Daniels, Van Herck, Wets 2015). Another study by Chen, Chen, and

Ewing examined the impacts of different kinds of left-turn phasing: permissive, protected-only, and both, and found that changing a signal from permissive to protected/permissive or protected-only did not lead to a significant reduction in total crashes. The change from permissive to protected only did reduce left-turn crashes and pedestrian crashes, but this reduction was offset by the potential for vehicle over-taking crashes (Chen, Chen, and Ewing 2015). Chen, Chen, and Ewing in 2012 found that split phasing reduced crashes involving pedestrians by 39 percent (CMF of 0.61) (Chen, Chen, and Ewing 2012).

FHWA Development of Crash Modification Factors (DCMF) Program Task B5 is currently evaluating protected left turn phasing for pedestrian safety. Additionally, NCHRP Project 03-118: Decision-Making Guide for Traffic Signal Phasing is working on a decision-making guide for various signal phasing alternatives, including protected left turns. Relevant findings from these efforts will be incorporated as they become available.

Chen, L., C. Chen, and R. Ewing. "The Relative Effectiveness of Pedestrian Safety Countermeasures at Urban Intersections - Lessons from a New York City Experience." Presented at the 91st Annual Meeting of the Transportation Research Board, January 22-26, Washington, DC, 2012.

Chen, L., Chen, C., & Ewing, R. (2015). Left-turn phase: Permissive, protected, or both? A quasi-experimental design in new york city. Accident Analysis & Prevention, 76, pp 102-109. Retrieved from http://dx.doi.org/10.1016/j.aap.2014.12.019

Chen, L., C. Chen, R. Ewing, C. McKnight, R. Srinivasan, and M. Roe. Safety Countermeasures and Crash Reduction in New York City—Experience and Lessons Learned. Accident Analysis and Prevention. In print, 2012.

De Pauw, E., Daniels, S., Van Herck, S., & Wets, G. (2015). Safety effects of protected left-turn phasing at signalized intersections: An empirical analysis. doi:10.3390/safety1010094

Pratt, M., P. Songchitruska and J. Bonneson. Development of Guidelines for Pedestrian Safety Treatments at Signalized Intersections. Texas Transportation Institute. College Station, Texas, 2012.

SECTION 2.15 – Red Period Countdown

Description: Red period countdowns inform a user at a signal of the upcoming change in indication from red display to green display. The treatment is intended to improve non-motorized compliance and reduce the anxiety associated with waiting at signalized intersections through real-time information.

Summary of Findings: Existing research primarily focuses on driver behavior with limited conclusions on its effect on non-motorized users. In a driver simulation study in Oregon, Islam found the presence of the red countdown reduced start-up headway by 0.72 seconds for drivers (Islam 2014). A study of red countdown in Japan and Turkey also focused on driver behavior and found the treatments reduced start-up lost time for drivers and resulted in increased premature start for drivers. Yu and Lu found that ending the red period countdown a few seconds early, showing only the red and green signal without a number for the final seconds, lessened the instances of premature start (Yu and Lu 2014).

A study of pedestrian behavior in Poland found that when red period countdown was enabled, pedestrians were more likely to enter the crosswalk during the red phase when the countdown was in its final seconds. Pedestrians were less likely to enter the crosswalk at the start of the countdown when the wait time displayed was longer. Researchers concluded the countdown timers improved compliance at the start of the red phase and worsened comliance at the end of the red phase (Sobota et al. 2017).

Islam, M. (2014). Safety and Efficiency Benefits of Traffic Signal Countdown Timers: A Driving Simulator Study. Oregon Station University.

Sobota, A., Klos, M. J., and Karon, G. (2017). The Influence of Countdown Timers on the Traffic Safety of Pedestrians and Vehicles at the Signalized Intersection. Silesian University of Technology, Katowice, Poland.

Yu, K. and Lu, H. (2014). Effects of Countdown Signals in Red Phase on Drivers: A Comparative Study between Japan and Turkey, Institute of Transportation Engineering, Tsinghua University, Beijing, China.

SECTION 2.16 – Rest in Walk

Description: Rest in Walk is a controller setting that dwells in the pedestrian walk interval while the coordinated phase is green, regardless of pedestrian calls (Figure 8). That way, if the concurrent vehicular green phase is longer, the Walk interval will be longer as well, instead of terminating after a specified duration, thereby reducing average pedestrian delay. This mode is often used when there are high pedestrian volumes, such as in downtown environment (Urbanik et al., 2015).

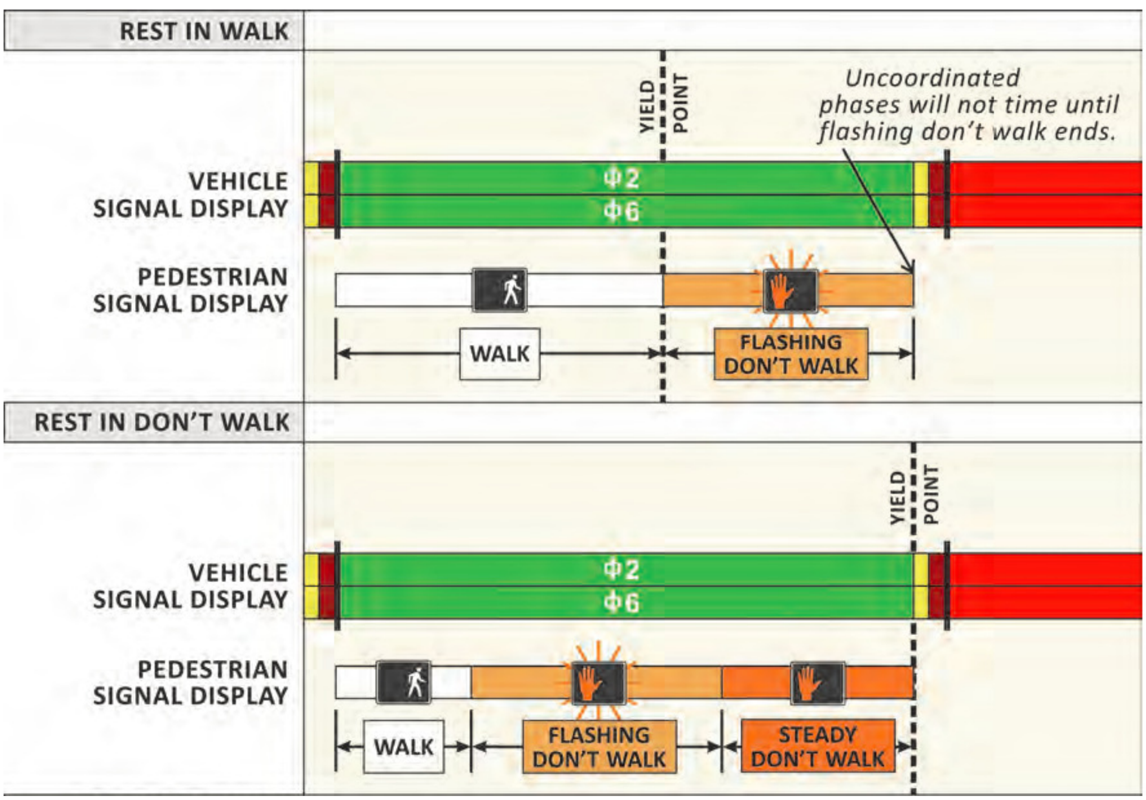


Figure 8: Rest in Walk and Rest in Don't Walk Modes (Urbanik et al., 2015)

Summary of Findings: Mirabella (2013) studied the effects of Rest in Walk and Pedestrian Recall at four signalized intersections in the Tampa Bay area. Two of the four locations operated with Rest in Walk and Pedestrian Recall and the other two operated without Rest in Walk and Pedestrian Recall. A total of 26 hours of data were collected at the four study sites. Results from the field data indicated that the presence of Rest in Walk along with Pedestrian Recall was found to encourage higher pedestrian and bicyclist compliance rates than their absence.

From an operations perspective, Rest in Walk reduces pedestrian delay by lengthening the WALK interval. Since pedestrian delay is directly related to red phase duration (HCM 6th Edition), its effect on pedestrian delay can be large where the specified WALK interval is short while the concurrent vehicular phase has a long green duration in many cycles. By design, Rest in Walk does not affect vehicular signal timing. As a result, its only potential impact on vehicular traffic is the additional interference (conflict) with the turning vehicles that may arise from allowing pedestrian crossings later in the phase. Unless turning volumes (this applies only to permitted turns) are high along with high pedestrian volumes, the impact on vehicular traffic is expected to be negligible.

Urbanik, T. et al. Traffic Signal Timing Manual Second Edition. NCHRP Report 812, Transportation Research Board, 2015.

Jacob A. Mirabella, 2013, Understanding Pedestrian and Bicyclist Compliance and Safety Impacts of Different Walk Modes at Signalized Intersections for a Livable Community, Master's Thesis, University of South Florida

Highway Capacity Manual, 6th Edition, Transportation Research Board.

SECTION 2.17 – Short Cycle Length and Phase Reservice for Pedestrian/Bicycle Phases

Description: The length of a signal cycle is the time from when one WALK or green bike interval ends until the next WALK or green bike interval ends, with all conflicting phases served in between. Cycle length may be fixed (as in the case with pretimed control or coordinated-actuated control) or variable (running free). Reducing the length of a signal cycle results in lower pedestrian and bicycle delay, and has the potential to make roads safer for walking and cycling by reducing speeding opportunities, as demonstrated in the paper referenced below.

Phase reservice is when pedestrian and bicycle phases come up more than once in a signal cycle. Providing reservice has approximately the same effect on pedestrian and bicycle delay as cutting the cycle length in half.

Summary of Findings: According to the 6th Edition of Highway Capacity Manual, the pedestrian delay while waiting to cross the major street is computed using the following formula:

$$d_p = \frac{(C - g_{walk})^2}{2C}$$

where d_p is the pedestrian delay, C is the cycle length, and $g_{walk,}$ is the effective walk time for the associated pedestrian phase. Recent research indicates that pedestrians typically continue to enter intersections with pedestrian signal heads during the first few seconds of the pedestrian clearance interval (Rouphail et al, 1998, Virkler et al, 1998). As a result, HCM assumed a conservative estimate of an additional four seconds walk time foe pedestrians. Therefore, g_{walk} is generally calculated as:

$$g_{walk} = Walk + 4.0$$

Therefore, it can be concluded that cycle length has a direct effect on average pedestrian delay and lower intersection cycle length also leads to lower pedestrian delay.

The choice of signal cycle length generally involves a tradeoff of capacity, delay, and progression:

- **Capacity.** Because phase switching always involves some lost time due to change intervals, intersections theoretically have more capacity when the cycle is longer. However, with very long cycle lengths, further capacity gains from lengthening a cycle are typically small due to the following reasons:
    - When auxiliary turn lanes are not long enough to reach to the back of the queue, long cycles may cause either queued left-turning vehicles spill onto the through lane and block the through lane or causing queued through vehicles to block entry to the left turn lane; in such situations, a shorter cycle will involve shorter queue lengths and may thus prevent this kind of blockage (Denney et al., 2009).
    - Where left turn lanes are lacking so that left-turning vehicles waiting for a gap can block a through lane, short cycles provide more opportunities per hour for left turns to proceed during phase switches (“sneakers”). In such cases, shorter cycles may provide more vehicular capacity.
- **Delay.** For vehicles, pedestrians, and bicycles arriving without a strong cyclical pattern determined by upstream signals, delay is roughly proportional to cycle length. As a result, a shorter cycle length means less delay.
- **Progression (green waves).** For vehicles arriving in platoons from an upstream intersection, delay can be small even when the cycle is long if the signals are timed (“offset”) so that the platoon arrives near the start of the green.

In addition to leading to low non-motorized delays at signalized intersections, a recent study conducted by Furth et al. (2018) using microsimulation showed that shorter cycle lengths along an arterial with eight signalized intersections will also limit speeding opportunities, thereby potentially improving safety for all users along a corridor. Speeding opportunities was measured by the number of vehicles arriving at a stop line while the signal is green but with no vehicle less than 5 seconds ahead of them. Table 5 shows various signal control strategies and their effect on signal cycle length on pedestrian delay, vehicular delay, and speeding opportunities. Small zone coordination is defined as providing coordination for up to three signalized intersections, allowing variable cycle lengths along the corridor while maintaining coordination for shorter stretches.

Table 5: Changes in Delay and Speeding Opportunities Compared to Coordinated-Actuated Control (Source: Furth et al., 2018, Massachusetts Avenue case study)

	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%

Denney Jr., R.W., E. Curtis, and L. Head (2009). Long Green Times and Cycles at Congested Traffic Signals. Transportation Research Record 2128, pp. 1-10.

Furth, P.G., A.T.M. Halawani, J. Li, W. Hu, and Burak Cesme (2018). Using Traffic Signal Control to Limit Speeding Opportunities on Bidirectional Urban Arterials. Transportation Research Record, to appear.

SECTION 2.18 – Vehicular Hold with Pedestrian Overlaps

Description: This treatment occurs when pedestrian phases that are normally considered in conflict with one another (because their concurrent vehicular movements are in conflict with one another) run concurrently for a short period of time while the concurrent vehicular movements are held in red phase (Figure 9). In the example below, during a short “hold” interval in which both N-S and E-W vehicular movements are red, both the north-south and east-west crosswalks are running. Note that while the north-south and east-west vehicular movements are in conflict with each other and therefore could never run concurrently, pedestrian movements are not in conflict with each other, and therefore can be allowed to overlap. It should also be noted that the overlap creates a Leading Pedestrian Interval for one of the crossings (for the north-south crossing in this case, but not for the east-west crossing).

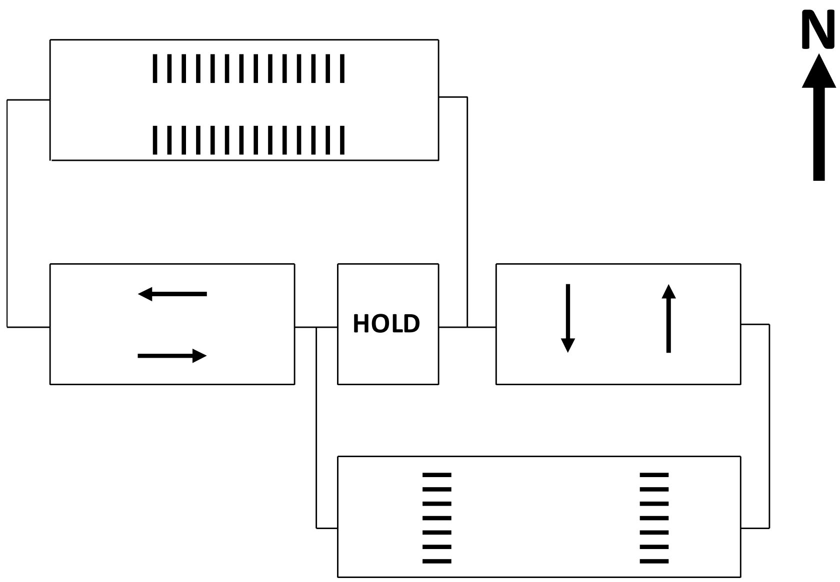


Figure 9: Example Ring-Barrier Diagram with Vehicular Hold and Pedestrian Overlaps

At intersections with long crossings but low vehicular volumes (perhaps during certain periods of the day), when the timing of the signal cycle is dominated by pedestrian timing needs, this treatment can lead to *shorter signal cycles* with lower pedestrian delay.

Summary of Findings: Using simulation at an intersection in Brookline, MA for a period of low vehicular demand, Furth et al. (2012) found that vehicular holds with pedestrian overlaps led to a 22 percent reduction in cycle length, with average pedestrian delay falling from 24 to 18 sec, 25 percent reduction in average pedestrian delay, with no measurable impact on vehicular delay.

Furth, P.G., T.H. Muller, M. Salomons, T. Bertulis, and P.J. Koonce. "Barrier-Free Ring Structures and Pedestrian Overlaps in Signalized Intersection Control." Transportation Research Record 2311, pp. 132-141, 2012.

SECTION 2.19 – Walk Countdown

Description: Walk countdown (also known as pedestrian countdown signals (PCSs)) are indications designed to begin counting down at the beginning of the clearance interval (flashing "DON'T WALK" symbol) and can be on fixed-time or on pushbutton (actuated) operation (sometime pushbuttons are used with fixed time signals to provide locator tones for the blind or to activate Leading Pedestrian Intervals). They indicate how much time is left in the crossing phase. According to the MUTCD, walk countdowns are required for all newly installed traffic signals where pedestrian signals are installed (Thomas, et al. (2016).

Summary of Findings: Except for one study, studies on the safety effects of walk countdowns have found that pedestrian compliance and crash reduction were improved with the Walk Countdowns. According to the NCHRP Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways, a CMF of 0.75 for pedestrian crashes was developed by Markowitz et al. (2006) when traditional walk/don't walk pedestrian signals were replaced with pedestrian countdown signal heads.

Van Houten et al. (2014) found that installing pedestrian countdown times reduced pedestrian-vehicle conflicts by 55-70 percent (CMFs of 0.45 to 0.30). The findings from PEDSAFE suggest that pedestrian countdown signal sites have a mixed impact on the percent of pedestrians who comply with the WALK signal phase, with some studies showing a decrease in compliance and some study sites showing an increase). Findings for rates of crashes involving pedestrians after installation of countdown signals ranged from a 70 percent reduction (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)).

Another recent study conducted by Rothman et al. (2017) compared the spatial patterns on crashes involving pedestrians pre- and post-installation of PCSs (across ages and across locations in Toronto). The results indicated that there was an overall reduction in crashes post PCS installation at both PCS location and non-PCS locations, with a greater reduction at non-PCS locations (22 percent vs. one percent). There was an increase in crashes involving adults (five percent) and older adults (nine percent) at PCS locations after installation, with increased adult crashes concentrated in downtown. Another study conducted by Kwigizile et al. (2017) used crashed data to study the effects of PCSs and showed more consistent findings. Results indicated an almost 32 percent reduction in crashes involving pedestrians for all ages and severities, but a particular decrease in crashes involving pedestrians age 65 and older.

Thomas, L., Thirsk, N.J., and Zegeer, C. (2016). NCHRP Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways, DC: Transportation Research Board

Markowitz, F., S. Sciortino, J.L. Fleck, and B.M. Yee. Pedestrian Countdown Signals: Experience with an Extensive Pilot Installation. ITE Journal, Vol. 76, No. 1, Institute of Transportation Engineers, 2006, pp. 43-48.
Van Houten, R., LaPlante, J, and Gustafson, T. "Evaluating Pedestrian Safety Improvements." Michigan DOT Final Report No. RC-1585, December 2012. Also published in: Huitema, B., R. Van Houten, and H. Manal. "An Analysis of The Effects of Installing Pedestrian Countdown Timers". Presented at the 93rd Annual Meeting of the Transportation Research Board, Paper No, 14-0227, Washington, D.C., (2014).

Huitema, B., R. Van Houten, and H. Manal. An Analysis of the Effects of Installing Pedestrian Countdown Timers on the Incidence of Pedestrian Crashes in the City of Detroit, Michigan. Presented at the 93rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2014.

Camden, A., R. Buliung, L. Rothman, C. Macarthur, A. Howard. The Impact of Pedestrian Countdown Signals on Pedestrian-Motor Vehicle Collisions: A Quasi-Experimental Study. Injury Prevention. Vol. 18, 2012, pp. 210-215. Open access copy: http://injuryprevention.bmj.com/content/18/4/210

Rothman, L., Cloutier, M.-S., Macpherson, A., & Howard, A. (2017). Spatial Distribution of Pedestrian-Motor Vehicle Collisions Before and After Pedestrian Countdown Signal Installation in Toronto, Canada. Presented at the Transportation Research Board 96th Annual Meeting, Transportation Research Board. Retrieved from https://trid.trb.org/View/1438802.

Kwigizile, V., Boateng, R. A., Oh, J.-S., & Lariviere, K. (2016). Evaluating the Effectiveness of Pedestrian Countdown Signals on the Safety of Pedestrians in Michigan. Presented at the 95th Annual Meeting of the Transportation Research Board. Retrieved from https://trid.trb.org/View/1393556.

SECTION 3.0 – AGENCY GUIDANCE POLICIES FOR NON-MOTORIZED USER TREATMENTS

A preliminary scan of agency guidance policies for non-motorized users ranged from long-range transportation plans to modal specific plans and design guidelines. Oftentimes, an agency with a long-range transportation plan that focuses on non-motorized users, a correlated master plan was available. Provided in Table 6 is a sample list of agencies that had reference documents readily available.

Table 6: Sample List of Agencies with Policies and/or Procedures for Treatment Design and Operations for Non-Motorized Users

	Agency	Reference Documents
1	City of Portland, Oregon	• PedPDX: Portland's Citywide Pedestrian Plan • Portland Bicycle Plan
2	Massachusetts Department of Transportation	• MassDOT Separated Bike Lane Planning and Design Guide
3	City of Chicago, Illinois	• Sustainable Urban Infrastructure, Policies and Guidelines • Complete Streets Chicago, Design Guidelines
4	City of Oakland, California	• Oakland Bicycle Facility Design Guidelines
5	City of Vancouver, British Columbia	• City of Vancouver Transportation 2040 Plan
6	City of Charlotte, North Carolina	• Charlotte WALKS • Charlotte BIKES

A range of agencies were identified and interviewed as part of Task 2 (Agency Engagement). Details of agency guidance and policies are reviewed and summarized in the Task 2 (Agency Engagement) memorandum.

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Signalized Intersection Treatments for Non-Motorized Users Summary Memorandum

Addendum to Task 1 (Literature Review) Memorandum

Kittelson & Associates, Inc.

In association with:

Northeastern University

Institute of Transportation Engineers

Accessible Design for the Blind

January 28, 2019

SECTION 1.0 – INTRODUCTION

Building upon Task 1 (Literature Review) findings, additional treatments and strategies for non-motorized users at signalized intersection are identified. A total of thirty-four (34) treatments are identified as methods of improving service, mobility and safety, to non-motorized users at signalized intersections. A few of them carry the double sense of a treatment and a policy. For example, having protected-only left turns so that crossing pedestrians and bicyclists don't encounter a conflict from left-turning vehicles is a well-known treatment; the tool that makes a difference in some cities is a policy that in certain contexts, left turns should be protected only. These treatments were grouped into six categories based on the problem they address.

Table 1 presents these treatments and their associated categories.

Table 1: List of Treatments and Their Associated Treatment Categories

Treatment Category	Treatment Name
Improving Pedestrian/Bicycle Crossing Experience	Walk countdown
	Red period countdown
	Independently mounted pushbuttons
	Accessible signals without push button actuation
	Call indicators
	Pedestrian Detection
	Bicycle Detection
	Bicycle indications
Reducing Pedestrian Delay	Evaluating pedestrian delay
	Short cycle length
	Maximizing walk interval length (including rest in walk)
	Pedestrian recall versus actuation
	Adapting minimum green to demand
	Adaptive walk intervals
	Permissive periods for pedestrian actuation
Reducing Potential Conflicts with Parallel Traffic Turns	Leading pedestrian interval (LPI)
	Leading through interval (LTI)
	Flashing right turn yellow arrow for permitted conflicts
	Flashing pedestrian/bicycle indicator for permitted conflicts
	Early right turn release
Eliminating Conflicts with Parallel Traffic Turns	No turn on red
	Exclusive pedestrian and bicycle phases
	Protected left turns to address non-motorized conflicts
	Concurrent yet protected crossings
	Delta islands for non-motorized crossings (includes guidance on dealing with them as well as potentially removing them)
Special Phasing Techniques Favoring Pedestrian and Bicycles	Multi-stage crossings with pedestrian overlaps with left turn phases
	Pedestrian phase overlaps with each other, with bicycle phases, and with vehicular holds
	Pedestrian/bicycle phase reservice
	Two-stage left turn progression for bicycles
	Pedestrian hybrid beacons (PHB) at intersections with minor streets
Bicycle Phases and Special Bicycle Needs	Bicycle phases with simple applications: contraflow, with exclusive ped phase, with LPI and LTI
	Diagonal bicycle crossing phases
	Single-stage bicycle crossings (where crossing islands are too small for bicycle queuing)
	Minimum green and change interval settings for bicycles

SECTION 2.0 – TREATMENT SUMMARY

This document provides Information Summary sheets for the nine (9) treatments that are more complete during the Phase I of this project. It should be noted that these Information Summary Sheets are still in the draft format and will be finalized during Phase II. Preliminary information for other treatments are described in the Task 1 (Literature Review) memorandum while some additional treatments are in development. The treatments with incomplete information will be completed during the Phase II of the project through additional information gathering, agency follow-ups (including case studies), and original research. Please refer to the Task 4 (Phase II Work Plan) memorandum for details.

The treatments in which the Information Summary sheets were created in this document are listed as follows:

i. Evaluating Pedestrian Delay,
ii. Maximizing Walk Interval Length,
iii. Rest in Walk,
iv. Leading Through Interval,
v. Early Right Turn Release,
vi. Exclusive Pedestrian and Bicycle Phases,
vii. Concurrent yet Protected Crossings,
viii. Two-stage Left Turn Progression for Bicycles, and
ix. Minimum Green for Bicycles.

Information Summary sheets for each of these treatments are provided in the next sections.

Treatment or Policy Name:

Evaluating Pedestrian and Bicycle Crossing Delay

Other Names:

N. A.

Description:

The “treatment” here is both a *policy option* and an *analysis tool*.

While intersection analysis routinely involves evaluating motor vehicle delay, it typically does not include evaluating pedestrian delay. Furth proposed a policy that in any study in which motor vehicle delay is reported, pedestrian delay should be, too *(1)*. A maxim of business is that “only what’s measured counts,” and failing to measure pedestrian delay can lead to intersection designs with inadvertently poor level of service for pedestrians.

The industry needs tools to estimate crossing delay. For simple situations (single stage crossing, pretimed phase), a simple equation can be applied. However, tools are lacking for evaluating pedestrian delay for actuated phases and, most urgently, for intersections with multistage crossings, which can involve extremely large crossing delay if the cycle is long and there is poor progression between stages. Furth and Wang *(1)* developed such a tool, but it has not been widely adopted because it involves downloading an executable program, something that many company firewalls will not allow.

Where bikes cross in their own phase, bicycle delay should likewise be estimated and reported. However, where bicycles follow vehicular phases, reporting bicycle delay may not be necessary because it will be similar to vehicular delay.

Variations and Relation to Other Treatments and Policies

An alternative to reporting pedestrian delay is reporting pedestrian Level of Service. The 2000 HCM had a direct Level of Service model for pedestrian delay, along with separate pedestrian LOS measures that accounted for the adequacy of crossing space and queuing space *(2)*. Since 2010, however, the HCM’s level of service method for pedestrians and bicycles at signalized intersections uses a multi-criteria scoring method based on the “multimodal level of service” method *(3, 4)*. This scoring method combines pedestrian delay with the other aspects of pedestrian service mentioned earlier. A drawback of a composite measure like this is that the impact of pedestrian delay gets diluted when combined with metrics for provision of adequate queuing space and sufficiently wide crosswalks. The scoring system is nonlinear, and with some values is extremely insensitive to pedestrian delay. For example, in some situations, an increase in average pedestrian delay from 30 s to 60 s has no impact on LOS.

Objectives, Context, and Operational Details:

The objective of measuring pedestrian/bike delay is to motivate designers to reduce pedestrian and bike delay (just as they do for vehicular delay) and, in impact studies, to ensure that impacts to pedestrians are accounted for.

Single Stage Crossings with Pretimed Control

For simple crossings, single stage crossings with pretimed signals, average pedestrian delay can be calculated using a simple, well established formula that appears in the Highway Capacity Manual as follows *(4)*.

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

In which, d_p is average pedestrian delay, C is cycle length, and g_{Walk} is the effective walk interval. HCM, referring to a prior study *(5)*, suggests 4 seconds of additional walk time on top of actual WALK time as a conservative estimate to obtain the effective walk interval, g_{Walk}. Therefore,

$$g_{Walk} = WALK + 4$$

The suggested amount is the result of a study that predates pedestrian countdown timers. It is expected that pedestrian countdown timers lead to a greater effective pedestrian green by allowing faster pedestrians start their crossings at later times during flashing DON'T WALK, in the absence of prohibitive enforcement. Since it is unknown how much pedestrian countdown timers can affect effective pedestrian green, it is a good subject for further research.

Single Stage Crossings with Actuated Control

Better methods are needed to evaluate pedestrian delay when either walk time or cycle length varies from cycle to cycle, and accounting for pedestrian actuation details. An approximate method is to use the formula for pretimed control with an average cycle length and average WALK interval length. For isolated actuated signals, expected values of cycle length and phase lengths can be estimated following the methods described in Furth et al. *(6)*. However, guidance on converting parameters of actuated signals to equivalent pretimed parameters is still needed because delay depends not only on timing parameters, but also on control choices and settings including whether pedestrian phase is actuated or not and whether rest-in-Walk is applied to coordinated phases.

Pedestrian actuation options also affect average delay but tend to not be appropriately accounted for in delay estimation. Pedestrian delay is typically shorter when the crossing phase is on recall if the cycle length is fixed, because under actuation, pedestrians will only be served in each cycle if they (or other pedestrians) arrive before the start of the parent green phase. However, if the cycle length is not fixed (fully actuated control), putting the crossing phases on recall may increase average delay by increasing cycle length.

Research is needed to explore these issues and improve responsive methods for estimating pedestrian delay.

Multistage Crossings

Where crossings have to be made in two or more stages, methods for estimating crossing delay are lacking and are urgently needed. Furth et al. *(1)* point out situations in which multi-stage crossings involve very long pedestrian delays, sometimes more than 120 s, due to failure to consider pedestrian delay for the crossing as a whole.

Microsimulation can be used, but it involves considerable time and expertise. There is still a need for simpler tools that correspond to those used to calculate level of service for motor traffic. Simply applying the standard delay equation to each partial crossing and summing yields a wrong result because pedestrians do not arrive uniformly at any stage after the first *(7)*. A few researchers derived the formula for delay at two-stage crossings *(8, 9)*. Wang and Tian *(8)* develop formulas for six different cases, and Ma et. al. *(9)* for four, depending on which signal (green or red) pedestrians see when arriving at the first and second stages. Both methods then involve averaging results for the many cases using appropriate weights. Because of their complexity, these formulas have not seen widespread adoption.

A more general tool was developed by Furth et al. for any number of stages which was written on a Matlab platform *(1)*. Their application program, the Northeastern University Ped & Bike Crossing Delay Calculator, is the only analytical software tool known (short of full-scale microsimulation) for evaluating pedestrian delay at single- and multi-stage crossings, published in 2015 and freely available for download *(10)*. However, as mentioned before, security and convenience issues have kept it from being adopted widely.

Policy Guidance:

Cities should consider a policy requiring that any traffic analysis that estimates and reports vehicular delay shall likewise estimate and report pedestrian delay. They should consider applying this policy to internal traffic signal studies, to externally done studies in connection with road improvement projects, and to traffic impact studies done in connection with land development proposals.

Application Instances:

Cambridge, Massachusetts has long required that traffic impact studies done in connection with land development proposals estimate and report pedestrian delay. Consultants who do such studies general estimate pedestrian delay using the HCM formula.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

Without question, one of the reasons for the poor service that pedestrians and cyclists get at traffic signals is that conventional design practice does not include any evaluation of their delay. For vehicular traffic, standard tools used for intersection delay not only evaluate but also minimize their delay; however, they report nothing about pedestrian delay. The business maxim “only what’s measured matters” applies: designers have every incentive to minimize vehicular delay, and no incentive to even think about pedestrian service beyond meeting minimum safety standards. Measuring pedestrian/bike delay and reporting it in operational and design analysis of traffic signals is a critical step toward improving intersection performance for non-motorized users.

References:

1) Furth, P. G., and Wang, Y. D. Delay estimation and signal timing design techniques for multi-stage pedestrian crossings and two-stage bicycle left turns. 94th Annual Meeting Transportation Research Board, 2015, pp. 1–16.
2) Highway Capacity Manual. (2000). Washington, D.C.: Transportation Research Board of the National Academies.
3) Highway Capacity Manual. (2010). Washington, D.C.: Transportation Research Board of the National Academies.
4) Highway Capacity Manual. (2016). Washington, D.C.: Transportation Research Board of the National Academies.
5) Rouphail, N., J. Hummer, J. Milazzo, and D. Allen. Capacity Analysis of Pedestrian and Bicycle Facilities: Recommended Procedures for the “Pedestrians” Chapter of the Highway Capacity Manual. Report FHWA-RD-98-107. Federal Highway Administration, Washington, D.C., 1998.
6) Furth, P.G., B.Cesme, and Th.H.J. Muller. Lost Time and Cycle Length for an Actuated Traffic Signal. Transportation Research Record 2128, 2009, pp. 152-160.
7) Wang, X., Z. Z. Tian, F. Ohene, and P. J. V. Koonce. Pedestrian Delay Models at Signalized Intersections Considering Signal Phasing and Pedestrian Treatment Alternatives. Presented at 88th Annual Meeting of the Transportation Research Board, Washington, D.C., 2009.
8) Wang, Xuan and Zong Tian. Pedestrian Delay at Signalized Intersections with a Two-Stage Crossing Design. Transportation Research Record 2173, 2010, pp. 133-138.
9) Ma, Wanjing, Yue Liu, Hanzhou Xie, and Xiaoguang Yang. Multiobjective Optimization of Signal Timings for Two-Stage, Midblock Pedestrian Crosswalk. Transportation Research Record 2264, 2011, pp. 34-43.
10) Northeastern University Ped & Bike Crossing Delay Calculator. http://www.northeastern.edu/peter.furth/delaycalculator/

Treatment or Policy Name:

Maximizing Walk Interval Length

Other Names:

N. A.

Description:

For pedestrian crossings that are concurrent, this set of treatments aims to make the WALK interval as long as it can be without significantly constraining the signal cycle. Where the parent phase has a fixed green duration, the WALK interval is set so that, together with the pedestrian clearance, it fills the phase split. Where the parent phase is actuated, the WALK interval is set so that, together with the pedestrian clearance, it fills the minimum phase split, which occurs when the parent phase green runs for its minimum duration.

Variations and Relation to Other Treatments and Policies

Where coordinated-actuated control is used, for the coordinated phase(s), the goal of this treatment can be accomplished most easily using the treatment ***Rest in Walk***.

The tactics ***Pretimed Control, Adapting Minimum Green to Demand***, and ***Adaptive Walk Intervals*** involve making WALK intervals longer by increasing minimum green settings. A common theme is that it is often possible to increase some minimum green settings in a way that will only slightly constrain the signal cycle, avoiding substantial changes to signal and traffic operations while substantially lowering pedestrian delay.

Objectives, Context, and Operational Details:

The objective of maximizing duration of walk intervals is to reduce pedestrian delay by providing a longer window to start crossing, without additional significant constraint to the signal cycle.

Maximizing WALK interval shortens pedestrian red which is synonymous with reducing delay for pedestrians. Today, at some locations it has become an unthoughtful cliché to set the duration of walk interval to its minimum, 7 seconds. However, for many of them, having longer walk intervals is no harm to other traffic. A basic instance of such wastefulness is seen at intersections in which a steady DON'T WALK sign is displayed to pedestrians far earlier than when the circular red is shown to adjacent parallel vehicular movement.

Appropriate treatments depend on the operational context:

1. Pretimed Phases
2. Coordinated Phases
3. Actuated Phases

1. Pretimed Phases

A pretimed phase is one whose start and end times are known. The parent phase must be long enough to accommodate minimum WALK interval and pedestrian clearance time even if the vehicular traffic does not need that much of green time. If W is length of the WALK interval; $PedClear$ is the needed pedestrian clearance time; and G, Y, and AR are respectively the green time, yellow time, and red clearance time of the parent phase, the following inequality should hold:

$$(W + PedClear) < (G + Y + AR)$$

So, the longest WALK interval within the parent phase can be achieved as follows:

$$W_{max} = \max\big((G + Y + AR - PedClear),\ \ W_{min}\big)$$

In which W_{min} is the minimum WALK interval allowed by policy (typically 7 s) and W_{max} is the maximum possible duration of WALK interval without any impact to the cycle length *(1)*.

2. Coordinated Phases

In coordinated-actuated signals, one or two phases are considered coordinated. Their start time may vary on a cycle by cycle basis, but their end time is fixed. For the coordinated phase, the treatment ***Rest in Walk*** can be used to maximize the duration of the walk interval.

3. Actuated Phases

Actuated phases can be the non-coordinated phases in coordinated actuated control, or any phase with fully actuated control. Their green time varies on a cycle by cycle basis, but is never less than their minimum green (a controller setting), G_{min}. In order to avoid constraining the cycle (or constraining it as little as possible), the greatest possible walk interval depends on G_{min}, and is given by this formula:

$$\boldsymbol{W_{max} = \max\big((G_{min} + Y + AR - PedClear),\ \ W_{min}\big)}$$

As a first step, then, the walk interval should be set equal to W_{max} as given by this equation. A further step is to increase G_{min}, which increases W_{max} correspondingly. While increasing G_{min} can be disruptive for some phases, for others it will hardly constrain the signal cycle if those phases' green times nearly always exceed their minimum green. There are three treatments that work by increasing G_{min}.

The first is ***Adapting Minimum Green to Demand.*** For example, suppose a phase has a minimum green of 10 s, but traffic is such that it almost always runs 18 s or longer. In such a case, increasing G_{min} to 18 s, and increasing the walk interval correspondingly, will hardly constrain the signal cycle while giving pedestrians a WALK interval that is substantially longer.

The second is increasing minimum green till it equals maximum green, which in effect makes it ***Pretimed Phase***. (Pretimed phases are part of pretimed control, of course, but they can also be part of actuated control.) This hardly constrains the cycle if the phase in question runs to its maximum green in most cycles.

The third treatment is ***Adaptive Walk Intervals***, in which G_{min} is set dynamically, on a cycle-by-cycle basis, using data from recent past cycles on how long the green is running. If the green has run for a long time in the last five cycles, for instance, one can expect the green to be long in the next cycle as well, and so it makes sense to increase G_{min}; likewise, if recent history shows that green times are getting shorter, G_{min} should get a lower value.

Policy Guidance:

In the *Traffic Signal Timing Manual* different values up to 15 s have been recommended for the duration of walk interval as in the table below *(2)*.

Conditions	Walk Interval (s)
High-pedestrian-volume area (e.g., school, CBD, or sports and event venue)	10 to 15
Typical pedestrian volume and longer cycle length	7 to 10
Typical pedestrian volume and shorter cycle length	7
Negligible pedestrian volume and otherwise long cycle length	4

Walk intervals recommended in this table can be used as lower bounds for the noted conditions.

Application Instances:

Many US cities with pretimed control in their downtowns apply this policy to set WALK intervals. Many US cities deliberately prefer pretimed phasing over actuated phasing because it allows them to have the longest possible WALK interval. Many US cities use Rest-in-Walk for crossings parallel to coordinated phases. Adaptive WALK intervals are used in Amsterdam, but are not known to be used in North America.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

Longer walk intervals lead to less delay for pedestrians. Delay, along with the safety, are the most important factors contributing to pedestrian service. There is no cost in increasing walk interval in anyway, except when large number of permitted turns are in conflict with pedestrians. In such circumstances, part of the parallel vehicular phase may be left free from pedestrians on purpose. Impact of maximizing pedestrian phase can be large where the specified WALK interval is short while the parent phase has a long green. For example, in a 100 s coordinated-actuated cycle with an average 60 s vehicular through phase in the main direction and 10 s required pedestrian clearance time, average pedestrian delay along the main street can be reduced by 73 percent, as in the table below. In the meantime, this change does not affect pedestrians on the other direction, nor any of the vehicular traffic unless there are many turns into the minor street.

Scenario	Average Walk Interval Duration (s)	Pedestrian Effective Green (s)	Pedestrian Red (s)	Average Delay for Pedestrians along the Coordinated Street (s)
Minimum WALK applied	7	11	89	40
Maximized walk interval, including the Rest in Walk option	50	54	46	11

References:

1) Manual on Uniform Traffic Control Devices. FHWA, U.S. Department of Transportation, 2009.
2) Urbanik, T. et al. Traffic Signal Timing Manual (2nd ed). NCHRP Report 812, Transportation Research Board

Treatment or Policy Name:

Rest in WALK

Other Names:

N. A.

Description:

Rest in WALK is a controller setting for a crossing concurrent with a coordinated phase. On a cycle by cycle basis, it makes the WALK interval last as long as will fit within the green time of its parent phase. That way, if the parent phase begins early and therefore has a longer green, the WALK interval will be longer as well, instead of terminating after a specified duration.

Figure 1 shows how the pedestrian phase is normally scheduled within the coordinated phase. If the parent phase begins early but doesn't have the rest-in-walk setting, the WALK interval will begin with the parent phase, run for its specified length, and then terminate (Figure 1b). Under "Rest in WALK," the controller calculates an ending time for the WALK by subtracting the pedestrian clearance time from the scheduled phase ending time and holds the WALK display until then (Figure 1c).

Variations:

None known.

Relation to Other Treatments and Policies:

Rest in Walk is one of four treatments that aim to maximize the WALK Interval. It is dynamic in that it accounts for the cycle-to-cycle variation in a coordinated phase's green interval.

Objectives, Context, and Operational Details:

The objective of Rest in WALK is to grant pedestrians the longest possible WALK interval without additional constraint to the signal cycle. Normally, the length of a WALK interval is a fixed number specified as a controller setting; typically, it is either set to a standard minimum WALK time (e.g., 7 s), or is calculated based on the policy of ***maximizing the length of the walk interval***. Under "Rest in Walk," the WALK interval will continue to time beyond its specified duration up to an end time calculated by the controller that represents the moment at which the WALK interval must end for the crossing phase to fit within the phase of a parent vehicular cycle. It applies to any crossing phase whose parent phase is a coordinated phase.

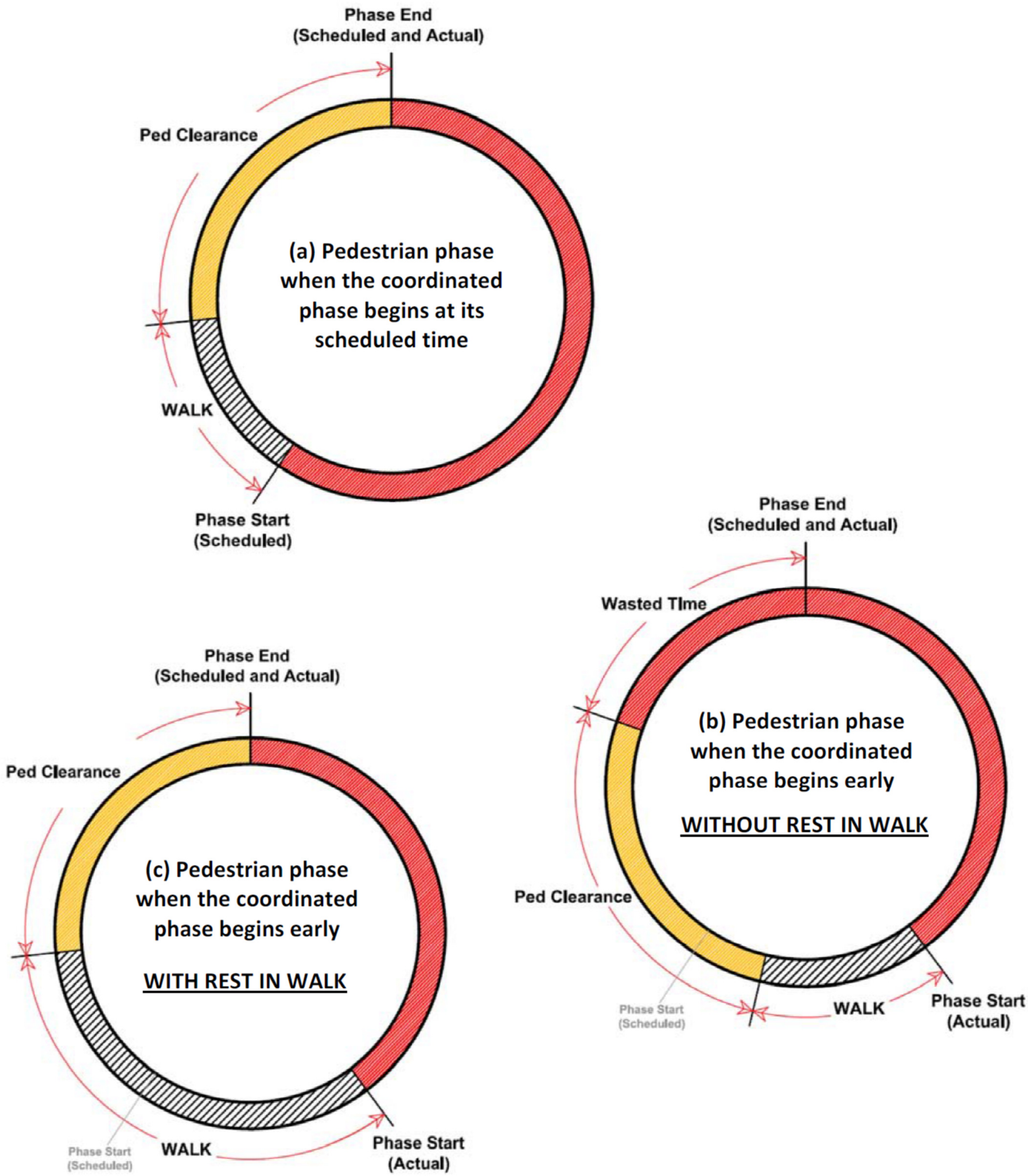


Figure 1 Relationship of WALK timing to coordinated parent phase timing (the circle represents the signal cycle)

Policy Guidance:

A policy to apply Rest in Walk to all coordinated phases is generally appropriate because there are marginal drawbacks for traffic flow or traffic operations (see below for documented and expected impacts).

Application Instances:

In many US cities, it is policy to apply Rest in Walk to all coordinated phases.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic:

By lengthening the WALK interval, Rest in Walk reduces pedestrian delay. Its impact can be large where the specified WALK interval is short while the parent phase has a long green in many cycles.

By design, Rest in WALK has marginal impacts on vehicular signal timing. Rest in Walk 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. In addition, it can affect motor traffic due to the additional interference with turns that comes from allowing pedestrian crossings later in the phase; however, that effect will often be null, because pedestrians forced to wait for the next cycle will interfere with turning traffic then. Unless right turning volumes and pedestrian volumes are both high, the impact to motor traffic is expected to be negligible.

At intersections with both high pedestrian volumes and a high volume of right turns, it may be appropriate to curtail the pedestrian phase in order to give turning vehicles a chance to go. In such a case, Rest in WALK may not be appropriate.

Issues (accessibility, physical layout etc.):

References:

Treatment or Policy Name

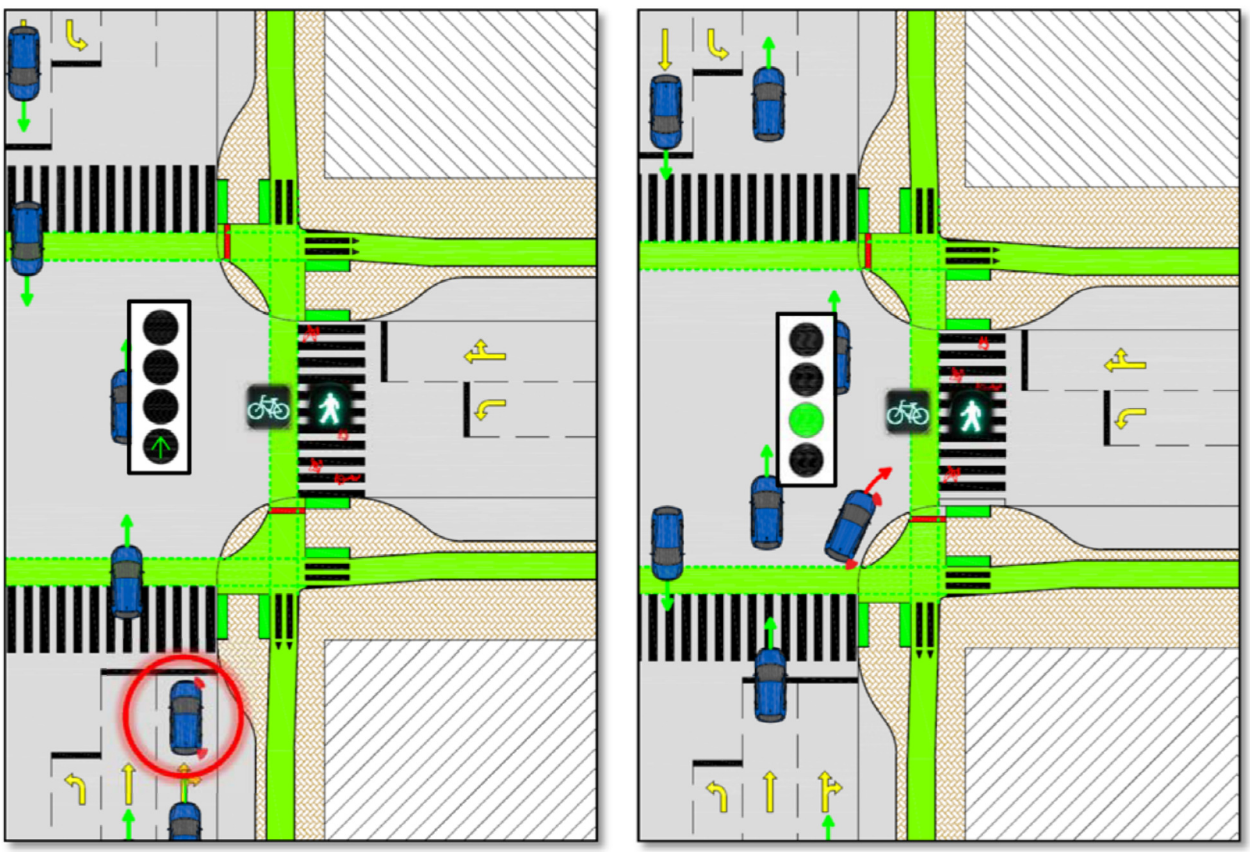
Leading Through Interval

Other Names

Leading Through Arrow (Montreal), Split LBI or Split Leading Bicycle Interval (New York City), LPI+ (Charlotte)

Description

A leading through interval (LTI) is a period of time at the start of a phase in which only through-going vehicles are allowed to proceed, together with bikes and pedestrians. As applied in Montreal, the indication to vehicular traffic is a through green arrow. At the end of the LTI, a green ball replaces the green arrow, allowing turning movements to proceed, while bike and pedestrian phases continue (see Figures 1 and 2).



(a) LTI **(b) after LTI**

Figure 1 Pedestrian, bike, and vehicular movements involved in an LTI

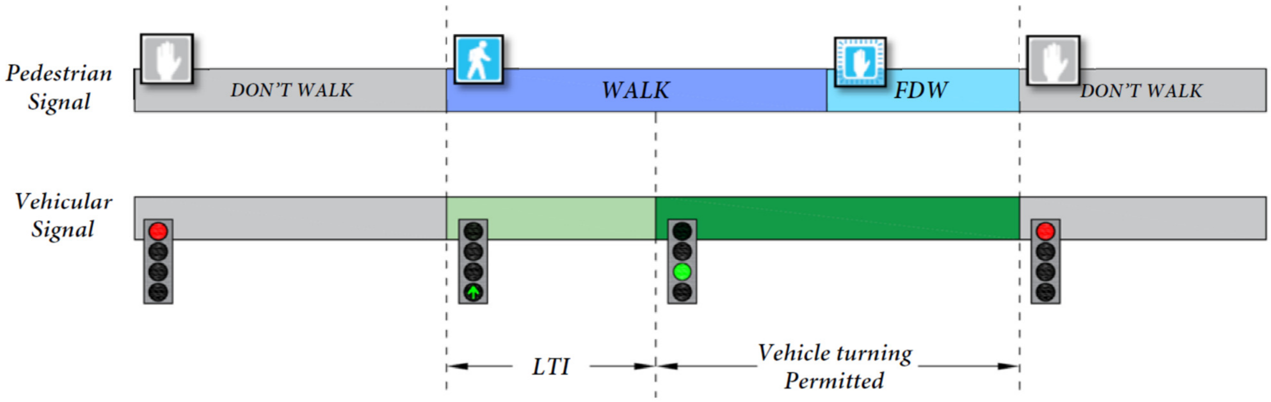


Figure 2 Relationship between pedestrian phase and parallel vehicular phase during and after LTI

Variations

In New York City, where LTI (known locally as Split Leading Bicycle Interval) is applied on one-way avenues with a left-side bike lane, the indication to vehicular traffic during the leading interval is a green ball together with a red left arrow. Where the cross street is one-way and therefore right turns are prohibited, Split LBI functions as a Leading Through Interval. At intersections with a two-way cross street, the leading interval under Split LBI holds turn in one direction while allowing them in the other direction, and so, strictly speaking, it is not a Leading Through Interval (though it is still a Partially Protected Crossing).

LTI can be applied when turning traffic has its own turn lane (as done in New York and Charlotte), as well as when turning traffic shares a lane with through traffic (as done in Montreal). When turns use a shared through-turn lane, then by stopping turning cars, an LTI can block through traffic as well.

When pedestrian phases are pushbutton actuated, the LTI occurs only when the pedestrian phase runs.

Relation to Other Treatments and Policies

LTI is similar to ***Leading Pedestrian Interval (LPI)*** in that both of them hold turning traffic for a few seconds while pedestrians, and perhaps bicycles, get a head start. However, because an LTI allows through traffic to proceed, it has less impact on traffic capacity than LPI, which means that from a capacity point of view, one can afford to make an LTI last longer than an LPI. However, where the turning vehicles are held from a shared through-turn lane, through-going motorists can be frustrated if they see a green signal but cannot proceed because a turning vehicle ahead of them is stopped waiting for the green ball. For this situation, if turn volumes are high and turning vehicles don't have an exclusive lane, LPI can be preferred over LTI.

LTI can be combined with ***Flashing Yellow Arrow***, displayed during the part of the phase in which turn conflicts are permitted. LTI can be done either in conjunction with or without ***bike signals***. Without, bikes follow the parallel vehicular signals. If the LTI is extended to the full length of the pedestrian phase, as done in some intersection in Charlotte outside of peak hours, it becomes a ***Concurrent Yet Protected Crossing***.

Objectives, Context, and Operational Details

The main objectives of LTI are:

- For pedestrians: to give them a head start over turning traffic, enabling them to establish their priority in the crosswalk before turning traffic is released. Longer LTIs enable not only near-side, but also far-side pedestrians who start crossing with the WALK to establish themselves in the conflict zone of the crosswalk before turning traffic is released.
- For bicycles: to give the first flush of waiting bicycles conflict-free passage through the intersection.

LTI applies where pedestrians/bikes have concurrent phasing and there is a permitted outside turn (right turn, or left turn from a one-way street) across the crosswalk / bike path. At most application sites in Montreal, turns are made from a shared through-turn lane; New York and Charlotte have applied it only where those turns have an exclusive turn lane.

An LTI should be long enough to allow near-side pedestrians establish their presence on the crosswalk; a longer LTI can sometimes allow far-side pedestrians to reach the conflict zone before turning cars. Montreal sets the duration of their LTIs equal to the duration of the WALK indication, which is a minimum of 7 s *(1)*; common LTI lengths are 7 and 9 s. Because a pattern of turning vehicles not complying with long LTIs has been observed, Montreal reports that, it limits LTIs to no longer than 14 s *(2)*. New York City's LTIs last 7 to 10 s *(3, 4)*. Charlotte's LTIs last 10 s *(5)*. However, in off-peak periods, at some intersections, they extend the leading interval to coincide with the entire pedestrian phase (WALK as well as pedestrian clearance), which is tantamount to the treatment ***concurrent-yet-protected phasing***.

During the Leading Through Interval, the display used in Montreal is a green through arrow only, as shown in Figure 3.

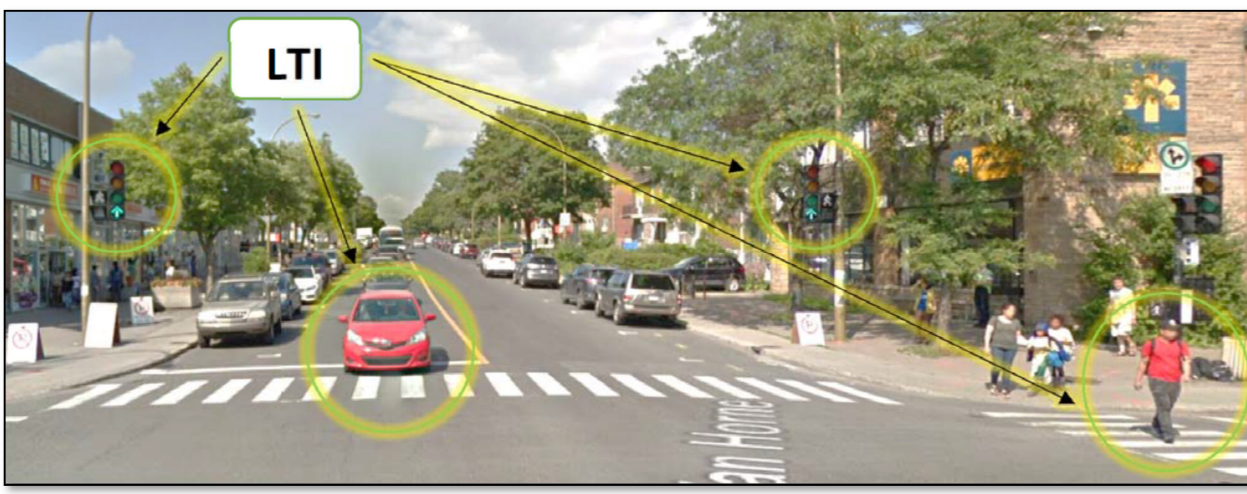


Figure 3 A leading through interval example in Montreal

In New York City and Charlotte, the display used during a leading interval is a green ball for the through lanes together with a red arrow for the left turn lane, as shown in Figure 4; after the leading interval, the red arrow is replaced with a flashing yellow arrow.

Figure 4   A leading through interval example in Charlotte (locally called LPI+)

While Montreal's and New York's LTIs are primarily in business districts with heavy pedestrian traffic, and occur every cycle, LTIs in Charlotte are applied mainly at intersections outside of their central business district, where cycle lengths tend to be long (around 120 s) and pedestrian volumes low. Pedestrian phases are pushbutton actuated, and the LTI occurs only in cycles with a pedestrian phase.

These display variations raise questions about signs and signals necessary to induce the desired behavior under U.S. laws:

(a) *Is it necessary to display red turn arrows to indicate that motorists may not turn, or is a simple green arrow sufficient?* According to the MUTCD, a green arrow is sufficient to forbid non-indicated movements. 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. *(6)*

If a state's vehicle code is consistent with this section of the MUTCD, then a red arrow is not necessary.

(b) *Will No Turn on Red signage be necessary to make it illegal to right turn on red (including left turn on red from a one-way street onto a one-way street) during a leading through interval?* If the only signal displayed during the LTI is a through green arrow, then laws regulating right turn on red are irrelevant, since no red signal is displayed. This may be an advantage of using a simple through green arrow.

If a red arrow is displayed, turns will be prohibited in some states, but not in others. Turns against a red arrow are prohibited in California (7) and North Carolina (8), for instance, but are permitted in states such as Florida (8), Massachusetts (9), Oregon, and Washington (10), whose right turn on red laws do not specifically exclude red arrows. In such states, a No Turn on Red restriction that applies at least during the leading interval would be necessary for the LTI to function as intended.

(c) *Will motorists comply with No Turn on Red restrictions?* Two of the jurisdictions that have applied LTIs (Montreal and New York City) happen to also be places in the U.S. and Canada that statutorily prohibit right turn on red. For those cities, then, there is no relevant experience to test whether drivers accustomed to turning right on red will comply with turn prohibitions during an LTI. In Charlotte, however, while state law prohibits right turn on red when a red arrow is displayed, drivers are accustomed to turning right on red. The city found noncompliance to be so common that they added LED blank-out signs with the words “No Turn on Red” during the pedestrian phase.

Policy Guidance

Application Instances

In Montreal, LTI has been a standard treatment for at least 15 years at intersections with high pedestrian traffic *(1, 2)*. It is used at more than 100 intersections.

In New York, leading through intervals, known locally as split-LBI, have been used since about 2015. An August, 2016, report states that split-LBI had been installed at 28 intersections without bicycle signals, and at 9 intersections with bicycle signals as a pilot program *(3)*.

A motivation for New York to apply LTI was experience with protected-only bicycle phasing, in which the phase serving the avenue was divided into a protected phase for bikes followed by a left turn phase during which the bike light was red. During the left turn phase – in which through traffic on the avenue still has a highly visible green light – there was a high rate of cyclists running the red light, without serious negative safety impact. This experience led city staff to believe that permitted left turn conflicts would be safe with the mitigation of a leading protected interval for the first flush of queued bike traffic and a flashing yellow arrow during the period of permitted left turns.

Kothuri et al. *(4)* report that in a survey of professionals regarding bicycle signal control strategies, of 69 respondents, about half were aware of split-LBI, but only one respondent’s city had used it.

Charlotte has applied LTI at about 10 intersections, and roughly another 10 are in progress to changing over to LTI. Their first application won an ITE innovation award in 2016 *(5)*.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

For pedestrians and cyclists, the leading protected interval is expected to improve safety and comfort by providing them a no-conflict head start. As with an Leading Pedestrian Interval, by helping pedestrians establish their priority in the crosswalk, it is expected to lead to increased compliance by motorists yielding to pedestrians. Because of the lesser traffic capacity impact of an LTI versus and LPI, using an LTI can make it practical to provide a longer protected period, with increased safety benefits.

Kothuri et al. *(4)* used traffic conflict analysis, based on video, to gauge the impact of LTI and other treatments on cyclists’ safety. One intersection, 6th Avenue @ 23rd Street, was observed for 11 hours each before and after implementing an LTI. Before, the 6th Avenue phase began with a short Leading Pedestrian Interval (which some bicycles used), followed by a (much longer) interval with permitted left-turn conflicts from the adjacent lane shared by left turning and through vehicles. After, the 6th Avenue phase began with a 7 s leading interval without left turn conflicts, followed by the remainder of the 6th Avenue phase in which left-turn conflicts were permitted from a newly created left turn lane (the left side parking lane was converted into an exclusive left turn lane, with bikes remaining on the outside of the turn lane, against the curb).

Table 1 shows a before-after comparison, normalized to indicate conflicts per 1000 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 after introduction of the LTI together with an exclusive left turn lane. There was a small increase in the frequency of bikes who had to ride around a car (something that occurs usually because a car began its turn, but then stopped for crossing pedestrians).

Table 1: Traffic Conflict Measures Before and After Implementation of a Leading Through Interval for 6th Avenue @ 23rd Street, New York. (Data source: 10; our analysis of that data).

	Before: Permitted Turn Conflict Throughout the Bicycle Phase	After: Leading Protected Interval (7 s) Followed by Permitted Turn Conflict
Bikes	1,952	1,300
Per 1000 bikes:		
Near misses	4	0
Collisions if no evasive action taken	75	35
Bike rode around car	32	41

A conclusion of that study *(4)* uses wording that may be easily misunderstood: "With the split LBI treatment, there is little to no risk for bicyclists during the leading interval. However, the risk for bicyclists is shifted towards the stale green portion of the phase." Some might imagine that means that the authors found that a lessening of risk in the early part of the phase was accompanied by an increase in risk in the latter part of the phase (which might imply that there is no net safety benefit). However, this study has no findings, or even discussion, of increased risk during the latter part of the phase. The authors are only pointing out that where LTI is implemented, cyclists will still face risk from turning conflicts after the leading interval has ended.

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

Kothuri et al. *(4)* used simulation to measure delay impacts of a 5 s LTI 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 – the traffic movement directly affected by a 5 s hold – was small, less than a second. This small impact is probably because Right Turn on Red was allowed during all red periods except the LTI, leading to very little queuing in the right turn lane.

References

1) Montreal Department of Transportation (2017). Feux pour Piétons à Décompte Numérique. Guide DT2001.
2) Hamaoui, J. (2018). Leading Through Interval. Interview with Peter Furth.
3) New York City Department of Transportation (2016). Don't Cut Corners - Left Turn Pedestrian & Bicyclist Crash Study. New York.
4) Kothuri, S. et al. (2018). Addressing Bicycle-Vehicle Conflicts with Alternate Signal Control Strategies. Portland (OR): National Institute for Transportation and Communities (NITC), pp.16, 23, 25-26, 29-30.
5) http://ncsite.org/2016/09/16poy-lpiplus
6) Manual on Uniform Traffic Control Devices. FHWA, U.S. Department of Transportation, 2009.
7) california-dmv-practice-test.org/turn-against-red-arrow/
8) https://www.charlotteobserver.com/news/local/dr-traffic-blog/article35563263.html
9) www.fdot.gov/traffic/faqs/trafsignalfaq.shtm
10) https://pemco.com/northwest/perspective/articles/Pages/road-rules-turn-on-red-arrow.aspx

Treatment or Policy Name:

Early Right Turn Release

Other Names:

Right Turn Head Start, Leading Right Turn Interval

Description:

In connection with a concurrent crossing, the start of the WALK interval is delayed in order to give the right turn movement a short conflict-free interval prior to pedestrians being released. The tactic is illustrated in Figure 1, with early release applied to east-west movements.

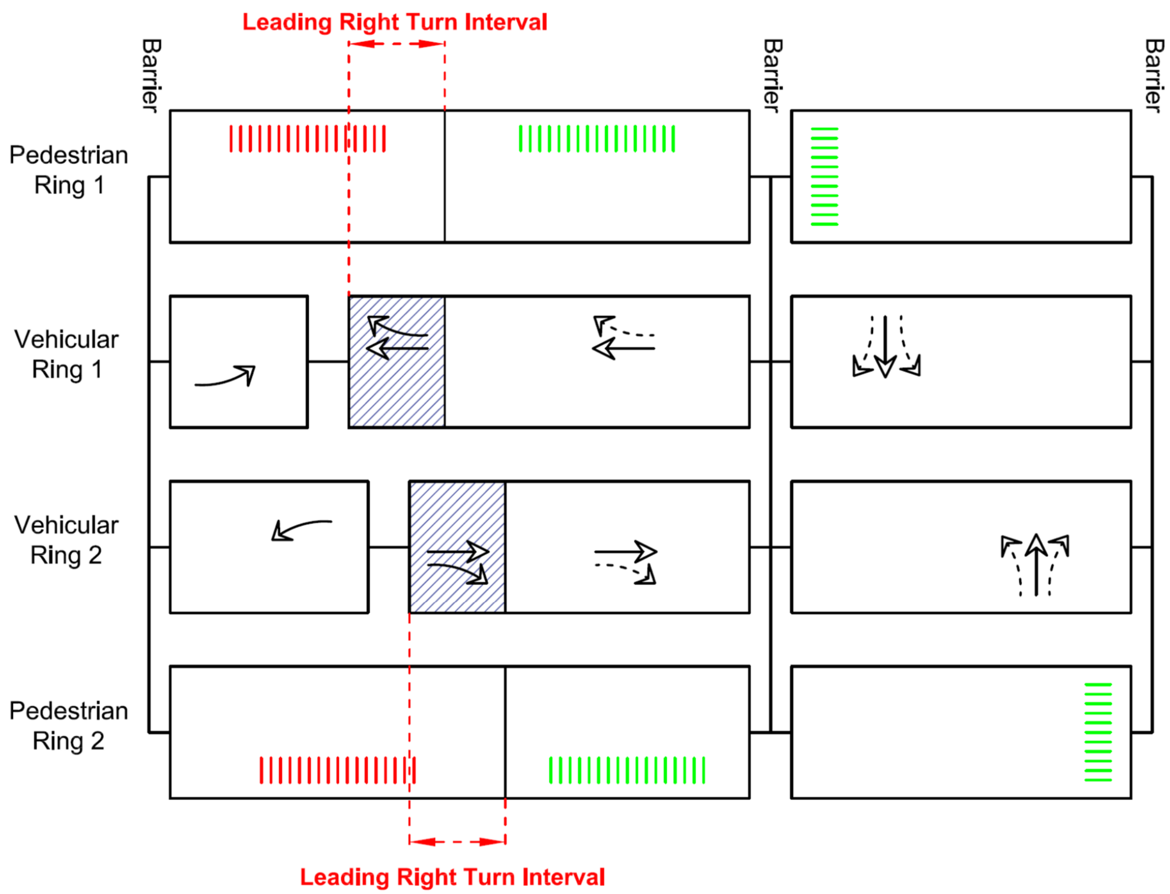


Figure 1. A ring diagram illustration for early release tactic

Variations:

N.A.

Relation to Other Treatments and Policies:

Early release is used to improve right turn capacity in situations in which high pedestrian volumes severely restrict right turn flow. In principle, however, early release should not offer more right turn capacity than releasing pedestrians are concurrently with vehicles, as long as the pedestrian phase is given the same duration as it would with early release. With early release there is a protected right turn interval at the beginning of the split; with concurrent release, the same protected right turn interval can be provided at the end of the split.

For pedestrian safety, early release is clearly inferior to traditional, concurrent release. With early release, the right turn flow has been established by the time the WALK interval begins, so that pedestrians are expected to walk into the midst of an established right turn flow, which is clearly a difficult and dangerous situation.

Policy Guidance:

Because early release offers no capacity benefit compared to traditional simultaneous release and is clearly inferior for pedestrian safety, it should not be used.

Application Instances:

Boston used to apply early release (for example, for NEBR at the junction of Huntington Ave. with Ruggles Street). That intersection has since been changed to concurrent release. Boston no longer uses early release.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

(Discussed earlier.)

References:

N.A.

Treatment or Policy Name:

Exclusive Pedestrian Phase and All Direction Ped-Bike Phase

Other Names:

Barnes Dance, Pedestrian Scramble, All-Ped Phase, Simultaneous Green for Bicycles

Description:

During an exclusive pedestrian phase (EPP), all traffic movements are held, and pedestrians are allowed to go on all crosswalks. Diagonal crossings may or may not be formally allowed. Figure 1 is an example of ring diagram for an EPP.

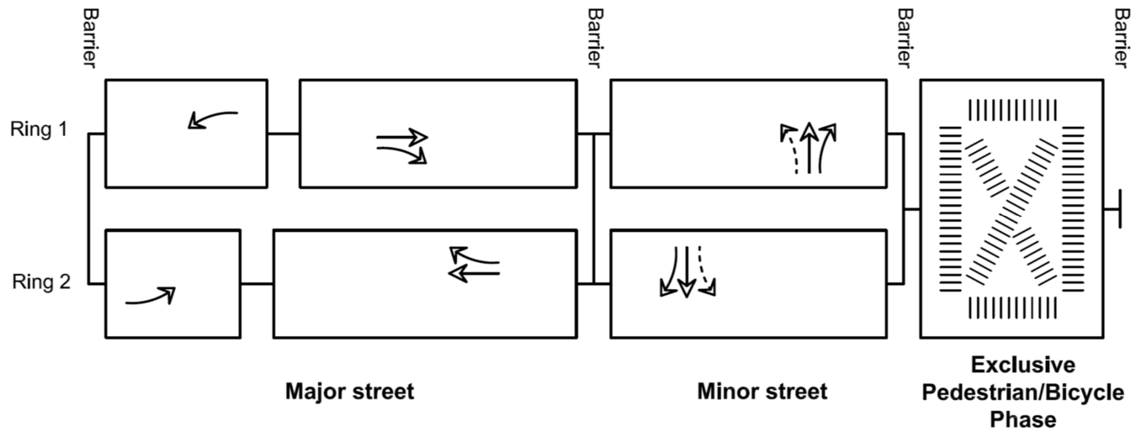


Figure 1 A ring diagram example for exclusive pedestrian phasing

Variations and Relation to Other Treatments and Policies

- Where diagonal crossings are formally provided for, the terms Barnes Dance and Pedestrian Scramble apply. Because diagonal crossings are longer than standard crossings, their inclusion can require a longer pedestrian phase.
- Pedestrians can be allowed to cross concurrently with vehicular phases as well as during an EPP.
- If bicycles are also allowed to cross in all directions, it is an All Direction Ped-Bike Phase. In the Netherlands, where this treatment is used in a few cities, it is called Simultaneous Green for Bicycles.
- EPP is often only in combination with No Turn on Red, because with EPP, vehicles turning right on red conflict with pedestrians on two active crosswalks.
- There are other treatments in which all traffic is held for a short interval, but they differ from Exclusive Pedestrian Phase in that the Hold interval is too short for all pedestrian and bicycle movements. They include *Diagonal Bike Crossing Phases* and *Pedestrian Phase Overlaps with Each Other, with Bike Phases, and with Vehicular Holds*.
- Another treatment that offers protected crossings but without holding all vehicular traffic is *Concurrent Yet Protected Crossings*.

Objectives, Context, and Operational Details:

By default, pedestrian crossings are concurrent with a parallel vehicular phase. Conflicts with cross traffic are thus eliminated. Conflicts with left turn traffic are often prevented by using exclusive left turn phases, but conflicts with right turning traffic are typically permitted. Exclusive pedestrian phasing (EPP) is a means of providing pedestrians a crossing that is free of all turning conflicts. There are three main reasons for implementation of EPPs: safety, capacity, and facilitating diagonal crossings.

Safety: Permitted conflicts can be unsafe when volume of turning traffic is high and where intersection geometry allows high turning speed. In such cases, fully protected crossings can be desirable. EPP offers one solution; the other is ***Concurrent Yet Protected Crossings***.

Capacity: In many contexts, EPP lowers traffic capacity because it involves a long period with all traffic held. However, where long queues develop because pedestrian volume is so great that it prevents vehicles from turning, and EPP can improve capacity by clustering all the pedestrian movements into one part of the cycle so that the rest of the cycle can operate free of pedestrian interference.

Facilitate diagonal crossings: Demand for diagonal crossing can be high in downtowns, especially in connection to walking routes to major transit stations, and where shared use paths make diagonal crossings. Providing for diagonal crossings generally requires a longer pedestrian clearance time, of course. To inform pedestrians that diagonal crossings are allowed, diagonal crosswalks are marked on the pavement.

Permitting concurrent crossing in addition to an EPP greatly reduces pedestrian delay and is often consistent with pedestrian behavior. It should therefore be considered unless right turn speed is high, or holding pedestrians is important for right turn capacity. It will facilitate traffic flow if the traffic movement with the greatest potential for pedestrian interference is sequenced immediately after the EPP, because the phase immediately after an EPP will see the least volume of pedestrian demand. (Of course, if pedestrians are allowed to cross concurrently, that questions the need for an EPP.)

Policy Guidance:

Application Instances:

Application of EPP is widespread across the US and around the world; for example, Australia, Canada, Japan, Netherlands, and the United Kingdom all have been using EPP. In North America, EPP is applied mainly at downtown intersections. In downtown Toronto, EPP with concurrent crossings is a common practice because pedestrian volumes are so great that, in combination with a fixed cycle length, there would not otherwise be room for them to queue at the corners. For Massachusetts (and no other US state, as far as we know), EPP has long been the default treatment for intersections on state highways and is common elsewhere.

In the US, one of the first cities that started using EPP was Kansas City. Denver also used to have pedestrian scramble almost at every intersection at its downtown. In 2011, the practice of allowing diagonal crossings in Denver was removed, though the EPPs remained. The change was made to avoid increasing the length of EPPs in response to a decrease in the design speed (from 4.0 to 3.5 ft/s) used to determine pedestrian clearance time.

There are many instances of EPP in Massachusetts cities among which are Boston and Cambridge. Massachusetts almost never formally allows diagonal crossing; many faster pedestrians cross diagonally, though. New York (NY), Pittsburgh (PA), New Haven (CT), and Portland (OR) are other cities that use exclusive pedestrian phasing.

In Netherlands, the combination of exclusive bicycle and pedestrian crossing is being used which is called *Simultaneous Green Light for Bicycles*.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

EPP introduces a lot of lost time to the signal cycle, which normally reduces vehicle capacity. That forces cycle length to be considerably longer, increasing delay for all users, including pedestrians (unless they are allowed to walk concurrently as well). Because of this added delay, and the observation that many pedestrians cross concurrently rather than waiting for their exclusive phase, the Massachusetts pedestrian advocacy organization WalkBoston generally favors concurrent crossings over EPPs except where high turning volumes or speeds make permitted right turn conflicts dangerous. EPPs can also require wider approach roadways in order to compensate for the capacity loss during the EPP.

An emerging issue regarding EPPs is whether or not bicycles should be allowed to cross during the EPP. By default, bicycles follow vehicular signals, and therefore should not cross during an EPP. If that restriction is enforced, EPPs increase cyclist delay. However, experience in US cities is that many cyclists routinely cross during EPPs, partly to reduce delay and partly because it’s safer than in other periods (because the receiving roadway will be free of traffic). Allowing bikes to move during an EPP creates a conflict; the question is whether that can be a permitted conflict. In Netherland, bikes have been allowed to cross with pedestrians during EPPs at a handful of intersections for many years without any reported safety problem.

Dedication of an exclusive phase to pedestrians means having an extra critical phase added to the cycle. Not only does it increase the cycle length because of the time needed for the exclusive phase, but also in order to maintain the original vehicular green ratios, cycle should be lengthened even more.

In order to show expected impacts of exclusive pedestrian phasing (EPP) on different users, an actual intersection in Boston is analyzed. With concurrent pedestrian crossing, the intersection of Centre St and Lagrange St in West Roxbury operates well with a 90 s cycle. The longest crosswalk is 60 ft which demands 17 s clearance time. With an 8 s minimum WALK (a standard Boston practice), that means the EPP will last 25 s. However, one can’t just add 25 s to the cycle for the EPP; the longer red time the EPP causes means the green times have to be lengthened as well. With an EPP, the cycle length would have to be 160 s to have adequate traffic capacity. This longer cycle more than triples pedestrian delay and more than doubles vehicular delay and shown in the following table. If concurrent crossings are allowed as well, pedestrian delay drops dramatically, but vehicular delay stays very high.

Pedestrian Crossing Type	Concurrent	EPP	EPP and Concurrent
Cycle Length (s)	90	160	160
Green Ratio of the Major Traffic	0.49	0.44	0.44
Average Pedestrian Delay (s)	22	69	13
Average Vehicular Delay (s)	34	74	75

A number of studies confirm improved safety, reduced crash rates, or reduced surrogate measures for crash rates *(1, 2, 3)*. At a same time, in order for a Barnes Dance to prove suitable, previous research emphasizes on two main required conditions: high pedestrian volume in conflict with high volume of turning vehicles *(2, 4, 5)* and low rate of pedestrian violations *(1, 6)*. As an instance for the former requirement, Abrams and Smith indicated that pedestrians find no justification for long wait times after application of exclusive pedestrian phases (EPP) at locations where vehicle volumes are low; and subsequently, they cross against the red light. They argued if violations are frequent, pedestrian scramble does not really improve pedestrian safety; it may become more of a threat *(6)*. Ivan et al. claimed EPP is often less efficient for both vehicles and pedestrians because of the increased delays *(7)*, yet they acknowledged the suitability of the EPP at signalized intersections with very high pedestrian and turning vehicle volumes.

In the literature, there is a general consensus on the negative impact of pedestrian scramble phasing on pedestrian compliance *(1, 3, 6, 7)*. Zegeer and Cynecki also identified close correlation between noncompliance and low pedestrian and traffic volumes *(8)*. As shown earlier, EPP can lead to long wait times, and there are several studies that find increased noncompliance as pedestrian delay increases *(9, 10, 11)*.

It should be noted that higher rate of noncompliance does not necessary mean degraded safety because noncompliance might partly happen on the “safe side crosswalk”. Bechtel et al. define safe side crosswalk as “the crosswalk parallel to moving traffic in which there are no opportunities for conflicts.” *(3)* In addition, Abrams and Smith concluded that pedestrian noncompliance is more frequent when EPP is implemented at narrower intersections, and thus EPP may not be suitable at such intersections *(6)*.

Zhang et al. compared severity of collisions at intersections with concurrent crossing versus EPP. They found out collisions at signals with EPP have a more severe nature than those of at signals with concurrent crossing *(12)*.

References:

1. Garder, P. Pedestrian Safety at Traffic Signals: A Study Carried Out with the Help of a Traffic Conflicts Technique. Accident Analysis and Prevention, Vol. 21, No. 5, Oct. 1989, pp. 435–444.
2. Vaziri, B. Exclusive Pedestrian Phase for the Business District Signals in Beverly Hills: 10 Years Later. Institute of Transportation Engineers. District 6 Meeting (51st, San Diego, Calif., 1998). Compendium of Technical Papers. Institute of Transportation Engineers, Washington, D.C., 1998.
3. Bechtel, A., MacLeod, K., and D. Ragland. Pedestrian Scramble Signal in Chinatown Neighborhood of Oakland, California: An Evaluation. Transportation Research Record: Journal of the Transportation Research Board, 1878, 2004, pp. 19–26.
4. Zaidel, D. M., and I. Hocherman. Safety of Pedestrian Crossings at Signalized Intersections. Presented at 66th Annual Meeting of the Transportation Research Board, Washington, D.C., 1987.
5. Zegeer, C. V., K. S. Opiela, and M. J. Cynecki. Effects of Pedestrian Signals and Signal Timing on Pedestrian Accidents. In Transportation Research Record 847, TRB, National Research Council, Washington, D.C., 1982, pp. 62–71.
6. Abrams, C. M., and S. A. Smith. Selection of Pedestrian Signal Phasing. Presented at 56th Annual Meeting of the Transportation Research Board, Washington, D.C., 1977.
7. Ivan, J. N., McKernan, K., Zhang, Y., Ravishanker, N., and S. A. Mamun. A study of pedestrian compliance with traffic signals for exclusive and concurrent phasing. Accident Analysis and Prevention, 98, 2017, pp. 157–166.
8. Zegeer, C. V., and M. J. Cynecki. Determination of Motorist Violations and Pedestrian-Related Countermeasures Related to Right-Turn-on-Red. In Transportation Research Record 1010, TRB, National Research Council, Washington, D.C., 1985, pp. 16–28.
9. Baass, K. G. Review of European and North American Practice of Pedestrian Signal Timing. Roads and Transportation Association of Canada, 5, 1989, pp. 55-74.
10. Hamed, M. M. Analysis of pedestrians' behavior at pedestrian crossings. Safety Science, 38, (1), 2001, pp. 63–82.
11. Houten, V. Pedestrian Push-Button Confirmation Increases Call Button Usage and Compliance. Transportation Research Record: Journal of the Transportation Research Board Transportation Research Board of the National Academies, 1982, 2006, pp. 99–103.
12. Zhang, Y., Mamun, S. A., Ivan, J. N., Ravishanker, N., and Haque, K. Safety effects of exclusive and concurrent signal phasing for pedestrian crossing. Accident Analysis and Prevention, 83, 2015, pp. 26–36.

Treatment or Policy Name:

Concurrent yet Protected Pedestrian Crossings

Other Names:

Right-Turn Overlap, Protected Right Turns

Description:

This treatment separates crossing pedestrians and cyclists in time from right turning traffic, while pedestrians and cyclists cross concurrently with through vehicles. (Separation from left turning traffic, by means of protected left turn phases, is assumed as well.)

Variations:

N.A.

Relation to Other Treatments and Policies:

Like Exclusive Pedestrian Phases, concurrent-yet-protected phasing provides fully protected crossings. It uses protected left turns and adds protected right turns as well.

Objectives, Context, and Operational Details:

The objective is to provide fully protected crossings, which may be needed because of high speed right turns, or a high right turn volume, or a very wide intersection, without the capacity loss associated with exclusive pedestrian phasing. Because it involves a protected right turn phase, this tactic requires a right turn lane. The right turn lane is governed by arrows just as a left turn lane.

This tactic works best when there are protected left turns from the cross street. Protected right turns from the subject street can then run concurrently with the parallel left-turn movement (e.g., NBR running concurrently with WBL). However, it can also be used if there isn’t a parallel left turn movement, with the time of the through phase split between a crossing interval and a right turn interval.

This tactic can be programmed with a standard dual ring (or even a single ring) if the right turn phases are simultaneous with their parallel left turns. In this arrangement, bicycles do not necessarily need their own signal, because they can cross with through vehicular traffic. Figure 1 shows a single-ring solution with concurrent-yet-protected crossings in all four quadrants. Figure 2 shows a dual-ring solution for a one-way street with only one crossing (which may be a two-way cycle track, for example) having a concurrent-yet-protected crossing.

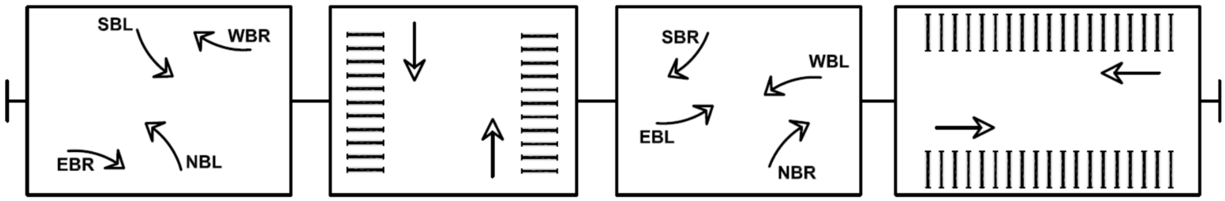


Figure 1 Concurrent-yet-protected crossing with a single ring and right turn overlaps

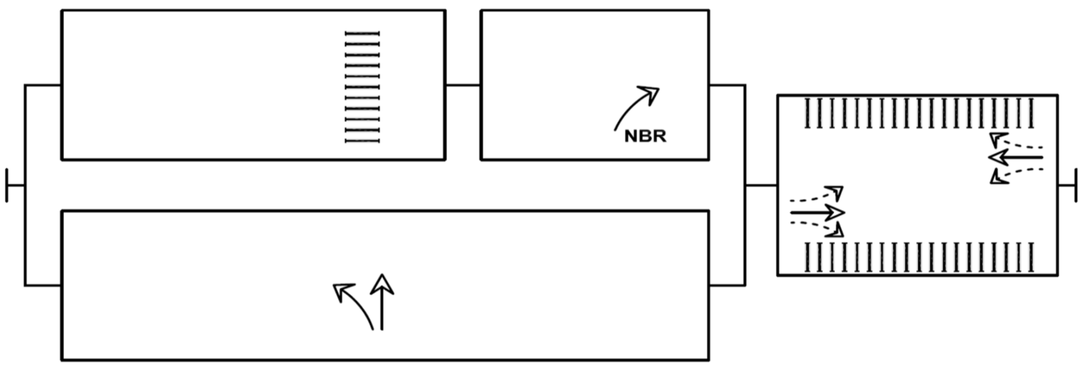


Figure 2 Phasing plan with one concurrent-yet-protected crossing and no overlaps

It is also possible to add additional flexibility so that a right turn phase overlaps its parallel left turn phase and its parallel through phase. That requires expanding to a quad-ring diagram *(1)*, as shown in Figure 3. In the two newly added rings, the protected right turn phases and the pedestrian crossing phases alternate, dividing between them the concurrent through interval. With this arrangement, the bicycle phase may end before (or begin later than) the parallel through vehicular phase, and so bikes will need their own signal *(1)*.

Policy Guidance:

N.A.

Application Instances:

Both New York City and Long Beach, CA use a simple version of concurrent-yet-protected phasing on streets with cycle tracks, giving the cycle track (and neighboring crosswalk) a protected crossing. The phasing scheme used is essential to the phasing shown in Figure 2.

Cambridge, MA has recently installed three instances of concurrent-yet-protected phasing that correspond to Figure 1. They use single or dual ring (not quad-ring) phasing, with right turns simultaneous with their parallel left turn. One of them uses bicycle signals, while the other two do not (bicycles follow vehicular phases). In none of these cases was it necessary to widen the street to find space for the necessary right turn lanes. Space for the right turn lanes was found by converting through lanes and, for some approaches, by removing some parking spaces.

Concurrent-yet-protected phasing is extensively used in several European countries. Many large intersections use the quad-ring phasing plan described earlier (Figure 3). It is one of the reasons that bicycle-specific signals are also routinely used there. American reviews of bicycle-specific traffic signals also recognize that one of their values is allowing bikes to have their own phases (*2, 3*).

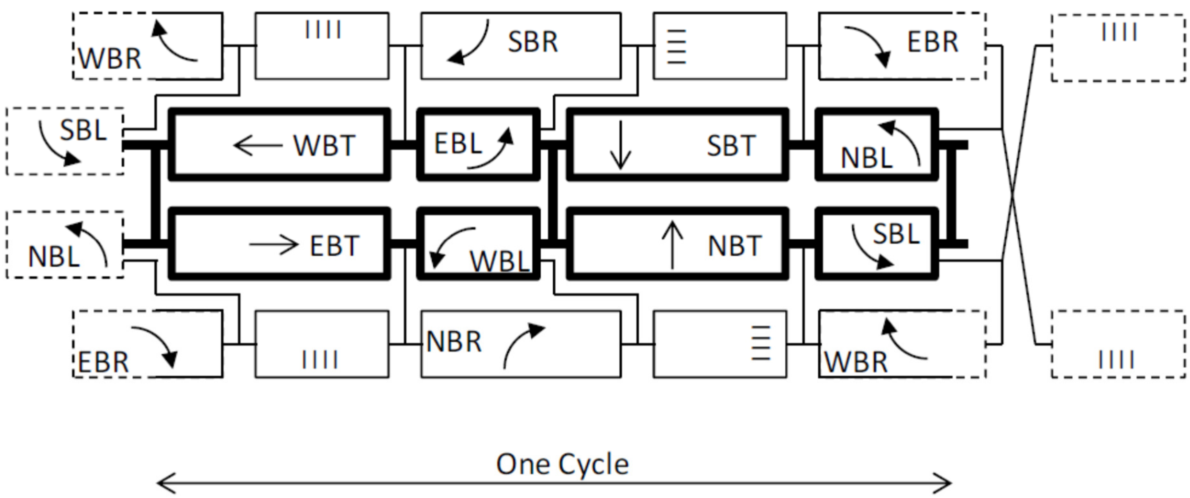


Figure 3 Quad ring structure for a full set of concurrent-yet-protected crossings at a 4-leg junction, drawn with lagging lefts and leading rights. Dashed lines indicate a phase that (partially) belongs to a previous or later cycle. Heavy lines indicate the standard dual ring. Vertical bars represent bike-ped crossings *(1)*.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

Compared to crossings with permitted right-turn conflicts, concurrent-yet-protected phasing eliminates right-turn conflicts with pedestrians and bicyclists, with a corresponding increase in pedestrian and bicyclist safety, with little additional delay to cyclists and pedestrians.

Compared to a phasing plan with permitted right-turn conflicts, concurrent-yet-protected phasing can increase delay for right-turning vehicles; other vehicular movements should be unaffected. Factors and tactics that help limit the added delay to right turns include having balanced demand between the conflicting right turn and a parallel, protected left turn, having only a few phases in a short cycle, re-service (in a longer cycle), and coordination with one or a few neighboring intersections (*1*).

Compared to exclusive pedestrian phases, concurrent-yet-protected phasing reduces delay for all users, while continuing to provide protected crossings.

Concurrent-yet-protected phasing requires right turn lanes, which may increase an intersection's footprint. However, the efficiency of this phasing plan can be such that no net new lanes are needed. In one study, compared to a solution with an exclusive pedestrian phase, concurrent-yet-protected phasing needed fewer lanes to serve the traffic. In another, it was found that six of the eight right turn lanes needed to apply concurrent-yet-protected phasing to a pair of intersections could be created by converting existing shared through-right lanes into right turn lanes (*1*).

References:

1. Furth, P., Koonce, P., Yu, M., Peng, F., and Littman, M. Mitigating the Right Turn Conflict Using Concurrent-yet-protected phasing for Cycle Track and Pedestrian Crossings. Transportation Research Board, Washington, D.C., 2013.
2. Thompson, S. et. al. Bicycle-Specific Traffic Signals: Results from a State-of-the-Practice Review. Submitted to TRR as paper 13-0536, 2013.
3. Monsere, C., M. Figliozzi, and S. Thompson. Operational Guidance for Bicycle-Specific Traffic Signals in the United States: A Review. Interim Report. Portland State University, 2012.

Treatment or Policy Name:

Two-Stage Left Turn Progression for Bicycles

Other Names:

N.A.

Description:

This treatment aims to improve progression for bicyclists making a two-stage left turn at an intersection by changing the phasing sequence. In a two-stage left turn, the left turn is broken down into two crossings. For instance, in Figure 1, the NBL turn is divided into stage (a) and then stage (b), shown by green arrows.

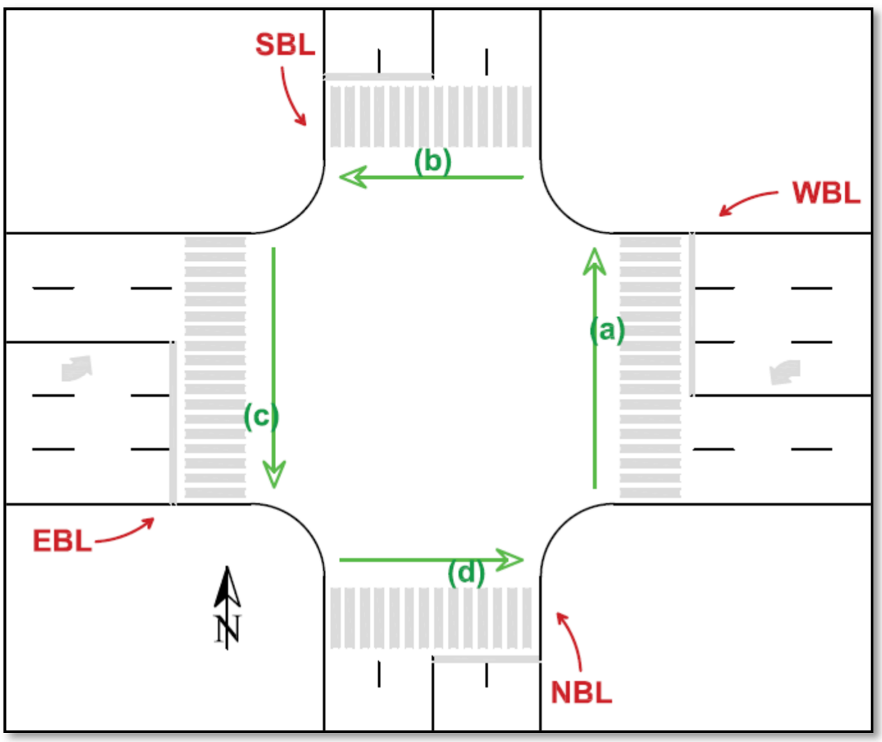


Figure 1. Unidirectional bicycle crossings for making a two-stage left turn

Variations:

Bicycle crossing at intersections can either be unidirectional or bidirectional. Figure 1 shows the legal bicycle crossing movements at an intersection with unidirectional bicycle crossings, while Figure 2 shows the legal crossing movements at an intersection with bidirectional bicycle crossings.

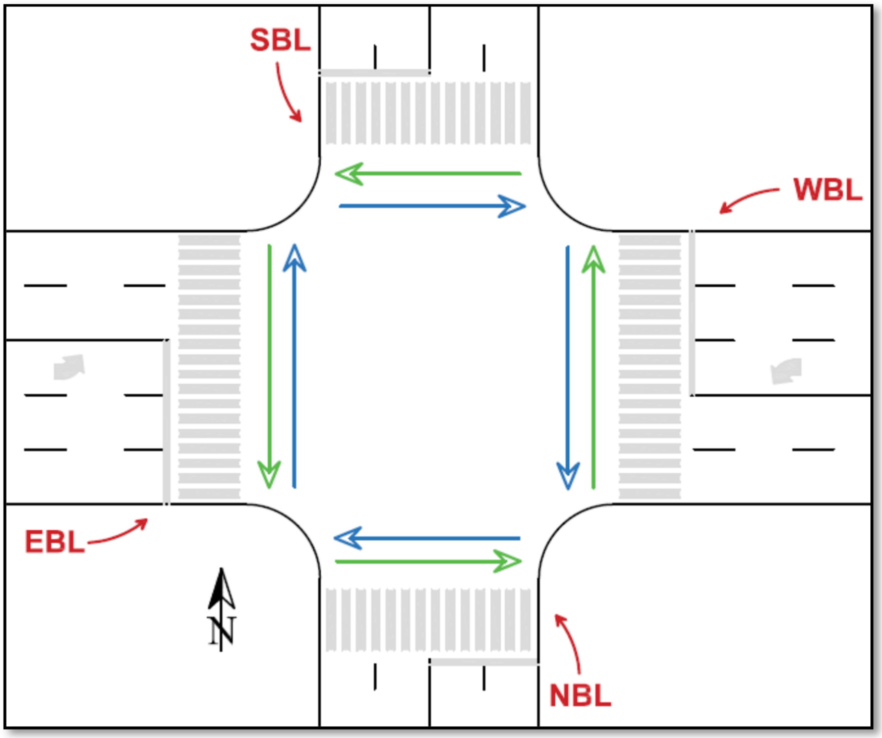


Figure 2. Bidirectional bicycle crossings, which allow additional crossing movements

Relation to Other Treatments and Policies:

N.A.

Objectives, Context, and Operational Details:

The objective of this treatment is to provide better progression for left turning bikes at four-leg intersections. This treatment is relevant when vehicular left turns are protected at least for one of the roads because this treatment tries to improve progression by making left turns leading or lagging.

With separated bike lanes and even conventional bike lanes, more and more cities are guiding cyclists to make their left turns in two stages in order to avoid the need to weave through traffic to enter a left turn lane. However, if two-stage turns are not explicitly considered in signal timing design, the delay involved in making a two-stage left turn can be large. One way to limit delay for two-stage cyclist left turns is to have good progression between the through phases involved in the two-stage turn *(1)*. This will occur naturally if an intersection has two-phase control and a short cycle.

Where intersections have left turn phases, however, some phase sequences provide better progression for two-stage turns than others *(2)*. Consider a junction of two streets, O Street and D Street— see Figure 3 — in which demand for left turns from O to D (the red arrows) is much greater than left turn demand from D to O, as might occur if an intersection is skewed. Good progression for left turns from O Street to D Street can be achieved by having O's through movement immediately succeeded by D's through movement. That implies that if both streets have left turn phases, O's left turn should lead while D's left turn lags.

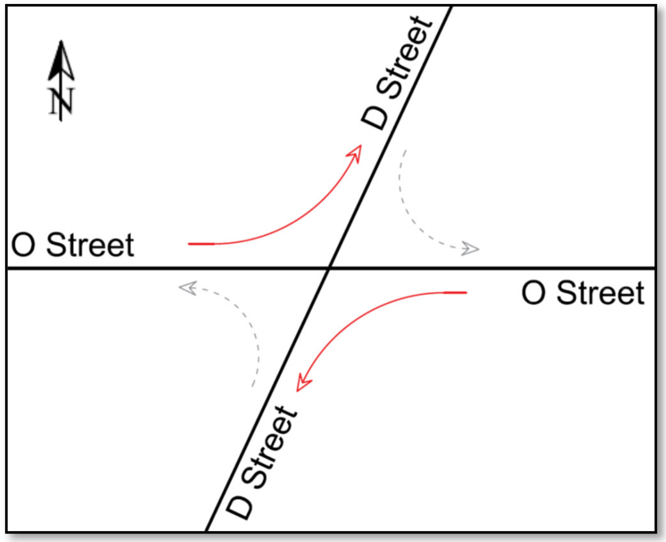


Figure 3. A skewed intersection with greater demand for some bicycle left turns than others

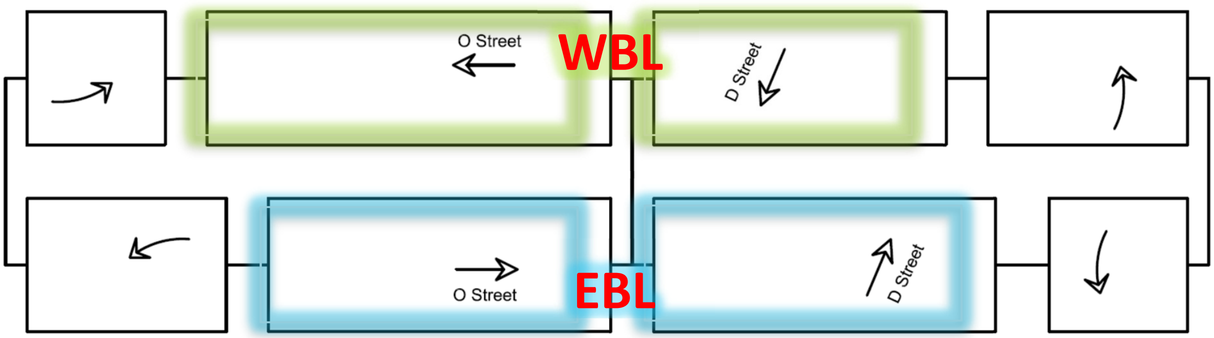


Figure 4. Providing good bike progression for two-stage bike left turns from O Street to D Street

Although the phase sequence shown in Figure 4 provides good bike progression for left turn beginning on O Street, progression is poor for left turns beginning on D Street. Where all four left turns are of equal concern and there is a full set of left turn phases, there is no sequence offering good progression for all four left turns if bicycle crossings are unidirectional (which they usually are).

However, if bicycle crossings are bidirectional, having one street's left turns lead while the other's lag allows all two-stage turns to be made with good progression. By making bicycle crossings bidirectional – a tactic recommended in the Dutch bikeway manual *(1)* – cyclists can take advantage of path choice, just like pedestrians making a diagonal crossing. Every one of the four possible bicycle left turns can begin using a *lagging* through phase followed by the *leading* through phase of the other street, as illustrated in Figure 5. Left turning cyclists approaching the intersection at A and C make their left turn by traveling counterclockwise — following the green arrows — and those approaching at B and D make their left turn by traveling clockwise, following the blue arrows. In this figure, the EW road has leading left turns, and the NS road has lagging left turns, ring diagram of which is shown in Figure 6.

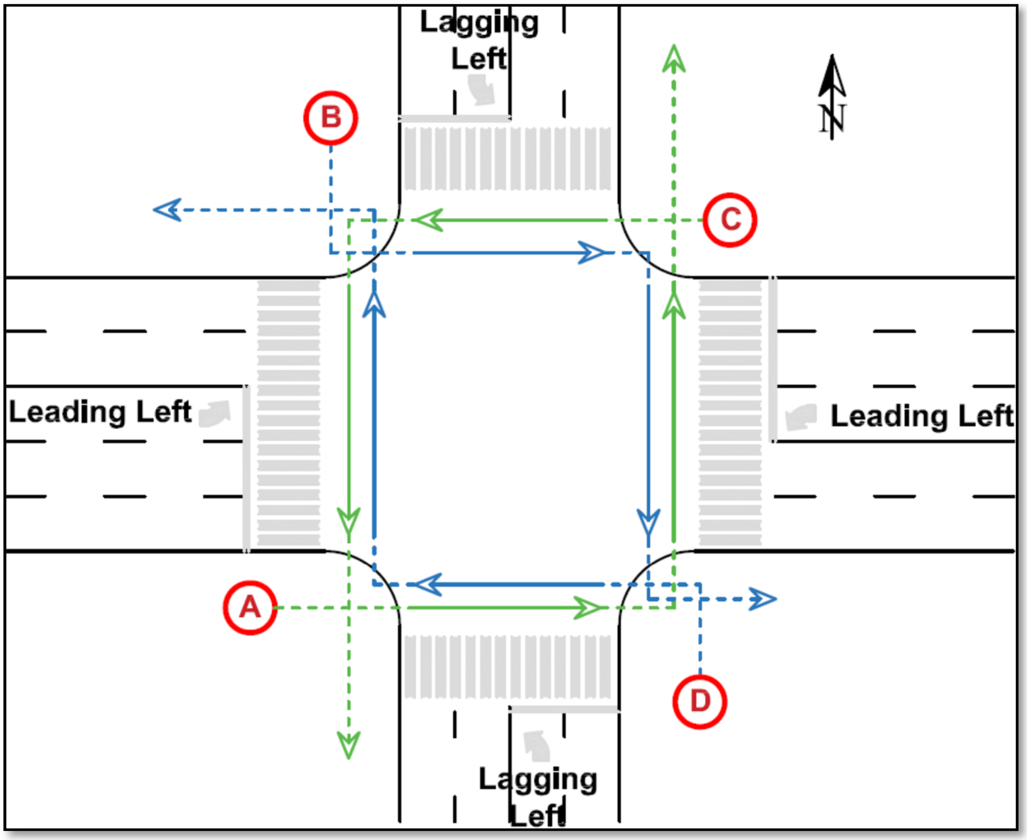


Figure 5 With bidirectional crossings and putting through phases right after each other — one lags on one street and the other leads on the other street — all four two-stage bicycle left turns get good progression

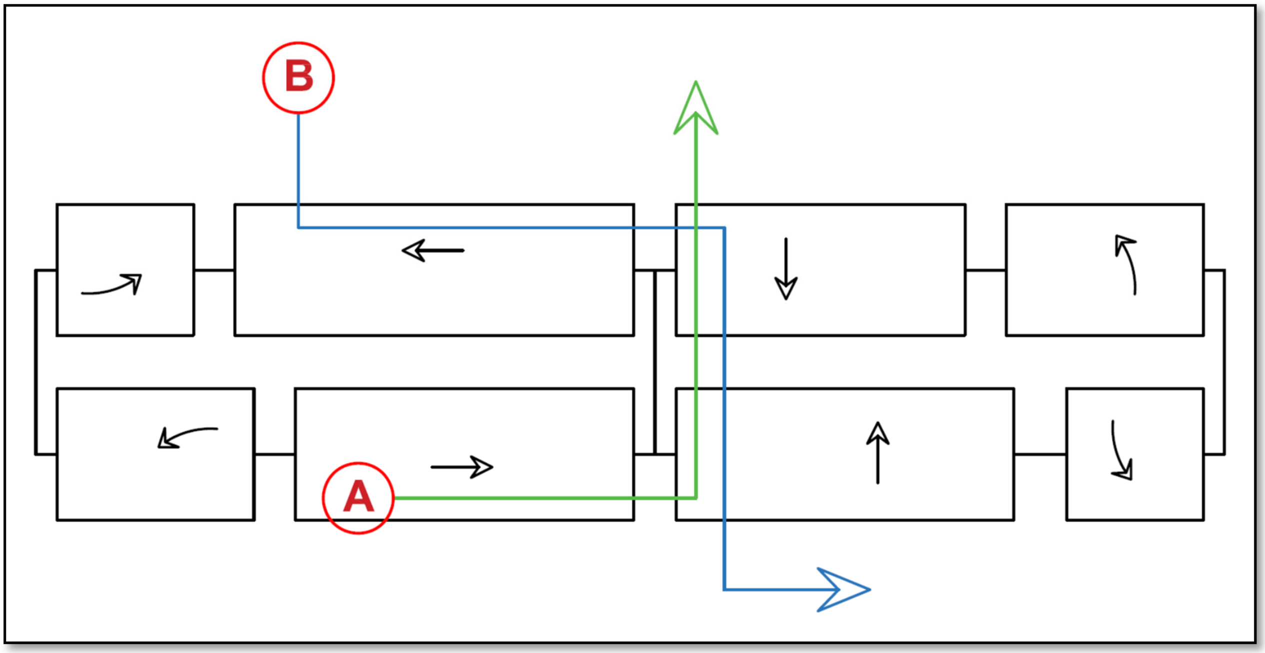


Figure 6 Dual ring diagram for the intersection shown in Figure 5 — EW through phase is lagging and NS through phase is leading

Policy Guidance:

N.A.

Application Instances:

N.A.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

Delay for left-turning cyclists will decrease. On coordinated arterials, delay for motor traffic may be affected to the extent that their progression is affected by whether left turns are leading or lagging.

References:

1. Design manual for bicycle traffic. CROW, Ede, Netherlands, 2007.
2. Furth, P., and Wang, Y. (2015). Delay Estimation and Signal Timing Design Techniques for Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Left Turns. Presented at 94th Annual Meeting of the Transportation Research Board, Washington, D.C.

Treatment or Policy Name:

Minimum Green and Safety-Based Green Extension for Bikes with Shared Traffic Signals

Other Names:

N.A.

Description:

Bicycles, like pedestrians and motorized vehicles, should be able to finish their crossing before a conflicting vehicular phase starts. This treatment applies for situations in which bicycles follow vehicular signals, which are typically timed to provide clearance for motor vehicles but not necessarily for cyclists, which are slower.

A bike-friendly minimum green, in combination with yellow and red clearance times, provides enough time for cyclists that have stopped at a red light to cross the intersection before a conflicting vehicular movement is released. Yellow and red clearance times are assumed to be set based on vehicular needs. Safety-based green extension for bicycles holds the light green to allow a cyclist who enters the intersection on a stale green to finish their crossing before conflicting traffic is released, again in combination with yellow and red clearance time. Both of these treatments are recommended in the AASHTO bike guide *(1)*.

Variations:

N.A.

Relation to Other Treatments and Policies:

N.A.

Objectives, Context, and Operational Details:

The objective of this treatment is to make sure bicycles have finished crossing when conflicting vehicular movements receive green signals. It is a potential threat for cyclists to be within the intersection when conflicting traffic is released, especially when crossing wider roads. As illustrated in Figure 1, the primary threat is from a vehicle approaching from the cyclists' right-hand side. A vehicle in an outside lane may accelerate without seeing the bicyclist who is screened by vehicles in an inside lane. Vehicles on the left are not usually a threat because by the time they start moving, cyclists have usually made it past the middle of the road. In addition, the bicyclist is farther from them, and therefore more easily seen by drivers.

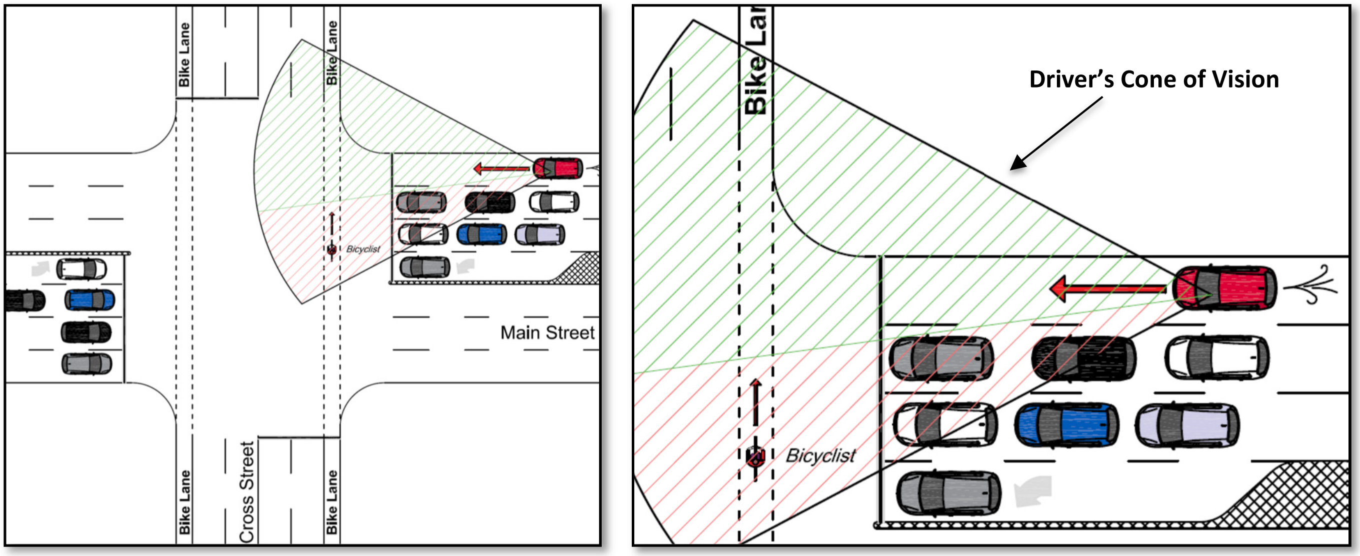


Figure 1 A cyclist screened by cars in inside lanes can be in danger because of a moving car in an outside lane

Two cases should be considered to assure safe crossing of bicycles:

- Case of a Standing Bicycle: fresh green
- Case of a Rolling Bicycle: stale green

Standing Bicycle on Fresh Green:

Generally, minimum green should be long enough to allow a standing bicyclist to perceive to the signal change, accelerate, and cross the intersection before the release of conflicting cars. Adjusting minimum green is preferred to adjusting yellow or red-clearance time; they are determined based on vehicular safety needs.

AASHTO provides the following formula to obtain minimum green required for cyclists, based on the crossing time need of a standing cyclist (1), with default parameters as shown:

$$\mathrm{MinGreen} = \mathrm{PRT} + \frac{\mathrm{V}}{2\mathrm{a}} + \frac{(\mathrm{W}+\mathrm{L})}{\mathrm{V}} - \mathrm{Y} - \mathrm{R}_{\mathrm{clear}}$$

In this formula, PRT is perception-reaction time for a cyclist (default = 1s), V is bicycle crossing speed (10 mph or 14.7 ft/s at level grade), a is bicycle acceleration rate (1.5 ft/s^2), W is the intersection width (ft), L is bicycle length (6 ft), Y is yellow time (s), and $\mathrm{R}_{\mathrm{clear}}$ is red clearance time (s).

Even when minimum green is chosen following policies that ignore cyclist needs, it will often be enough for the cyclist to safely finish the crossing. The situation in which cyclist needs are likely to constrain the minimum green is a long crossing that would otherwise use a short minimum green.

Rolling Bicycle Arriving on a Stale Green:

In order to protect rolling cyclists who arrive during a stale green, *AASHTO* recommends extending the green using an upstream bike detector. A detector that can identify bicycles should be located at the critical distance upstream of the stopline, which is the point after which a moving bicycle seeing the signal turn yellow can no longer stop before crossing the stop line. This distance is called braking distance, BD, and is computed as follows *(1)*:

$$BD = PRT \times V + \frac{V^2}{2a}$$

in which PRT and V are as defined previously, and a is bicycle deceleration rate for wet conditions (default = 5 ft/s^2). Using default values, *BD* = 36 ft.

Whenever a bike is detected during green, green should be extended by the amount $T_{extension}$ which is calculated using the formula below *(1)*:

$$T_{extension} \geq \frac{BD + W + L}{V} - Y - R_{clear}$$

As with the minimum green calculation, *AASHTO*'s guidance on green extension assumes that yellow and red clearance times are determined based on cars' safety needs.

Policy Guidance:

N.A.

Application Instances:

Bike-friendly minimum green is used in some American cities including Portland (OR), Berkeley (CA), and Madison (WI). While several US cities use bike detectors for other purposes, it is not known whether safety-based green extension for bikes is applied in the US.

Documented and Expected Impacts on Non-Motorized Users and on Motor Traffic

In general, securing bike crossings by adding a few seconds to minimum green is expected to have very little impact on traffic delay. In a case study, Shladover et al. found that the impact was far smaller, for example, than the impact of 20 pedestrian actuations per hour *(2)*.

The expected impact of safety-based green extensions is also very small, because it applies only when a bike appears just as a signal is ready to change to yellow. However, implementing this tactic would require installing detectors and changing controller logic.

References:

1. American Association of State Highway (2012). Guide for the Development of Bicycle Facilities.
2. Shladover, S. E., Z. Kim, M. Cao, A. Sharafsaleh, and J.-Q. Li. Bicyclist Intersection Crossing Times: Quantitative Measurements for Selecting Signal Timing. In Transportation Research Record: Journal of Transportation Research Board, No. 2128, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 86-95.

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Task 2 – Agency Engagement Memorandum

Kittelson & Associates, Inc.

In association with:

Northeastern University

Institute of Transportation Engineers

Accessible Design for the Blind

January 28, 2019

SECTION 1 – INTRODUCTION

The objective of agency engagement is to actively engage staff and practitioners and solicit targeted feedback on the traffic signal design and operations strategies for non-motorized users. This feedback expands the written guidance and best practices identified in Task 1 (Literature Review) and documents implementation challenges experienced by practitioners. This technical memorandum describes key findings from the conducted agency interviews. The insights from agency engagement combined with the Task 1 findings add further depth to the gap assessment, which will in turn help the Team develop the Phase II work plan.

This document first provides a general overview of outreach objectives. Next, a summary of the one-on-one interviews conducted with several national and international cities, states, and counties on treatments and existing policy/guidance for non-motorized users at signalized intersections is provided. Finally, the last section presents an online survey, which will be distributed during Phase II to identify candidate agencies for supplemental interviews to collect additional data and conduct case studies for treatments that have already been implemented and/or evaluated by agencies.

SECTION 2 – OUTREACH OBJECTIVES

The agency engagement plan aims to solicit input from agency staff, practitioners, and advocates from various stages of project development, including planning and engineering staff. The learning objectives include:

- Identify best practice for non-motorized user policy, including how agencies balance operations and safety for all modes at signalized intersections;
- Identify common challenges for non-motorized users for signals;
- Identify current guidance being used and the gaps in current guidance;
- Understand common pitfalls to implementation of innovative treatments; and
- Learn the results for implemented treatments and identify candidate agencies for further research and case studies during Phase II.

SECTION 3 – ENGAGEMENT ACTIVITES

The engagement plan includes one-on-one interviews with state, city, and international agencies and practitioners to determine current practices and challenges associated with non-motorized signal design and operations strategies. The team identified a diverse mix of agencies, as listed below, that implemented innovative solutions for non-motorized users at signals with a variety of land use and jurisdictional contexts.

Additionally, as noted above, a web survey was developed and could be distributed during Phase II to identify opportunities for additional supplemental interviews and case studies to evaluate certain treatments.

Follow up Online Survey

As noted above, an opportunity to conduct an online survey may be facilitated during Phase II to identify candidate agencies for supplemental interviews to collect additional data and conduct case studies for treatments that have already been implemented and/or evaluated by agencies.

Participants will be invited via an email invitation to an online survey accessible through an anonymous link. The project team will create a database of federal, state, city, and international agencies and practitioner contacts. To do this, the team may make use of stakeholder lists from other ongoing NCHRP efforts including NCHRP 3-125: Evaluation of Change and Clearance Intervals Prior to the Flashing Yellow Arrow Permissive Left-Turn Indication. The project team will leverage ITE and NACTO to advertise the survey to their membership. Similarly, the project team will send the survey to the League of American Bicyclists, PeopleForBikes, and America Walks to reach members of the advocacy community. The solicitation will also encourage people to forward it on to others who may be interested in responding.

The proposed survey questions for an online survey are provided in Appendix A. These questions also served as a basis for many of the one-on-one interviews.

One-on-One Interviews

The research team interviewed seven (7) agencies that cover six (6) different locations, as listed in **Table 1**. This report also draws on information about agency practices gained from interactions outside the context of this project, including New York City, Toronto, and Long Beach. In identifying the list of agencies, the study team sought agencies that were leaders and innovators for multi-modal traffic signal operations.

These interviews were intended to inform the more comprehensive survey and data collection in Phase II. The information gathered from the interviews provides insight into how agencies and jurisdictions currently account for non-motorized users' needs at signals and how they decide which treatments to implement. The interviews also focused on understanding where agencies lacked guidance on treatments, what information they might need to implement new treatments, and what research opportunities may exist as part of the Phase II.

Table 1: List of Interviewed Agencies

Agency Name	Person(s) Interviewed	Learning Objective
Arlington County (Virginia, USA)	Amit Sidhaye	• Details on work being done to retrofit suburban arterials for non-motorized users
City of Amsterdam (Netherlands) – Staff	Sjoerd Linders and Marcel Mulder	• Comprehensive, mature policies for bike-friendly traffic signals based on years of experience and experimentation.
City of Amsterdam (Netherlands) – Advocates	Dick de Jong and Marjolein de Lange	
City of Cambridge (Massachusetts, USA)	Patrick Baxter and Cara Seiderman	• Multiple innovative treatments and policies for urban intersections with limited right-of-way.
City of Charlotte	Nathan Conrad	• Details of their Leading Through Interval treatment, locally referred to as LPI+ • Use of bicycle LOS (BLOS) and pedestrian LOS (PLOS) at signalized intersection
City of Montreal	Jean Hamaoui	• Details on Leading Through Interval and Leading Pedestrian Interval.
City of Portland (Oregon, USA)	Paul Zebell*	• Results of implemented treatments such as bicycle detection, leading pedestrian intervals, bicycle signals, and red period countdown. • Policy for non-motorized users and relative priority of modes at intersections

*Paul Zebell worked at the City of Portland for 32 years in the Transportation Signals Section and is currently employed by Kittelson & Associates, Inc.

Several agencies approached turned down the interview. While they expressed excitement about the research and opportunity to learn what other agencies are doing, they indicated they did not have a specific program/policy for non-motorized users, nor have they implemented any innovative treatments for non-motorized users. Their approach is one of compliance and status quo. While not based on an interview, the following are key observations from practitioners on the standard practice of many state agencies' approach to non-motorized users at signalized intersections:

- Where sidewalks exist, agencies follow MUTCD guidance for pedestrian signal heads and phasing, with countdown signals starting from FDW in most locations. Pedestrians phases are timed with standard 5 or 7-second walk and required FDW time.
- Pedestrian signal phases to cross side streets may be on recall, and pedestrian signal phases to cross main arterials generally require push-button actuation, often knocking the signal out of progression
- Generally, agencies do not use special features such as rest in walk or special settings regarding permissive windows to reduce pedestrian delay. Furthermore, non-motorized performance measures are not standard practice to evaluate intersection conditions and agencies do not set cycle length limits to limit pedestrian delay.
- Where pedestrian facilities do not exist, pedestrian signal heads are typically not installed.
- There are rarely specific treatments for bicyclists at signals.

The following sections summarize overall themes identified from the interviews; detailed interview notes are provided in Appendix B.

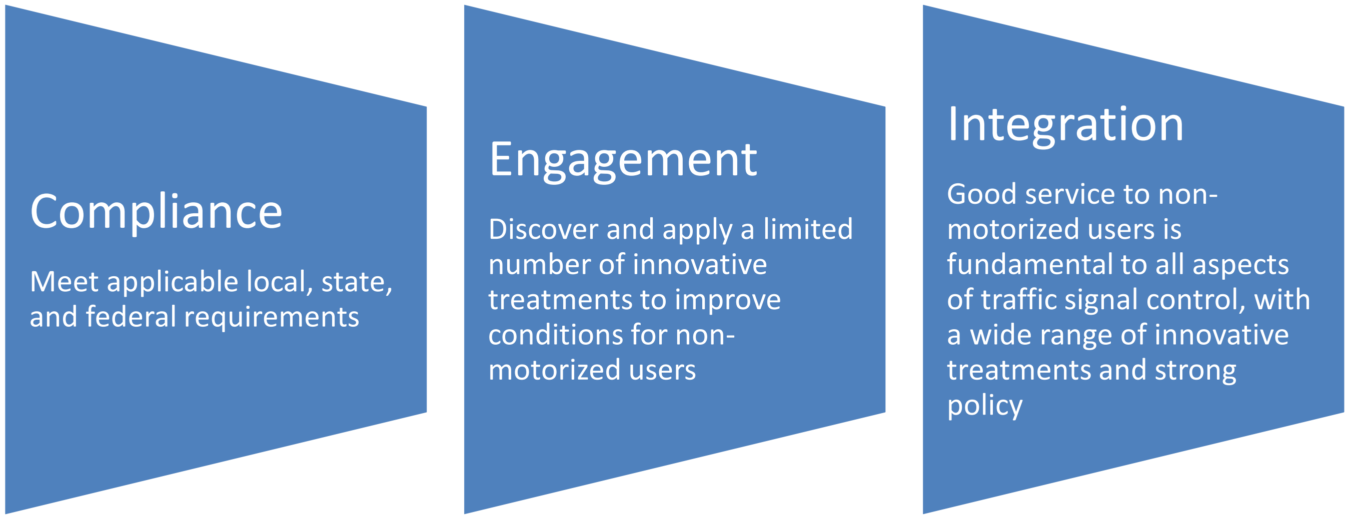
Section 4 – Key Agency Interview Findings

The following summarize key findings from the agency interviews:

- Certain treatments, such as the Leading Pedestrian Interval (LPIs), are being implemented more often and agencies are typically developing their own policy regarding interval length (ranging from 3 seconds to 7 seconds) and appropriate LPI locations.
- Agencies seemed comfortable testing treatments that use standard phasing/timing features of traffic control such as LPI. This contrasts with flashing yellow arrow (FYA), which many cities were reluctant to apply until tested for a long time in other cities.
- Most agencies interviewed are limiting cycle lengths to 150 seconds or less. Amsterdam and Cambridge limit cycle lengths to 90 to 100 seconds. In high-pedestrian areas, Charlotte and Arlington County do the same (e.g., downtown Charlotte or Rosslyn-Ballston corridor in Arlington).
- Existing technology does not appear to be a barrier for the interviewed agencies. Arlington County, for example, mentioned their signal controllers allow them to test and implement various treatments they are interested in.
- As funding is a challenge, agencies are using routine maintenance and signal retiming to start to implement treatments for non-motorized users.
- To help prioritize locations, some agencies are classifying streets by mode. Amsterdam, for example, classifies streets for priority at signals. If a street isn't primary for vehicles, then queues on that street are acceptable. If it's primary for vehicles, providing sufficient capacity is important.
- Measures of effectiveness (MOE) for non-motorized users are limited. Arlington County and Amsterdam have used VISSIM to measure delay for non-motorized users. Cambridge requires pedestrian delay in all developer traffic studies, typically calculated manually using the Highway Capacity Manual (HCM) formula.

Another key finding is the range of agency approaches to addressing non-motorized users. As shown in **Figure 1,** agencies have adjusted their perspectives, policies, and practices to integrate non-motorized users in all aspects of signal control. This includes the planning, design, and operations of traffic signals

Figure 1. Evolving Agency Approach to Integrate Non-Motorized Users at Signalized Intersections



Common Non-Motorized Treatments at Signalized Intersections

Table 2 summarizes the treatments discussed by each agency interviewee. The treatments listed are not an exhaustive list being covered by this research project but rather the treatment agency staff focused on during the interviews. Specific considerations for each treatment are provided in the subsequent summary. Detailed descriptions of each treatment are provided in the Task 1 (Literature Review) memo. It is important to note that there are other treatments listed in the survey as shown below, but these treatments were not implemented by the interviewed agencies, and thus not included in the table below.

Table 2: Summary of Implemented Treatments

	Arlington County, VA	Amsterdam, Netherlands	Cambridge, MA	Charlotte, NC	Montreal, Canada	Portland, OR
Leading Pedestrian Interval	Early application	Situational[1]	Widespread	Situational	Widespread	Situational
Leading Through Interval	**	**	Early application	Situational	Widespread	**
Exclusive Pedestrian Phases	Not Preferred	**	Not Preferred	**	Situational	**
Pedestrian Recall	Situational	Situational	Widespread	Situational	**	Widespread
Bicycle Detection	Widespread	**	**	**	**	Widespread
Bicycle Signal Heads	Interest	**	**	Early application	**	**
Leading Bicycle Interval	**	**	Early application	**	**	**
Bicycle Countdown	**	Early application	**	**	**	Early application
Bicycle Boxes	Situational	**	Situational	**	**	Widespread
Protected Turn Phasing	--	Widespread	Widespread	--	Situational	--

[1] Amsterdam has large stop line offsets (car stop line is set back from crossing), so pedestrians and bicyclists get a bigger head start in space, limiting need for LPI/LBI.

Widespread: Treatment is routinely considered and used at a variety of locations
Situational: Treatment is considered and implemented on a case-by-case basis in specific contexts
Early Application: Agency has recently started implementing the treatment at few locations
Interest: Agency is open to testing the treatment in the future
Not Preferred: Agency prefers to avoid the treatment when possible (see discussion in sections below)
** Treatment not discussed during interview

Leading Pedestrian Intervals (LPI)

All six agencies interviewed are currently using LPIs, where the pedestrian phase begins a few seconds before the concurrent vehicle phases to limit vehicular-pedestrian conflicts. Arlington County and the City of Portland currently use LPIs on a case by case basis; Cambridge has implemented them citywide; Charlotte has been doing widespread implementation of LPIs over the last few years. Most agencies reported using LPIs between 3 and 5 seconds. The City of Charlotte had implemented LPIs as long as ten (10) seconds in high pedestrian areas, such as near schools and universities.

Cambridge would like to release bikes during the leading interval, as well as pedestrians but hasn't figured out how to do so in a way that complies with the MUTCD. Informally, cyclists have learned to go at the start of the WALK signal. On one street with a cycle track, there is a 7-second LPI that formally is shared with bikes, using bike signals that turn green when the WALK sign begins.

Amsterdam provides pedestrians and bicyclists a head start using intersection geometry rather than signals, and thus either has no LPI or a very short LPI. At most intersections, the stop line is set back so far that pedestrians and bicyclists get a bigger head start in space than what's common from an LPI (**Figure 2**). The City will install LPIs where the head start in space isn't enough; the combined head start from geometry and

LPI will be enough that pedestrians will reach the conflict point with right-turning cars just before the cars would arrive.

Figure 2: Stop Line Setback Example from Amsterdam that Provides a Bigger Head Start for Pedestrians in Space (source: Google Earth)

Leading Through Intervals

Three of the agencies interviewed have moved beyond LPIs and started implementing Leading Through Intervals (LTI), locally called LPI+ in Charlotte and Split-LBI in New York. The LTI holds only right-turning traffic (left turning traffic can also be held for one-way streets such as New York City) while allowing vehicular through traffic and pedestrians phases to begin simultaneously. Because it holds back much less traffic, LTI allows the leading protected interval to be longer than is normally allowed with LPI. In Charlotte and New York, LTI is implemented only at intersections with exclusive right-turn lanes (as to not block through traffic behind a turning vehicle), while in Montreal it is implemented almost only where there is no exclusive turn lane, in which case right-turning vehicles that are held can block through-going vehicles behind them.

Charlotte has some LTIs where left turns are normally permitted; in such cases, they have installed turn signals to hold the left turns during the LTI, just as right turns are held. New York also uses LTI for left turns (with an exclusive left turn lane) at intersections of two one-way streets.

The length of the LTI varied by agency:

- City of Montreal: Typically, 7 to 9 seconds, and by policy never longer than 13 s
- City of Charlotte: Typically, 10 seconds, in some cases the length of the entire pedestrian phase
- City of Cambridge: No LTI currently, plans to implement LTI with a 15 s leading interval at one intersection that now has a 3-s LPI.

Where an exclusive right turn lane is not available, Charlotte uses LPI instead of LTI. In Montreal, while they use LTI with shared through-right lanes, they have found that complaints and non-compliance make LTI with shared lanes less desirable where the volume of right turning traffic is high and opt in such cases for LPI instead.

Exclusive Pedestrian Phases and Concurrent-Yet-Protected Phasing

Two agencies interviewed, Arlington County and City of Cambridge, specifically try to avoid exclusive pedestrian phases because of the longer signal cycles and associated pedestrian delay. Instead, they prefer to run pedestrians concurrent with vehicular phases. This policy is unique in Cambridge because exclusive pedestrian phases are common in Massachusetts and are used in the neighboring City of Boston. In some cases, Cambridge will implement exclusive phasing. At one intersection where a two-way cycle track crosses an arterial, they plan to have an exclusive pedestrian-bicycle phase. At another intersection where two high-volume roads meet, Cambridge has an exclusive pedestrian phase because of high (permitted) right turn volumes.

Where there are high turning volumes, especially at large intersections, the City of Cambridge has applied concurrent-but-protected phasing, with pedestrians walking concurrently with through traffic while both left- and right-turning traffic run at a different time. Portland, likewise, uses concurrent-but-protected phasing at some intersections with high right-turn volume, giving part of the through vehicle phase to pedestrians and the remainder to right turns.

Toronto includes exclusive pedestrian phases at some of its downtown intersections while also allowing pedestrians to walk concurrently. This treatment is driven by adherence to a fixed cycle length along with very high volumes of pedestrians, more than the street corners could hold if pedestrians were only allowed to cross once per cycle.

Pedestrian Actuation vs. Recall

Agencies had different approaches to pedestrian actuation. In their central business districts (CBD), all of the interviewed cities except Amsterdam use pretimed control with pedestrian phases on recall. Outside the CBD, most of the interviewed cities commonly use coordinated-actuated control on their arterials

Cambridge, with relatively strong pedestrian demand citywide, uses pretimed control at almost all of its signals, with pedestrian phases on recall. They prefer pretimed to actuated control because it makes the phase length predictable, allowing them to make the WALK as long as possible. They occasionally use actuated phases where there are left-turn phases at some of their large intersections and at intersections with very low side street traffic s and crossing demand.

In Portland, where coordinated-actuated logic is used, pedestrians are generally on recall unless there is high volume on the arterial. In this case, pedestrians may be actuated during a short portion of the peak.

In Amsterdam, most signals are fully actuated, based on a desire to keep cycles short and responsive to traffic demands. They follow a "co-realization" model. As a rule, they prefer actuated pedestrian phases in order to prevent longer cycles and unnecessary delay to others. However, anywhere the pedestrian phase would fit into a vehicular phase without lengthening the cycle length, they make it on recall.

The City of Charlotte routinely places the pedestrian phase to cross the side street on recall, using the "rest in walk" setting. However, the arterial main line crossing is usually actuated. In Portland and Arlington, the side street crosswalk is typically pushbutton actuated. Some have permissive periods that provide an immediate WALK signal when a pedestrian pushes the button after the coordinated phase has begun, if the pedestrian phase can still fit into the remainder of the coordinated phase.

Cambridge has installed Accessible Pedestrian Signals (APS), which have pushbuttons, at many intersections. The pedestrian phases remain on recall regardless. To help clarify to pedestrians that they don't have to push the button to get a WALK signal, they affix a sign "Push Button for Audible WALK." At a few intersections in busy commercial areas, the audible signals are also on recall; more often, they are not (to reduce ambient noise), but instead are pushbutton actuated.

Pedestrian Hybrid Beacon

Cambridge has installed three Pedestrian Hybrid Beacons (PHB) at midblock crossings and found they work best when pedestrian volumes are not very high. When pedestrian volume is high, they've noticed that when pedestrians approach the crosswalk and the traffic signal displays nothing, they tend to assert priority (as they would at other unsignalized crossings). Also, PHB operation presents a safety challenge for pedestrians who start to cross near the end of the WALK interval when. vehicles already have a flashing red. In one location, they are replacing the PHB with a full, actuated signal.

Portland is using the PHB for bicyclists to cross an arterial without attracting traffic to the bicycle route. There is a concern because the conflict monitor doesn't function when the signal is dark. Additionally,

pedestrians may assume they can cross during FDW, when vehicles are already allowed to proceed. To help mitigate this, Portland only uses the flashing red interval for the last few seconds, in case another pedestrian starts crossing well after the PHB has been activated.

Bicycle Detection

Arlington County has widespread use of floor heating infrared detection, which allows them to pick up vehicles and bikes. For trails, they have added detection, so bicyclists don't need to push the button to cross the intersection.

The City of Portland generally uses parallelogram bicycle loops and places them about 50 feet from the intersection for the call and at the stop bar. The advanced loops have 5 to 6 seconds of carry over time. The City uses blue lights emanating from an opposite-direction signal head to indicate that a bicycle request has been registered.

Bicycle Signals

Several agencies interviewed use bicycle signals. Portland has many. Arlington County has implemented bicycle signal at three locations. Charlotte has bicycle signals at one intersection with plans to add them at five to ten more. **Their current and planned applications have high volumes of traffic and they are running the bicycle signal fully protected, concurrent only with a non-conflicting right-turning movement. Applications are still limited, however, because FHWA interim approval will only allow their use where bicycles are fully protected. Charlotte cycle tracks typically use signs to tell cyclists to follow the pedestrian signal; bikes run during both WALK and flashing DON'T WALK, using the countdown signal to determine when to stop.**

In Montreal and Amsterdam, where the FHWA restriction doesn't apply, bicycle signals are often concurrent with a combined through-right phase. Sometimes, however, bike phases are separated in time from right turn phases.

Most agencies are defaulting to vehicle clearance times. Amsterdam recently lowered their yellow time for bikes from 3 s (the value used for vehicles) to 2 s, which in effect gives bikes an extra second of clearance time. At a few intersections, for phases serving only bicyclists, Arlington County is exploring different minimum green and clearance interval settings for bicyclists. In Portland, some signals are programmed to extend the green in response to bike detection, such as for left-turn phases with very short minimum green.

Other Bicycle Phasing Treatments

As mentioned earlier, the City of Cambridge, in one corridor with a cycle track, uses a 7 s leading interval for pedestrians as well as bikes. Bicycle signals are used to let bikes know they can use the leading interval. (Charlotte often uses "Bikes Follow Pedestrian Signal" signs to let bikes know they can cross during LPIs.) . Both Cambridge and Portland use bike signals for a diagonal bike crossing.

In Amsterdam, where bikes have a separate phase from right turning cars, the signal alternates the right-turn vehicle phase and through bicycle phase until the through vehicle phase ends. They start with the bicycle phase and can serve the bicycle phase multiple times in the cycle, reducing bicycle delay.

Portland and Amsterdam have started using "wait" countdown for bicyclists. Portland **gives relative length of time to wait, not an absolute number of seconds because other phases are actuated. Amsterdam reports that they don't really improve compliance, but that citizens like them.**

Bike Boxes

Amsterdam typically uses bike boxes with bike lanes, giving bikes an expanded space between the stop line and crosswalk. They have a version that goes from a cycle track into a space in front of the crosswalk for places with very high bike volume. Cambridge and the City of Portland use bike boxes for two-stage lefts.

Protected Turn Phasing

Amsterdam has a policy of using protected left-turn phasing. There are exceptions where there isn't space for a left-turn lane (common for minor streets where they cross an arterial), but they never have permitted left-turns from a left-turn lane, and they never have permitted left turns on multilane roads. Where there are permitted left turns from a minor street onto a wide road, they sometimes use a large flashing yellow ball – mounted outside the normal signal display – to warn left-turning vehicles of conflicts with crossing pedestrians/bicyclists. The ball is mounted on the far left, where the conflict happens, and is angled diagonally facing a left-turning car about halfway through its turn. Where possible, Montreal prohibits left turns across cycle tracks. On some streets, where left-turns are permitted after an LTI, it can be hard for motorists to find a gap between bikes and peds – by the time you've checked your blind spot, it's too late. It is important to note that most agencies in the U.S. are making decisions about left-turn phasing based on vehicle volumes and conflicts, not so much based on the conflicts between vehicles and non-motorized traffic.

Cambridge uses No Right Turn on Red (NTOR) at nearly all signalized intersection approaches. The NTOR treatment improves the effectiveness of the LPI. At a few intersections, they have posted "Except Bikes" as a sub-plaque to the NTOR sign and are planning to add this at more locations.

In a recent effort to improve bike and pedestrian safety, Cambridge has programmed some intersections to offer full protection by running left and right-turns together, exclusively, and running bicyclists and pedestrians with through traffic ("concurrent-yet-protected" phasing).

Amsterdam went through a period in the 1970's of separating cyclists in time from right turning vehicles in time. However, this led to long cycles and poor compliance (by cyclists). Since the 1980's, they have made it the default that bikes can run concurrently with permitted right turns, except where right turn volumes are high or intersection geometry allows fast right turns. New York City's move toward LTI's instead of protected phasing was similarly motivated – many cyclists were crossing during the "protected" turn phase, so they chose to allow bikes and turns to be concurrent, along with giving bikes (and pedestrians) a leading interval so that the concentrated queue of bikes can still have a protected crossing.

Existing Challenges for Treatment Implementation

Common challenges for treatment implementation include lack of guidance, funding, and staff resources. Some agencies, for example, are trying to figure out how to implement certain treatments that would improve non-motorized conditions at signalized intersections but are not MUTCD compliant. For example, Cambridge is interested in allowing bicyclists to enter the intersection during the LPI, but the FHWA interim rule does not allow this with bicycle signals because after the leading interval ends, bikes would be running concurrently with a shared through-right phase. The City of Charlotte noted funding is a challenge when addressing ADA compliance, especially when ramps require additional right-of-way.

Portland mentioned that communication about trade-offs between modes can be challenging. In the past, they have over emphasized motorist and freight benefits of certain projects, such as signal priority, that also benefit non-motorized users. They have struggled to communicate that signal operations is not a zero-sum game.

Available Data & Future Research Opportunities

During the agency interviews, the research team inquired about existing data sources as well as intersections in which agencies are planning to test certain treatments in the near future that could be used as part of Phase II. Agencies interviewed currently have the following data:

- Amsterdam has done Informal measurements on compliance for bicycle wait indications. They have found it doesn’t stop bikes from running the light.
- City of Charlotte has a vehicular compliance study on its LTI treatment (i.e., whether right-turning vehicles hold in response to the red arrow and “No Turn on Red” signs displayed during the LTI). This study was not published, but the City shared a copy of the results with the research team.

The team also asked agencies about their willingness to participate in research projects during Phase II of this project. Arlington County agreed to test operation treatments if there is no physical disturbance. Their communication is 100% on fiber so they can test treatments and bring the data back easily. The City of Charlotte is planning additional LPI Plus implementation in the next year. They mentioned willingness to participate in a before and after study at an upcoming location to explore vehicular-pedestrian conflicts with the LPI plus. Cambridge is working with a local, private research and development team on improving intersection safety, and may be able to apply that team’s machine vision capability do to field studies.

APPENDIX A – ONLINE SURVEY QUESTIONS

- Contact Information
    - Name
    - Agency/Organization
    - Department/Unit
    - Title
    - Phone
    - Email
- Which of following have you helped implement at signalized intersections (check all that apply)?
    - Short cycle length
    - Pedestrian phase on recall
    - Bicycle signals
    - Maximum walk interval length (including rest in walk and lengthening minimum green)
    - HAWK/Pedestrian Hybrid Beacon
    - Pedestrian overlap with left turn phase
    - Permissive periods for pedestrian actuation
    - Multi-stage pedestrian crossing
    - Leading pedestrian interval
    - Leading through interval
    - Exclusive pedestrian and bicycle phases
    - Protected left turn phases
    - Bicycle two-stage left turn progression
    - Adaptive walk intervals
    - Phase re-service for ped/bike phases

  - Bicycle detection
  - Flashing yellow arrow for permitted conflicts
  - Eliminating delta islands
  - Bicycle minimum green and change interval settings
  - Red period countdown
  - Pedestrian countdown signals
  - Flashing pedestrian and bicycle indicators
  - No turn on red signs
  - Other (please specify)
- If you implemented any of the above, are there quantitative results that have been published? Please provide a link if applicable. [short answer]
- What common obstacles do you see to implement bicycle and pedestrian treatments at signals? [short answer]
- What guidance do you currently rely on for planning, design, and operation of signals for non-motorized users? [short answer]
- What treatments for non-motorized users at signals need additional guidance for in order to implement (check all that apply)?
  - Short cycle length
  - Pedestrian phase on recall
  - Bicycle signals
  - Maximum walk interval length (including rest in walk and lengthening minimum green)
  - HAWK/Pedestrian Hybrid Beacon
  - Pedestrian overlap with left turn phase
  - Permissive periods for pedestrian actuation
  - Multi-stage pedestrian crossing
  - Leading pedestrian interval

- Leading through interval
- Exclusive pedestrian and bicycle phases
- Protected left turn phases
- Bicycle two-stage left turn progression
- Adaptive walk intervals
- Phase re-service for ped/bike phases
- Bicycle detection
- Flashing yellow arrow for permitted conflicts
- Eliminating delta islands
- Bicycle minimum green and change interval settings
- Red period countdown
- Pedestrian countdown signals
- Flashing pedestrian and bicycle indicators
- No turn on red signs
- Other (please specify)

▪ What performance measures do you use to evaluate ped/bike accommodation at signals? [short answer]

▪ What agency policies exist to address non-motorized users at signals? Please include the name of the agency.

APPENDIX B – NOTES FROM PRACTITIONER INTERVIEWS

List of Interview Participants

Agency Name	Person(s) Interviewed
Arlington County (Virginia, USA)	Amit Sidhaye
City of Amsterdam (Netherlands) – Staff	Sjoerd Linders and Marcel Mulder
City of Amsterdam (Netherlands) – Advocates	Dick de Jong and Marjolein de Lange
City of Cambridge (Massachusetts, USA)	Patrick Baxter and Cara Seiderman
City of Charlotte (North Carolina, USA)	Nathan Conrad
City of Montreal	Jean Hamaoui
City of Portland (Oregon, USA)	Paul Zebell*

Interviewee: Amit Sidhaye, Arlington County

What treatments do you use (or plan to use) to improve safety and mobility for non-motorized users?

Pedestrians:

- The County is currently developing a policy and criteria for LPI implementation. This is currently an internal document and the County has already started using it to determine if LPI implementation is feasible.
- LPIs have been implemented at 5 intersections so far, and the County is in the process of expanding it.
- The County uses 5-7 seconds for LPI.
- During signal optimization, the County looks for opportunities to implement LPI and sometimes exclusive pedestrian phases, based on pedestrian volume data. However, they are avoiding all-pedestrian phases mostly due to the associated high delay for pedestrians.
- The County has different approaches for different corridors. For example, for the Rosslyn-Ballston corridor or Crystal City corridor, both transit corridors, they have pre-timed intersections and use rest-in walk with pedestrian recall. For intersections beyond Glebe Road, intersections have coordinated-actuated phases and pedestrians need to use the push-button to activate the pedestrian phase on the actuated approaches. Where they have push-button actuation, they allow permissive periods for pedestrian actuation. In other words, if a call comes up after the concurrent vehicular phase has started and if there is enough green time to insert the pedestrian phase, the pedestrian phase gets activated during this cycle.
- All intersections have Countdown signals for pedestrians and the countdown starts from FDW, not from Walk.

Bicyclists:

- The County is using floor heating infrared detection for all detection, which allows them to pick up anything, including bikes. Most intersections already have floor heating detection.
- At a few intersections, if no vehicles are present except for bicyclists, the County is exploring different minimum green and clearance interval settings for bicyclists.
- The County has implemented bicycle signal faces for three locations as part of the FHWA interim approval: https://mutcd.fhwa.dot.gov/resources/interim_approval/ia16/ia16.pdf
- The County is exploring further use of bicycle signals as per MUTCD recommendation. They are still trying to figure out how to implement the bicycle signals when bicyclists are running parallel to vehicular movements, which is not MUTCD compliant If the vehicular movement includes permitted turns across the bike path.

- For trails, the County is using detection to ensure bicyclists don't need to push the button to cross intersection. A similar concept is being used at Walter Reed and 11th Street for contraflow a bike lane that does not have an exclusive bicycle phase.
- For the left turn phasing schemes, they use a flowchart to make left turn phasing decisions. The flowchart was built off VDOT's standard and has additional information for the County context. They mainly they use pedestrian volume along with judgment for the left turn phasing.
- The County has implemented protected bike lanes and protected intersections. They are looking for more guidance on bike boxes and signalization of protected bike lanes.

How do you assess and select alternatives at signalized intersections to integrate and/or promote non-motorized users?

- Mostly based on data (pedestrian/bicycle counts, crash data, traffic volumes, activity centers, library/schools etc.) and take into account intersection spacing

What are common barriers to implementing treatments for non-motorized users at signals?

- Lack of guidance and data
- There is not enough guidance on the parallel bike lanes at intersections and for raised crosswalks.
- The County stated that they don't have any problem on the hardware/software side. Existing technology allows them to test new treatments.
- Their main concern and challenge is staff resources.

What local guidance or common practice exists (if any) for non-motorized users? Is it documented?

- MUTCD, NACTO
- LPI checklist that was developed internally

What MOE's do you focus on for evaluating and selecting treatments?

- Crash data, pedestrian/bicycle volume data, delay
- The County sometimes uses VISSIM so they can measure delay for vehicles and non-motorized users
- Their policy is that cycle length should not exceed 150-160 seconds overall and to keep it as low as possible, based on context. Cycle in high-pedestrian corridors like Ballston-Rosslyn are around 90-100 seconds.

What new or innovative treatments have you started implementing recently and/or at a smaller scale?

- The County has started looking at treatments related to connected vehicles. The County is doing pilot testing at 5 intersections. They are working with an AI company from Atlanta for the non-motorized applications.

How do you measure outcomes of treatment implementations?

- Mostly based on data and customer feedback, sometimes simulation
- The County talks to the pedestrian/bicycle committees for outreach and feedback after implementation.
- They are exploring automated traffic signal performance measures (ATSPMs), Intelight specifically, but they are not using ATSPMs right now.

Where is your agency heading with respect to non-motorized users at signals? Do you have any plans to create new guidance or implement new treatments?

- The County has bicycle counters at 40 locations, available online: http://www.bikearlington.com/counter-data/. A special pedestrian/bicycle group is working on this. They are trying different things, including infrared, to improve accuracy of detection.

What is your willingness to test treatments you have not seen before? What information would you need before deciding to implement a new treatment?

- Fact-based data and analysis, specifically pedestrian/bicycle and crash data
- On the technology side, if there is no physical disturbance, they are willing to test and open to the idea. They are always looking for the opportunity.
- County's communication is 100% on fiber. As a result, they can do many things quickly and can bring the data back easily. Amit was open to the idea of testing new treatments for certain locations and mentioned that would also be easy to do data collection.

Interviewee: Sjoerd Linders and Marcel Mulder, City of Amsterdam

What treatments do you use (or plan to use) to improve safety and mobility for non-motorized users?

Pedestrians:

- As a rule, they prefer actuated pedestrian phases in order to prevent delay to others. However, anywhere the pedestrian phase would fit into a vehicular phase, they make it automatic. They call it "co-realization" – green for cars automatically triggers green for ped). A recent study of one site (Stadthouderskade at Westeinde, where trams cross over) they found that in 95% of cycles, there was enough time for pedestrian phase, so they made it automatic.
- They have some delta islands, but they are undesirable. They stay away from big streets. Generally, they try to make one-stage crossings possible but will use multistage crossings to reduce clearance time needs. Having a pedestrian signal at the median allows pedestrian signals on the curb side to start earlier than it could otherwise.

Bicyclists:

- They don't have any intersections with all-bike phases as a normal part of the signal cycle. As a rule, they don't like all-bike phases, because bicycles want to go concurrent.
    - They have one intersection where all-bike phases often happen, with the orthogonal bike conflicts (EW bikes meet NS bikes) that occur with an all-bike phase. It's a special situation. Weesperzijde, a N-S street with very little vehicular traffic and lots of bike traffic, meets Berlagebrug, a bridge / street with a lot of cars and bikes. In many cycles, there is no vehicular demand on the N-S street, while there is bike demand. In a cycle like that, when the light turns red for E-W vehicles and green for N-S bikes, the light stays red for N-S cars and green for E-W bike. As a result, there is all-red for cars, all-green for bikes. Unlike other intersections with all-bike phases, this intersection assigns priority between bike movements using sharks teeth (yield lines) where the bike paths meet. N-S bikes are supposed to yield to E-W bikes. This legal bike conflict has been going on since the 70's.
- They used to use protected right-turn phasing, but they run right turns and thru bikes concurrent.
- "Wait" countdown for bikes is popular. It gets high ratings and politicians like it, but informal measurements they've made indicate that it doesn't stop bikes from running the light.
- It was recently decided to decrease bicycle yellow from 3s to 2s. Implementation is mostly complete. They calculate and enforce clearance for bikes just as for cars. Occasionally use islands with two-stage crossing to reduce clearance need. When signal ends on gap-out, they end bikes and cars simultaneously. They don't give bikes the yellow first because they won't stop if they see car signal is green.
- They had a historically rigid view that with two-way cycle tracks, there must be no permitted turns at all. This view led to there being few two-way cycle tracks in Amsterdam. However, this

view is being relaxed now as they see two-way cycle tracks becoming more popular in other Netherlands cities.

- They use bike boxes with bike lanes (giving bikes an expanded space between stopline and crosswalk), and they have a version that goes from a cycle track into a space forward of the crosswalk (for places with very high bike volume).

Both

- For the most part, they don't formally do LPI or LBI, but they do believe in giving pedestrians and bikes a head start, mainly through their intersection geometry. The vehicle stop line is often set back 50 ft or more from the start of the crosswalk and the bike crossing. Where the head start given by geometry isn't enough, they will increase clearance time for the previous phase so that first right-turning car is expected to arrive at the conflict point at the same time as the first pedestrian – that is, in effect, an LPI.
- They implement protected left-turn phasing from the main street as a rule. There are exceptions where there isn't space for a left-turn lane, but they never have permitted left-turns from a left-turn lane, and never have permitted lefts from a multilane street.
- They have only a few places with coordinated cycles, mostly with short signal spacing and with the motivation being priority for tram. An example is Wibaustraat. They have an intermediate alternative, which they call "soft coupling," in which two nearby signals follow free actuation logic. A green signal or tram detection at one intersection will generate a call at the next, so the green waves can be provided without forcing a common cycle.

How do you assess and select alternatives at signalized intersections to integrate and/or promote non-motorized users?

- Amsterdam classifies streets as to the most important user, which influences priority at signals. There is a priority network for bikes, for cars, for public transport. If a street isn't part of the priority network for cars, then queues on that street are acceptable. If it's primary for cars, providing sufficient capacity is important. It used to be that public transport got priority everywhere, but minor routes are no longer on the priority network for public transport, and don't get priority where it would worsen conditions for bikes and pedestrians.
- They care about signal control being "credible." A signal is considered credible when users follow it apart from fear of enforcement. Credible means having concurrent crossings, allowing the kind of turn conflicts that pedestrians/bicycle don't consider dangerous. Two prime examples of "not credible" are holding pedestrians/bicyclists until an exclusive phase and holding thru bikes during a thru-right phase, something they did a lot in the 1970's. Bikes would run when there were gaps, because they felt they could manage that simple, 1-lane conflict themselves. Credible also means a strong preference for actuated signals so that people don't have a red when there is no cross traffic.

What local guidance or common practice exists (if any) for non-motorized users? Is it documented?

- Pedestrian clearance is calculated using 1.0 m/s (3.3 ft/s) for start of flashing green (advice to slower pedestrians not to start) and 1.2 m/s (4.0 ft/s) for start of red man (don't start to cross).
- Maximum cycle length is 100s. The maximum wait is 45s. As a practical matter, if you hold to the first of these maxima, you achieve the second. Maximum average delay for public transportation is 30s.

What MOE's do you focus on for evaluating and selecting treatments?

- They routinely calculate pedestrian delay along with auto delay. Their software can evaluate pedestrian delay for two-stage crossings if the two stages are coupled, meaning one stage's green triggers a green for the other. Otherwise they can use VISSIM.

Interviewee: Dick de Jong and Marjolein de Lange, Cyclists Union (an advocacy organization), Amsterdam branch

What treatments do you use (or plan to use) to improve safety and mobility for non-motorized users?

Bicyclists:

- In some places, they freely alternate right-turn phase and thru bicycle phase, during the thru vehicle phase, starting with the bicycle phase. Bikes may get 2, even 3, phases in a cycle if the through phase runs a long time.
- Reservice for bicyclists is well-known tactic.
- Flashing right hook warning – standalone signal head with white curved arrow across a white elephant's feet crossing with a wide red exclamation point that flashes 0.5s on / 0.5s off. The graphic described is often used in static signs; Amsterdam has a few intersections where it's a flashing warning.
- Exclusive bicycle phases – Not really done (they prefer concurrent). However, like cities in Netherlands that use exclusive bike phases, their policy is that bicycle phases at right angles to each other are not treated as conflicting and are therefore allowed to run simultaneously when there are no vehicular conflicts. Shark's teeth regulate the bike-bike conflict; bikes turning left make diagonal movements, much like pedestrians during an exclusive pedestrian phase

Both:

- Flashing yellow crossing warning
  - As needed, they have a flashing yellow ball to warn permitted left-turning vehicles of conflicts with crossing pedestrians/bicyclist. The ball is mounted on far left (where conflict happens) and is angled diagonally facing a left-turning car about halfway through its turn. The flash is 0.5 s on/ 0.5 s off.
- **Bicycle and pedestrian overlap with left-turn phase – left-turns are lagging; if a left-turn phase comes up in one direction (say, EB) while the opposing approach (WB) has no left turn demand, the cross street's bicycle phase (NB) and neighboring pedestrian phase will begin.**

Interviewee: Patrick Baxter and Cara Seiderman, City of Cambridge

What treatments do you use (or plan to use) to improve safety and mobility for non-motorized users?

Pedestrian:

- The City uses LPI at a majority of their 134 signalized intersections, usually with a 3 s leading interval, occasional 5 s where there's a long crosswalk.
- They are planning to replace the LPI they now use at one intersection (Mass Ave / Prospect / Western) with an LTI, which they know of by names Super LPI and LPI+. They learned the idea from Charlotte. Instead of 3 s LPI, there will be a 15 s LTI on three of the legs, all of which have right-turn lanes. The 4th leg has low right turn demand. They say it will improve things for thru traffic (no LPI lost time). For right-turn traffic, it will hardly make a difference because the right-turn is usually blocked by crossing peds for about 15 s anyway. During permitted period, there will be a flashing yellow right-turn arrow, like NYC and Charlotte.
- Instead of stopping FDW with start of yellow, they let FDW continue until the end of yellow (yellow usually lasts 3 s). The next 3s of buffer (2 during red clearance and 1 during the next phase's LPI) become additional clearance time.
- They prefer to countdown from the start of WALK, since their signals are pretimed. Sometimes, due to transit priority, the countdown timer will suddenly jump, say, from 31 to 13, with "13" being the start of pedestrian clearance. New signals don't allow that option; they count down only during FDW.
- They prefer pretimed control to coordinated-actuated or fully actuated control because it makes the phase length predictable, which then allows them to make the WALK as long as possible. With pretimed, the ped phases are on recall.
- They have a few fully actuated signals, where cross street has little traffic, and there is also little pedestrian demand
- They maximize their WALK intervals using the formula WALK interval length = (green + yellow – pedClearance). This is not an output in synchro, nor can they get this effect using "rest in walk", so they calculate it and set it for each period.
- They prefer concurrent crossings to exclusive pedestrian phases. They have exclusive phases at only a few intersections, such as Mass Ave @ Alewife Brook Parkway, where two four-lane roads meet with high turning volumes. At those, they'll let the phases (including the pedestrian phase) all be actuated. They have a new two-way cycle track along Ames Street, and where it passes through a four-leg signalized intersection at Broadway, it will have an exclusive phase (not concurrent with vehicles), concurrent with parallel pedestrians only.
- They have three HAWK signals. They've found that it doesn't work well where pedestrian volume is high (e.g. Binney & 6th). Pedestrians see a crosswalk and no real traffic signal and just cross

whether they have a WALK or not. They're going to replace it with a full signal, actuated. Where pedestrian volume is lower, crossing Memorial Drive near Longfellow, it works ok. They're just installing one now to cross Main Street.

Bicyclists:

- The City has one corridor, Western Ave., with a cycle track and bike signals that use a 7 s LPBI (leading ped and bike interval).
- They consider bike boxes important for bicyclists at intersections. For two-stage lefts, they have some jughandles and auxiliary lanes.
- They have a diagonal crossing for the Linear Path where it crosses Mass Ave. Previously, bicyclists were expected to use crosswalks in a two-stage crossing. At this location, they are experimenting with four-inch, near side bike signals.
- At Ames (which has a two-way cycle track on one leg and is an off-road path on the other leg) and Broadway, there is a bike phase that's concurrent with a non-conflicting left turn.

Both:

- They use No Right Turn on Red at 90% of signalized intersection approaches. It makes LPI work better. At three or four intersections now, they have posted "Except Bikes" as a sub-plaque to NTOR and plan to add more. At most intersections, bikes ignore NTOR restrictions anyway, but where they complain, or where intersection geometry makes it harder to ignore (e.g., when the stop line is set back a long distance), adding the sign is valuable.
- Concurrent yet protected
  - They have applied this recently at three intersections: Mass Ave & Vassar (10/18), Broadway & Hampshire (2017), and Broadway & Galileo (2017). The latter was a "night and day" improvement for pedestrians and bicyclists because it was such a wide intersection. In all cases, the phasing has no unusual overlaps: right-turn runs strictly with parallel left-turn, bicyclists and pedestrians run with thru traffic. Bicycle signals aren't necessary because bikes go with thru cars, although at Mass Av & Vassar they use bike signals.
  - Full protection at a cost of about $20,000. They didn't widen any roads – they found space for right turn lanes either by converting a thru lane to a right-turn lane or by removing some parking.

What are common barriers to implementing treatments for non-motorized users at signals?

- Bike riders in Cambridge have learned the LPI system and routinely start to go when the WALK begins, even though the signal is still red. The City is interested in making this a legal movement, however, they aren't sure how to do it (FHWA interim rules on bike signals wouldn't let them do it with bike signals).

- They need to have pushbuttons to have audible WALK signals. To inform pedestrians that they don't need to push the button to get a WALK, they created a sign "Push Button for Audible WALK". Unfortunately, the standard (MUTCD) sign about how to use the crossing still says, "Push button to cross."

What local guidance or common practice exists (if any) for non-motorized users? Is it documented?

- Their standard cycle lengths are 90 s peak, 75 s off-peak. One intersection, with light traffic, has a 45 s cycle (Harvard & Inman).
- They insist on protected left-turns (if space is available) where the left turn conflicts with a bicycle lane or cycle track. Otherwise, no general policy on protected left turns.

What MOE's do you focus on for evaluating and selecting treatments?

- For at least 20 years, Cambridge has required that traffic impact studies done by developers estimate pedestrian delay at signals. They also require, regarding bike impact, estimates of additional turning volumes. Engineers who do the studies calculate pedestrian delay manually, using the HCM formula. Because they have almost no intersections with two-stage crossings, the challenge of calculating multistage crossing delay has not come up.

Interviewee: Nathan Conrad, City of Charlotte

What treatments do you use (or plan to use) to improve safety and mobility for non-motorized users?

Pedestrians:

- **LPI+ (the local name for Leading Through Interval)**
  - **Where there's a right turn-lane, the City installs a dedicated signal with a standard 4-head set including a flashing yellow arrow. When pedestrian phase is activated, the right-turn signal stays red while the pedestrian phase and through traffic phase begin. They hold the right turn between 10s up to the entire walk + clearance time; where the latter is done, it completely separates the pedestrian and right-turn phase**
  - **When there is a single-left turn with a permitted turn (flashing left-turn arrow), the left-turn phase is held red just like the right-turn**
  - **They are starting to retrofit existing signals with LPI Plus. They can fund 5 to 6 intersections a year and currently have 20 to 25 implemented or planned**
- **Where they don't have a right-turn lane, they use LPIs to hold all traffic for 3 to 5s,**
  - **Near schools/universities they've gone up to 10s**
- **They use a right-turn yield to pedestrian blank out sign**
  - **Nathan will send video**
  - **City would be open to research team doing a before and after study on an upcoming LPI+ implementation**
- **Pedestrian signals countdown from flash don't walk. They used to countdown from walk but had to phase it out a few years ago as the new signal equipment didn't support it.**
- Pedestrian timings extend walk to use all green time
- **Actuated vs Recall – if crossing distance on side street is short, typically have not installed put push buttons and put the phase on recall, now installing APS push buttons everywhere for ADA compliance**

Bicyclists:

- **One intersection in the city has bicycle signals and have planned to add 5 to 10 more**
  - **Bicycle phase at existing intersection runs concurrently with a non-conflicting right-turning movement only**
  - **Current and planned applications have high volumes of traffic and they are running the bicycle signal fully protected**

    - **Where there are not bicycle signals, bicyclists use the pedestrian signals and can judge based on the countdown**

How do you assess and select alternatives at signalized intersections to integrate and/or promote non-motorized users?

- **Most MOEs are focused on vehicle operations**
- **Planning division uses BLOS and PLOS at intersections for larger area studies, this is not currently required in traffic studies, but they are looking to revise the TIA process**

What are common barriers to implementing treatments for non-motorized users at signals?

- Sufficient ROW at intersection (e.g. to add compliant ramps)
- Funding, resources and staff to implement treatments

What local guidance or common practice exists (if any) for non-motorized users? Is it documented?

- Whenever they add a signal, they make a strong effort to install pedestrian signals
- Any new pedestrian signals are installed with APS pedestrian push buttons for PROWAG/ADA compliance, and they are retrofitting some existing signals with APS
- Rarely use cycle lengths greater than 150s
    - They do not have the storage lengths for turning vehicles with higher cycle lengths and want to minimize delays for the side streets
    - In CBD, they use 90s during peak and 80s during off-peak, typically pretimed with detection for left-turn movements
- **One pilot study measured compliance of right-turns during the LPI, have not looked at crash comparison**
    - **Compliance study is not published, Nathan will provide a copy if available**
    - **Generally, have found compliance to be good**

What information would you need before deciding to implement a new treatment?

- **Look for more detailed implementation, not likely to implement based on a single, specific applications**

Interviewee: Jean Hamaoui, City of Montreal

What treatments do you use (or plan to use) to improve safety and mobility for non-motorized users?

- **LTIs and LPIs are usually 7 to 9 s, usually equal to the WALK interval**
  - **It can be increased in increments of 2s**
  - **In some places, they are extending the WALK interval as long as possible to fit within the concurrent vehicular phase, in which case WALK goes longer than LTI/LPI**
- **If there's leading green for all approaches, it becomes better to have an all-ped phase. Otherwise, you get situations where nobody moves (e.g. one-way street where car in right-lane is turning right, car in left-lane is turning left)**
- Where two one-ways meet, the City is moving toward separating the pedestrian phases, so that the pedestrian signal across the entry legs can run concurrently as well as during all-ped

What local guidance or common practice exists (if any) for non-motorized users? Is it documented?

- **The City is revamping their written criteria. There may be new criteria within a year.**
- "Protected phase for pedestrians." Normally 7 s, can increase it in 2 s intervals. The City will provide a copy of guidelines (in French). It's the City's complement to MUTCD.
- Where possible, they prohibit left turns across the cycle track. Otherwise they have protected left-turns and the left lane will have to be a left-turn lane. They can remove parking in places to get a third lane. In the current regime (permitted lefts after LTI) it's hard for motorists to find a gap between bikes and peds – by the time you've checked your blind spot, it's too late.

What MOE's do you focus on for evaluating and selecting treatments?

- **Use LPIs over LTIs when there's sufficient excess capacity and where turning proportion is high**
- **LTI compliance isn't perfect, so LPI provides better protection**

What new or innovative treatments have you started implementing recently and/or at a smaller scale?

- Trial going on now where two one-ways cross, St Catherine & Robert Bourassa, to have all pedestrian between both phases. Part of the problem was that the corners didn't have space for all the queuing pedestrians! The cycle downtown is going to 80 to 90 s. Fifteen years ago all was 70 s, but they couldn't meet pedestrian requirements after they dropped pedestrian speed from 1.2 m/s to 1.1 m/s, now dropping to 1.0 m/s.
- On Blvd. de Maisonneuve they are reviewing all the signals. They will continue to use LTI when there aren't too many pedestrians. They are moving in the direction of separate phases: pedestrian, thru /right, cross street.

Interviewee: Paul Zebell, City of Portland

What treatments do you use (or plan to use) to improve safety and mobility for non-motorized users?

Pedestrians:

- Pedestrians are generally on recall unless they need to actuate because of volume on the arterial. In some places, pedestrians are only actuated during a short portion of the peak.
- In some cases, it's better for pedestrians to shorten the pedestrian time to allow for turning vehicles and allow time when right-turns are not permitted across the pedestrian movement
- Usually rest in walk on the coordinated phase. There are some cases where this isn't the best for pedestrians. Need to use judgement to limit phase when there are a lot of turn conflicts.
- **The City has very few multi-stage crossings. They use internal logic on controller to progress pedestrians based on location the call was placed.**
- Some intersections have so many overlaps, the pedestrians are served multiple times in the same cycle, even though it's not a different phase.

Bicyclists:

- **In Portland, the yellow/red clearance is based on vehicle approach speed, grade, and stopping distance. Sometime red and minimum green is changed for bicyclists.**
  - **Where there's difficult geometry the minimum green would be extended. For left-turns Portland often has 3 s minimum green.**
- **Detection is usually set to short gaps for vehicles**
- **The City uses parallelogram bicycle loops, small quadra pole with inductive loops for bikes about 50 feet for the call and at the stop bar. The Advanced loops has 5 or 6 seconds of carry over time.**
  - **They use microwave in a couple locations.**
  - **They've had little success with Sensys detection**
- **Portland uses blue lights to show when a bicycle is detected**
- **The City gives relative length of time to wait, not an absolute number of seconds because other phases are actuated.**

Both:

- **Portland is using the HAWK for bicyclists to cross an arterial without increasing traffic on the bicycle route. Started this when MUTCD forbade half signals**

    - **Concerned that dark signal means go, can't have conflict monitoring when off means go to the driver**

    - **Portland only did the flashing red interval for the last few seconds, in case another pedestrian is approaching the HAWK after it's been activated, they may assume they can run across during FDW, but vehicles are already allowed to proceed**

How do you assess and select alternatives at signalized intersections to integrate and/or promote non-motorized users?

- The City of Portland has a systematic approach to add bicycle facilities and improvements, it is not driven by requests
- They are investing in ramps and ADA accessibility and sidewalks in underserved areas, equity is a big component to sidewalk spending
- **The City has a hierarchy that need to be met. Vision Zero, safety, is the highest, followed by bicycle mode shift.**

What are common barriers to implementing treatments for non-motorized users at signals?

- **Political push back, complaints from motorists and the trucking community**
    - **A trucking priority project has improved conditions for non-motorized users and freight**
    - **Need to communicate it's no a zero-sum gain, if you improve one mode you're not automatically disbenefiting others**

What local guidance or common practice exists (if any) for non-motorized users? Is it documented?

- **The City's policy is that pedestrians be able to cross at every corner**
- **When the City started using LPIs it was usually based on crashes or public demand. They are working on a policy of when to put them in.**

What MOE's do you focus on for evaluating and selecting treatments?

- **Vehicles LOS is not as useful to promote non-motorized modes. They use person delay and VMT.**

What is your willingness to test treatments you have not seen before? What information would you need before deciding to implement a new treatment?

- Portland is always looking at new treatments/policies, often as a result of a problem (e.g. crash problem)
- Want to be ahead of the curve – always testing new detection

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Task 3 – Toolbox Vision

Kittelson & Associates, Inc.

In association with:

Northeastern University

Institute of Transportation Engineers

Accessible Design for the Blind

January 28, 2019

SECTION 1.0 – INTRODUCTION

The purpose of this memorandum is to present the initial vision for the toolbox potential delivery methods as well as the toolbox content. First, in **Section 2,** various toolbox delivery options (e.g., website, PDF, etc.) was discussed and toolbox delivery examples are provided for each delivery option. **Section 3** introduces toolbox guiding principles for this project and discusses our team's recommendation for the toolbox delivery method. Finally, **Section 4**, presents the vision for planned organization and content based on the recommended toolbox delivery method. In addition, the team provides a mock-up treatment example to the Panel, using the Leading Pedestrian Interval (LPI) in **Section 4**. LPI was selected as an example because it is frequently used in the industry with more documented findings in the literature than are available for some other treatments. These other treatments will require more research during the Phase II of this project.

SECTION 2.0 TOOLBOX DELIVERY OPTIONS

A main resource used to consider toolbox delivery options and visioning is current toolboxes and collections of treatments available to the transportation field. A review of other toolboxes and treatment lists was completed during this task. The goal of this review was to help identify aspects that have worked in other similar deliverables and key elements to consider (and avoid) to deliver a successful toolbox that will be easy to use to follow by practitioners and can be applied into their practice. A high-level list of desired characteristics was formed from the toolbox visioning and review activities. This includes a desire for an accessible format that is both user friendly and easily searchable. Ideally, the toolbox should also be no (low) cost and easily updatable as continued work and research are completed in this topic area.

Through the review of other toolboxes and collections of treatments, a set of potential delivery types were considered for this document. The main delivery forms include the following:

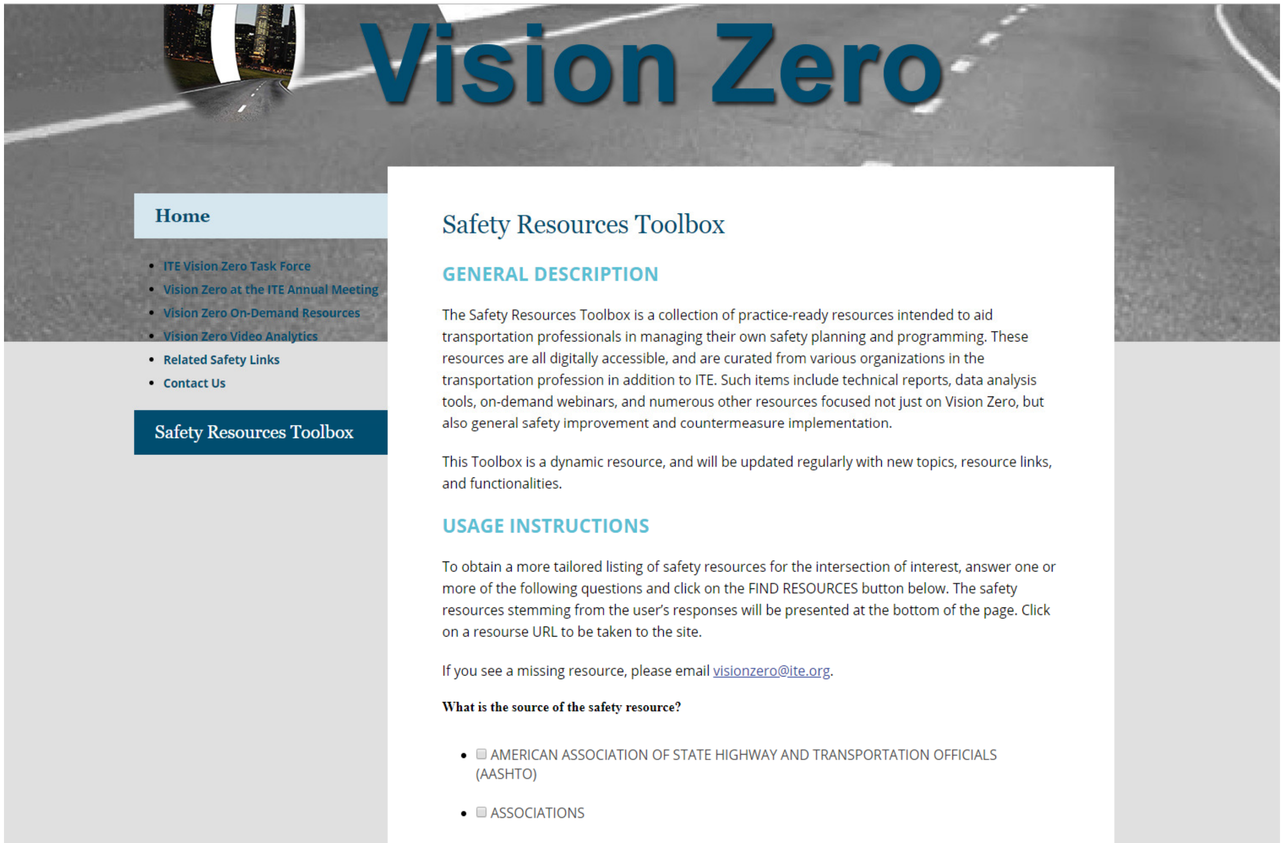
- A website, ideally hosted by an entity such as ITE or FHWA,
- A webpage on an already hosted website, or
- A PDF that can be made available online or for print.

Table 1 outlines the seven (7) toolbox delivery options that were considered and provides an example of each.

Table 1 Toolbox Delivery Options

<table>
<tr><th>Toolbox Delivery Option</th><th>Example Interface</th></tr>
<tr><td>Interactive Website

Option 1 – Free

Option 2 – Subscription-based</td><td>ITE Vision Zero Safety Resources Toolbox


http://toolkits.ite.org/visionzero/toolbox/default2.aspx</td></tr>
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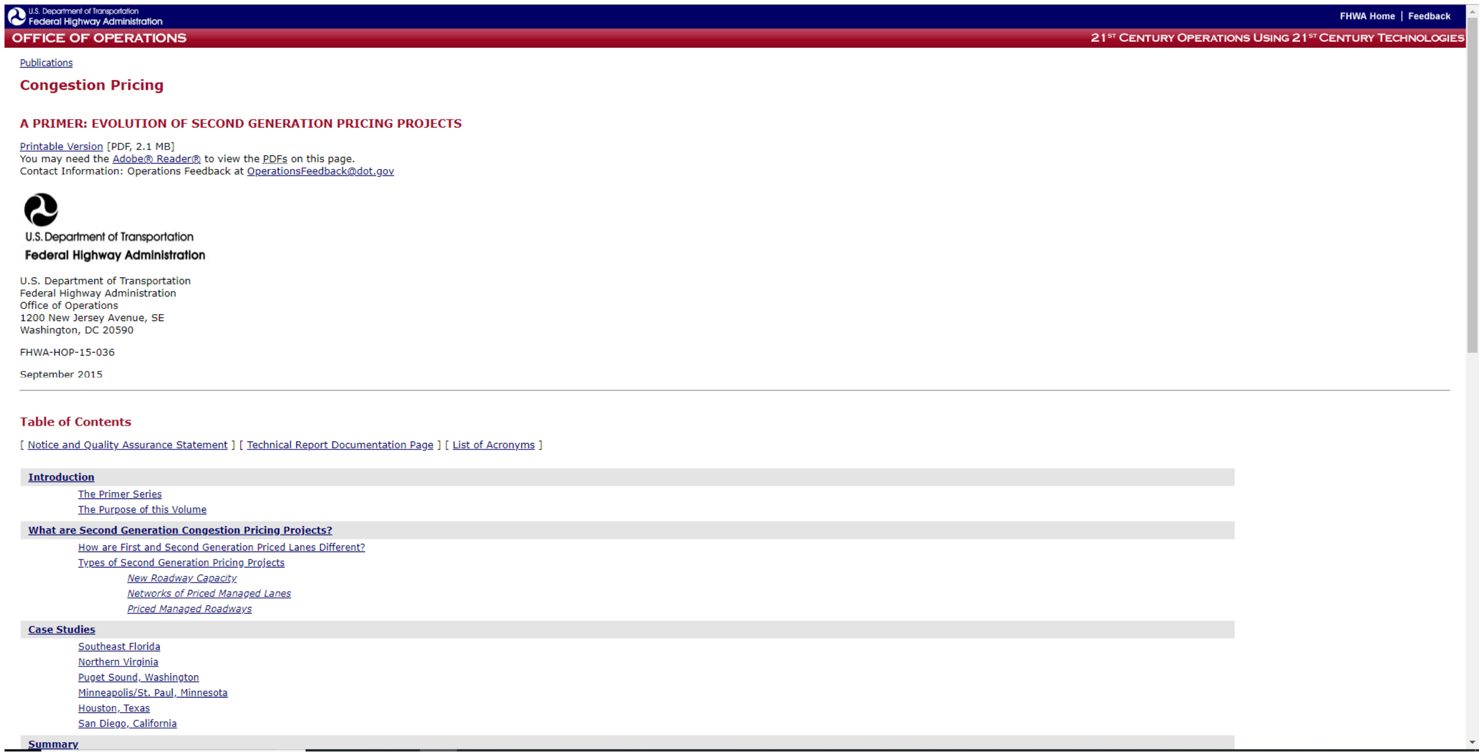
Option 3 - Free Interactive Webpage

FHWA Congestion Pricing: A Primer


U.S. Department of Transportation
Federal Highway Administration
FHWA Home | Feedback
OFFICE OF OPERATIONS
21ST CENTURY OPERATIONS USING 21ST CENTURY TECHNOLOGIES

Publications

Congestion Pricing

A PRIMER: EVOLUTION OF SECOND GENERATION PRICING PROJECTS

Printable Version [PDF, 2.1 MB]
You may need the Adobe® Reader® to view the PDFs on this page.
Contact Information: Operations Feedback at OperationsFeedback@dot.gov

U.S. Department of Transportation
Federal Highway Administration

U.S. Department of Transportation
Federal Highway Administration
Office of Operations
1200 New Jersey Avenue, SE
Washington, DC 20590

FHWA-HOP-15-036

September 2015

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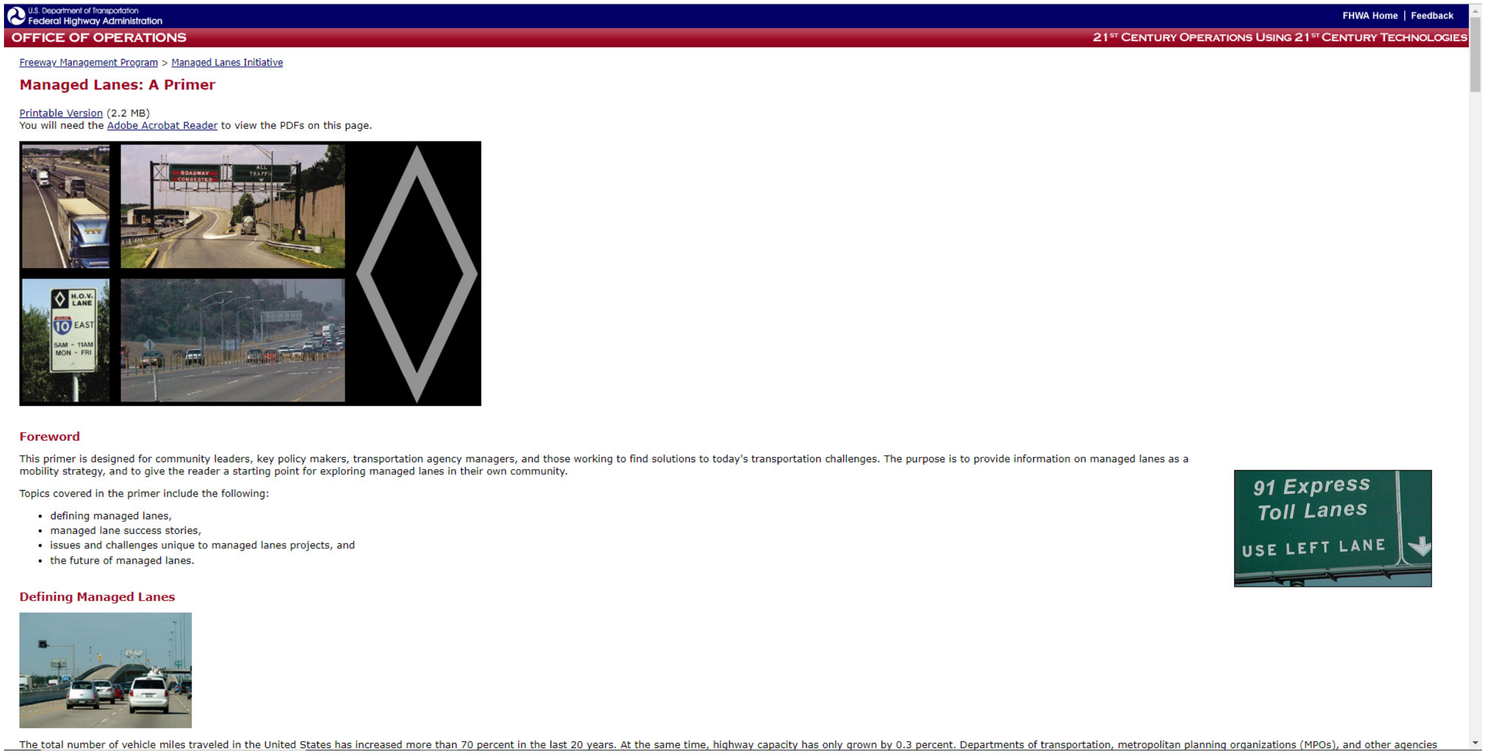
Summary

https://ops.fhwa.dot.gov/publications/fhwahop15036/index.htm

Option 4 - Free Webpage with Links and References

FHWA Managed Lanes: A Primer


U.S. Department of Transportation Federal Highway Administration

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OFFICE OF OPERATIONS

21ST CENTURY OPERATIONS USING 21ST CENTURY TECHNOLOGIES

Freeway Management Program > Managed Lanes Initiative

Managed Lanes: A Primer

Printable Version (2.2 MB)
You will need the Adobe Acrobat Reader to view the PDFs on this page.

Foreword

This primer is designed for community leaders, key policy makers, transportation agency managers, and those working to find solutions to today's transportation challenges. The purpose is to provide information on managed lanes as a mobility strategy, and to give the reader a starting point for exploring managed lanes in their own community.

Topics covered in the primer include the following:

- defining managed lanes,
- managed lane success stories,
- issues and challenges unique to managed lanes projects, and
- the future of managed lanes.

91 Express Toll Lanes USE LEFT LANE

Defining Managed Lanes

The total number of vehicle miles traveled in the United States has increased more than 70 percent in the last 20 years. At the same time, highway capacity has only grown by 0.3 percent. Departments of transportation, metropolitan planning organizations (MPOs), and other agencies

https://ops.fhwa.dot.gov/publications/managelanes_primer/

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PDF

Option 5 – Purchase

Option 6 - Free

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Washington County Bicycle Design Guide

https://www.co.washington.or.us/LUT/Divisions/CPM/upload/WaCo_Toolkit_Dec2012.pdf

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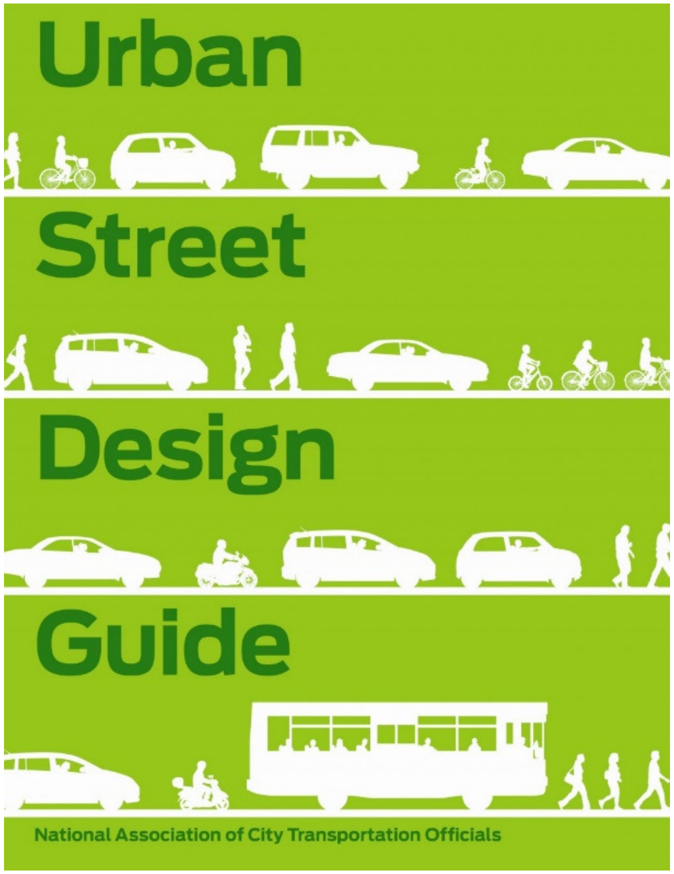
Option 7 – Print for Purchase	***NACTO Urban Street Design Guide*** 

Within each of the forms that a toolbox might take (website, webpage, PDF, print), there are different characteristics that can impact its usability, costs, and maintenance. For each potential delivery option, the following characteristics were considered for the decision-making process and our recommendation for the toolbox delivery:

- **Accessibility/purchasing**
  - How easy it is to access this toolbox? Will users need to pay for access?
- **User experience**
  - How does a user get to the toolbox? Is it an interactive website? Is there a link that connects to the toolbox? Is it a static toolbox that needs to be hunted down in a document?
- **Information gathering**
  - How does a user search and use the toolbox? Is it available electronically and can be searched via computer? Is there a user guide that helps point a user in the right direction?
- **Production costs**
  - Are there additional production costs besides content creation? Will the toolbox be accessed in a new website or webpage that needs to be developed? If it is a website, will it be an interactive or a static website?
- **Maintenance costs**
  - What costs are associated with maintaining access to the toolbox? Are website or webpage update necessary to keep content up-to-date and provide up-to-date links? Will the toolbox require frequent maintenance?
- **Long-term costs**
  - What costs are associated with the long-term sustainability of the toolbox? Does an entity need to host a website where the information is kept? Does an entity need to handle housing, printing, and distribution of the document?
- **Updates**
  - What is the long-term vision of the toolbox? Can it be updated periodically or is it a static document that will have complete overhauls and new versions take its place?

Table 2**Error! Reference source not found.** provides an assessment of the characteristics of the seven (7) potential toolbox delivery option discussed above. Boxes highlighted in green color show positive aspects of that delivery option while red color indicates characteristics that may provide challenges. Additional considerations for each delivery option are provided in the last column.

Table 2 Toolbox Delivery Options – Characteristics

Toolbox Delivery Option	Accessibility/ purchasing	User Experience	Information Gathering	Production Costs	Maintenance Costs	Long-term Costs	Updates	Pros	Cons	Other Considerations
1 – Free Interactive Website	Free	Interactive	Searchable	Content creation and website development	Website updates	Hosting of website	Static	- Widely accessible - User-friendly - Searchable	- Costs for hosting - Site development - Outdated	- Who pays for hosting? - How often can the website reasonably be updated?
2 – Subscription - based Interactive Website	For purchase through subscription	Interactive	Searchable	Content creation and website development	Website updates	Hosting of website	Ongoing (through subscription)	- Offset costs with fees - User-friendly - Update opportunities - Searchable	- Reduced access - Cost structures - Site development - Higher expectations	- Subscription can help with hosting, maintenance, and update costs - Who is in charge of payment system and hosting?
3 – Free Interactive Webpage	Free	Interactive	Searchable	Content creation	Webpage updates	None	Static	- Widely accessible - User-friendly - Lower production and long-term costs - Searchable	- Costs for hosting - Page development - Links within another website (potentially harder to find) - Outdated	- Who pays for hosting? - How often can the webpage reasonably be updated?
4 – Free Webpage	Free	Links/ references	Searchable	Content creation	Webpage updates	None	Static	- Widely accessible - Lower production and long-term costs - Searchable	- Costs for hosting - Page development - Links within another website (potentially harder to find) - Outdated	- Who pays for hosting? - How often can the webpage reasonably be updated?
5 – PDF for Purchase	For purchase	Links/ references	Searchable and user guide	Content creation	None	None	Static	- Offset costs with fees - Lower costs - Searchable	- Less accessible - Outdated - Need a payment system and an entity to support it	- Who is in charge of the payment system? - Fees pays for housing and distribution of PDF
6 – PDF for Free	Free	Links/ references	Searchable and user guide	Content creation	None	None	Static	- Lower costs - Searchable	- Less accessible - Outdated - Need an entity to support distribution	- Who houses and distributes the PDF?
7 – Print for Purchase	For purchase	Static	User guide	Content creation	None	Printing/ distribution	Static	- Offset costs with fees - Lower production and maintenance costs	- Least accessible - Outdated - Need an entity to support distribution - Search document is more difficult	- Who houses, prints, and distributes the document? - Fees pay for housing, printing, and distribution

SECTION 3.0: TOOLBOX DELIVERY OPTION RECOMMENDATION:

The guiding principles for the toolbox delivery methods are shown in Figure 1. As a resource that can better inform and improve facilities from planning through design and implementation, this document is envisioned as a free resource for all. As a free resource, the cost of hosting and maintaining a website or webpage is a major concern. By providing the document through an online forum, it can be reached by more potential users while creating a minimum continual cost as a PDF. In addition, the research team believes that by keeping the production, maintenance, and long-term costs minimal, the project resources will be utilized more effectively for the actual toolbox content development through additional research and thorough synthesis rather than spending resources on the website development. This will eliminate the risk for developing a toolbox that has limited information and guidance for practitioners. **Therefore**, **it is suggested that the document take the form of a PDF that is available online**.

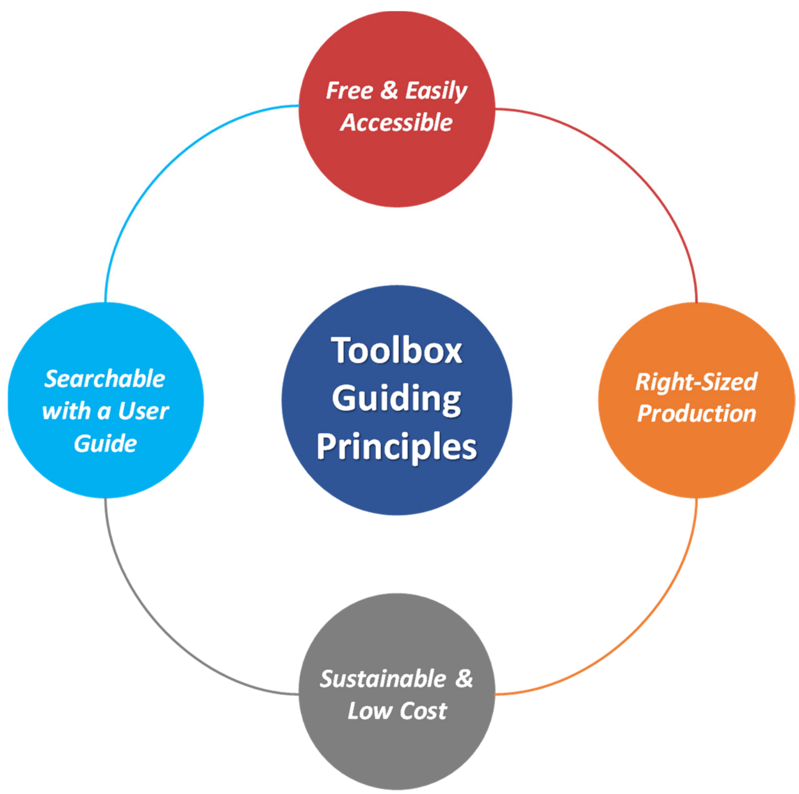


Figure 1 Guiding Principles for the Toolbox Delivery Methods

With a clear structure and “how to use” section upfront, a PDF document will be able to provide users a path forward when considering potential treatments. For users that create high-level policies and funding decisions, the overview and toolbox will provide clarity and guiding information. For engineers and planners that are prioritizing and selecting treatments, the toolbox and appendices will provide targeted information that will inform a preferred treatment selection. For technicians and those implementing treatments, the toolbox and appendices will provide details, guidance materials, and references to establish proper installation and maintenance of selected treatments.

SECTION 4.0 – TOOLBOX VISION AND FRAMEWORK

This section presents a vision and strategy framework for practitioners to effectively integrate an outcome-based process to address non-motorized user needs at signalized intersections. The next section details this framework and provides an annotated outline for the overall product, describing the envisioned organization, planned section content, and the anticipated length for each chapter.

Section 4.1 – Toolbox Organization

This section presents the envisioned organization for the developed toolbox. The toolbox organization uses the term "chapter" to describe how the team envisions content to be broken up in the final guidebook. Anticipated count pages are provided as well for each chapter. This is based on the assumption that the final toolbox will be a PDF document and follow a more traditional guidebook. If the decision on the final format for the toolbox is a website, these sections can become pages on a website.

1. **Chapter 1: Introduction (2-3 pages)**
   Chapter 1 will provide an introduction and overview for the toolbox, describing non-motorized challenges at signalized intersections and outlining the developed content.
   a. Non-Motorized Problems/Challenges at Signalized Intersections
   b. Guidebook Contents
2. **Chapter 2: How to Use the Toolbox (3-4 pages)**
   Chapter 2 will discuss how the research team envisions practitioners to use the toolbox. Additional guidance will be provided on how to navigate/use the toolbox.
   a. For details about pedestrian and bicycle treatments, refer to Section 3.
   b. For descriptions of specific treatments including their applications and documented effects, refer to Section 4.
   c. For system level policies and programs supporting enhanced pedestrian and bicycle operations and safety, refer to Section 5.
3. **Chapter 3: Treatment Types (3-4 pages)**
   Chapter 3 will introduce various international and national treatment types applied for non-motorized users. We will also present categories for each treatment type based on the problems the treatments are addressing. It should be noted that this section will provide an overall summary where the details of each treatment types will be discussed in the next Chapter.
   a. National and international treatment types for non-motorized users by the following category
      i. Treatments improving non-motorized crossing experience
      ii. Treatments reducing pedestrian delay
      iii. Treatments reducing potential conflicts with parallel traffic turns
      iv. Treatments eliminating potential conflicts with parallel traffic turns
      v. Special signal phasing techniques favoring non-motorized traffic
      vi. Bicycle phases and special bicycle needs

4. **Chapter 4: Toolbox (60-70 pages)**
   Chapter 4 will include the toolbox that describes treatments, their applications, as well as documented and expected operational and safety effects. Each toolbox entry is envisioned to be between one to four pages (depending on the content), following the same format, ideally fitting the essential, decision-making information on a double-sided sheet of paper. Examples will be provided from agency case studies and additional research performed during this project. It should be noted that this Chapter will provide only key findings based on the literature review, agency engagements, and additional research that will be performed during the Phase II of the project. The details of each treatment will be included in the Appendix Sections, which will allow us to follow a similar format and content length for each treatment, regardless of their level of maturity.
   a. Core Treatment Attributes
      i. Treatment name
      ii. Other or alternative names
      iii. Description (includes equipment components, phasing diagrams, geometrics, and supporting systems)
      iv. Variations and relationship to Relevant Treatments
      v. Problems addressed
      vi. Operational detail and other considerations
      vii. Context and operating environment
      viii. Documented impacts (where there is no documentation available, expected impacts on motorized and non-motorized users will be presented)
   b. Supporting Treatment Information
      i. Application Examples
      ii. Guidance
      iii. Other considerations
      iv. References
5. **Chapter 5: Guide to Implementing Pedestrian- and Bike-Friendly Traffic Signal Practices (8-10 pages)**
   Chapter 5 will offer a roadmap for an agency to make their traffic signals pedestrian- and bicycle-friendly. It will suggest policies agencies should consider adopting and actions agencies should consider taking, accounting for different contexts and size. These policies and actions will refer the reader to applicable treatments described earlier in this manual. Examples will be provided to illustrate the process.
   a. **Agency context**
      Important differences in context will be described so that readers will understand when this section is (and isn't) recommending policies and actions intended for their context.
   b. **Policies and practice regarding non-motorized crossing experience**
   c. **Policies and practice regarding non-motorized delay targets and estimation**
   d. **Policies and practice for reducing non-motorized delay.**
   e. **Policies and practice for reducing potential conflicts with parallel traffic turns**
   f. **Policies and practice for eliminating potential conflicts with parallel traffic turns**
   g. **Policies and practice regarding bicycle phases and special bicycle needs**

6. **Chapter 6: Future Research Opportunities and Recommended Guidance Document Updates (6-8 pages)**
   Chapter 56will describe issues recommended for future research and for consideration in other guidance documents. Related ongoing research efforts will be reviewed and their likely role in addressing any of these issues will be integrated into this chapter.
   a. **Ongoing and anticipated related research efforts**
   b. **Known gaps and future research opportunities**
      This document will outline areas of research that continue to be gaps for this topic and that could be focused on in the future.
   c. **Future updates to guidance documents (application/integration with other guides)**
      Relevant guidance documents (e.g., AASHTO A Policy on Geometric Design of Highways and Streets, NCHRP Report 812: Traffic Signal Timing Manual, etc.) will be reviewed for potential language updates for future versions based on this document.

Appendix A: Literature Review
A summary of the completed literature review will be available, including references and links to sources that users may access for further information.

Appendix B: Agency Engagement
A summary of the agency engagement activities, including agency interviews and the results of the agency survey, will be provided.

Appendix C: Research Conducted during this Project
A summary of the conducted additional research during the Phase II of this project including field studies (e.g., before and after field studies) and developed simulation models to assess and document safety and operational benefits for selected treatments.

Appendix D: Case Studies
A summary of the case studies with agencies through supplemental interviews that was performed during the Phase II of this project to collect additional, readily available data, to evaluate various treatments.

It should be noted that the Toolbox will be a separate document than the final report. Recent NCHRP publications have not included project-related appendices and only included them as part of the final report. This is an option for further discussion with the Panel.

Section 4.2 – Leading Pedestrian Interval (LPI) Mockup Example

This section provides an example treatment for the toolbox following the outline content and structure described in Section 4.1 of the Annotated Outline discussed above. As previously noted, LPI was selected as the mockup example due to its high level of maturity and broad implementation both in the U.S. and abroad.

Treatment or Policy Name:

Leading Pedestrian Interval (LPI)

Other or Alternative Names:

Pedestrian Head Start, Leading Hold

Description:

In a concurrent pedestrian signal phasing scheme, a leading pedestrian interval (LPI) is when a walk signal indication is shown to pedestrians a few seconds earlier than a green signal being shown to the adjacent parallel vehicular movement. The duration between start of the walk signal indication and start of the vehicular green indication is called an LPI. Figure 2, using a simplified ring diagram, shows how concurrent pedestrian and vehicular phases are aligned in an LPI setting *(1)*. Figure 3 is also a schematic illustration of an LPI *(1)*.

Duration of an LPI is usually set to 3 to 7 seconds. In fact, in order for an LPI to serve its purpose it should be at least 3 seconds to allow pedestrians to cross at least one lane of traffic.

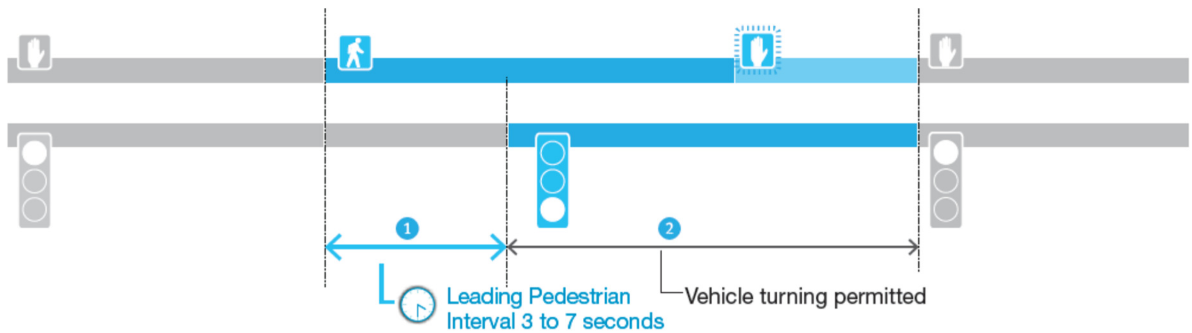
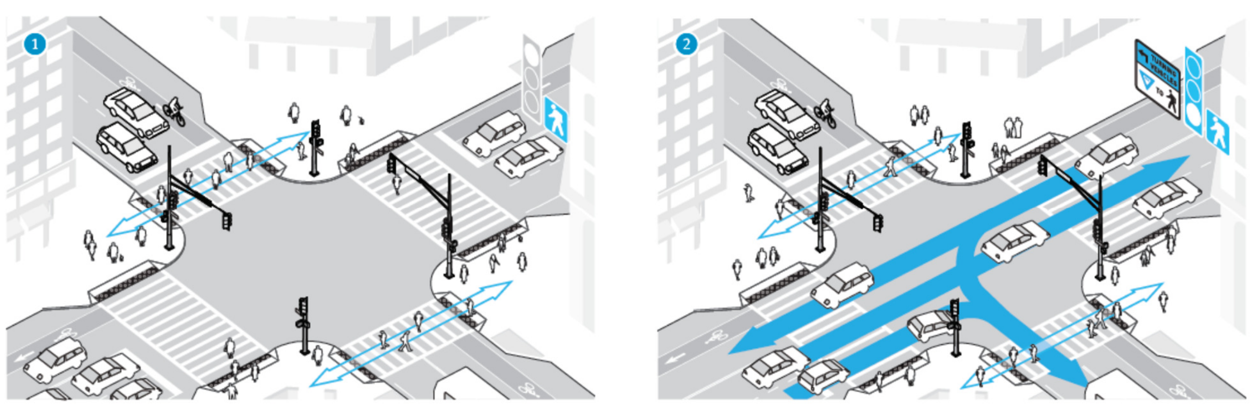


Figure 2 Pedestrian phase and its parallel vehicular phase during and after LPI *(1)*



(a) LPI **(b) Vehicle turning permitted**

Figure 3 Pedestrian and parallel vehicular movements involved in an LPI *(1)*

Variations/Relevant Treatments:

Some agencies that use LPIs at signalized intersections to mitigate conflicts are also interested and/or implemented Leading Through Interval (e.g., City of Toronto, Canada), also known as LPI Plus in Charlotte. Please refer to the Leading Through Interval (LTI) treatment for the detailed information.

Problems Addressed:

The main objective of an LPI is to reinforce the priority that pedestrians should have over right-turning vehicles on two-way streets (Figure 4a) and over left-turning vehicles as well on one-way streets (Figure 4b). This allows pedestrians to have a clear presence on the crosswalk by the time the concurrent vehicular phase gets the green display, making it clearer that right-turning vehicles are to yield to them. This, in turn, improves pedestrian crossing experience by making it less stressful and ultimately safer by reducing the number of conflicts between pedestrians and vehicles.

(a) Two-way street **(b) One-way street**

Figure 4 Phases involved in an LPI

Operational Details and Other Considerations:

LPI is typically used at signalized intersections with concurrent pedestrian phasing. In concurrent crossing context, right turns do not have a dedicated phase (i.e., they follow the green/red circular signal indications that govern through traffic). On one-way streets, this permitted type of turn also applies on the left side of the street if the leftmost travel lane is a left/through option lane.

With an LPI, a green signal indication is displayed to vehicular movements 2 and 6 in Figure 3 a few seconds later than when a WALK signal indication is shown to pedestrian movements. Length of the LPI is the delay between WALK signal indication and green signal indication. Agencies typically use three to seven seconds of an LPI at intersections.

Context and Operating Environment:

LPIs are generally implemented at signalized intersections where there is heavy pedestrian traffic along with high right-turning traffic (left turning vehicles as well on one-way traffic) *(1, 2, 3)*. In addition, as noted above, LPIs are typically applied at intersections where there is concurrent pedestrian phasing and a through and a shared right turn lane. LPI is also more suitable at locations with a large population of elderly or school children who tend to walk slower *(2, 3)*.

Documented Impacts:

Key documented impacts of LPI are summarized below:

- Considerable reduction in pedestrian-turning vehicle crashes *(4)*, ranging from 28 percent reduction *(5)* to approximately 60 percent reduction *(6)*.
- When the severity of crashes is considered, 64 percent reduction in pedestrian-turning vehicle crashes were reported *(5)*.
- A study conducted by New York City Department of Transportation (DOT) reported similar findings *(7)*; 13 percent decrease in turning vehicles vs. pedestrian and bicyclist injuries, and 62 percent decrease in turning vehicles vs. pedestrian and bicyclist killed or severely damaged at locations in NYC where LPIs were installed from 2003 to 2011.
- As a result of documented studies, FHWA currently assigns a Crash Modification Factor (CMF) of 0.413 for intersections with LPI to be used in the Highway Safety Manual (HSM) *(8)*.

// Note to the Panel: The documented impacts are summarized in a bullet format for the mockup example, however the research team plans to present this information in a more visual format in the final toolbox to make the material easy to follow and digest. //

Application Examples:

Table 3 presents a list of cities with moderate to high LPI implementation (more than 10 intersections) in the U.S. and abroad. It should be noted that the list provided below is not an exhaustive list, but rather provides key LPI application examples in different cities around the world.

Table 3 Application of LPI treatment in different cities around the world

City, State, Country	Application Level
New York, NY, USA	High (more than 1,000 intersections)
Cambridge, MA, USA	High
Montreal, Canada	High
Boston, MA, USA	Moderate
Toronto, Canada	Moderate
Chicago, IL, USA	Moderate
State College, PA, USA	Moderate
Washington, DC, USA	Moderate

// Note to the Panel: The above table will be replaced by a figure in the final toolbox to make the material visually appealing and easy to follow. //

Guidance:

Use of the LPI is fully consistent with the *Manual on Uniform Traffic Control Devices* (MUTCD). MUTCD, 2009 edition, considers the LPI as an option for situations where high pedestrian volumes and high conflicting turning vehicle volumes exist: *"…, a brief leading pedestrian interval, during which an advance WALKING PERSON (symbolizing WALK) indication is displayed for the crosswalk while red indications continue to be displayed to parallel through and/or turning traffic, may be used to reduce conflicts between pedestrians and turning vehicles." (9)*

City of Toronto has developed an LPI implementation and assessment guideline as an easy-to-use tool to help city staff identify suitable locations for LPI *(3)*. It also suggests a formula for the duration of LPI:

$$LPI = \frac{\left(\frac{TL}{2} + PL\right)}{WS} > 5\ s$$

in which, *LPI* is seconds between onset of the WALK signal for pedestrians and the green indicator for vehicles, TL is distance on crosswalk to clear the total width of all moving lanes between curb and centerline, not including the parking lane, *PL* is width of the parking lane that the pedestrians have to cross (if any) in ft, and *WS* is walking speed for older pedestrians. It has also been reported that an informal formula for the LPI duration that is used in NYC requires a minimum of 6 s or half the pedestrian clearance time *(10)*.

Newly-installed LPIs should provide accessible pedestrian signals to notify visually-impaired pedestrians of the LPI because otherwise, without an accessible pedestrian signal, visually-impaired pedestrians who rely on the sound of starting traffic to know when the green begins may miss LPI and begin to cross with the vehicular movement when motorists are less likely to yield to them.

Other Considerations:

Several studies indicated how preventing RTORs may be necessary to achieve the potential benefits of an LPI. In a study conducted by Hubbard et al. *(11),* it is reported that the benefits associated with an LPI reported in a downtown environment may not be fully transferable to crosswalks in suburban environment.

Another important consideration with an LPI is, as also discussed above, is its effect on pedestrians with disabilities. Existing research suggests that newly-installed LPIs should provide accessible pedestrian signals to notify visually-impaired pedestrians of the LPI so that visually-impaired pedestrians can start walking with the Walk display to get benefit from an LPI.

References:

1. City of Boston (2013). Boston Complete Streets Design Guidelines.
2. U.S. Department of Transportation, Federal Highway Administration (2001). Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians. p.35.
3. Saneinejad, S. and Lo, J. (2015). Leading Pedestrian Interval. Transportation Research Record: Journal of the Transportation Research Board, 2519, pp.85-94.
4. Houten, R., Retting, R., Farmer, C. and Houten, J. (2000). Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections. Transportation Research Record: Journal of the Transportation Research Board, 1734, pp.86-92.
5. King, M. (2000). Calming New York City Intersections. In: TRB Circular E-C019: Urban Street Symposium. Washington, D.C.: TRB, National Research Council.
6. Fayish, A. and Gross, F. (2010). Safety Effectiveness of Leading Pedestrian Intervals Evaluated by a Before–After Study with Comparison Groups. Transportation Research Record: Journal of the Transportation Research Board, 2198(1), pp.15-22.
7. New York City Department of Transportation (2016). Don't Cut Corners - Left Turn Pedestrian & Bicyclist Crash Study. New York.
8. Cmfclearinghouse.org (2018). CMF Clearinghouse >> CMF / CRF Details. [online] Available at: http://www.cmfclearinghouse.org [Accessed 29 Jun. 2018].
9. Manual on Uniform Traffic Control Devices. FHWA, U.S. Department of Transportation, 2009.
10. San Francisco Municipal Transportation Agency Pedestrian Program and University of California Traffic Safety Center (2008). San Francisco PedSafe Phase II - Final Implementation Report and Executive Summary.
11. Hubbard, S., Bullock, D. and Thai, J. (2008). Trial Implementation of a Leading Pedestrian Interval: Lessons Learned. ITE Journal, (October).

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Task 4 – Phase II Work Plan Memorandum

Kittelson & Associates, Inc.

In association with:

Northeastern University

Institute of Transportation Engineers

Accessible Design for the Blind

January 28, 2019

SECTION 1.0 – INTRODUCTION

The purpose of this memorandum is to present the proposed Phase II work plan. **Section 2** provides a gap assessment of treatments for non-motorized users at signalized intersections. The gap assessment takes into consideration the existing knowledge base gathered in Task 1 (Literature Review) and Task 2 (Agency Engagement). **Section 3** introduces a work plan development framework and prioritization of activities. The framework to prioritize Phase II activities highlights three distinct types of work plan categories ranging from documentation to original and additional research. **Section 4** provides details proposed activities, levels of effort for additional information synthesis, and proposed original research for the identified treatments. The overall work plan is based on balancing synthesizing existing practice and opportunities to expand common agency interests and needs.

SECTION 2.0 – GAP ASSESSMENT OF TREATMENTS

There is a broad set of treatments for non-motorized users that can be applied at signalized intersections to improve pedestrian and bicycle safety and service. The team's Phase I efforts identified these treatments through an extensive literature review and by conducting interviews with domestic and international agencies with a reputation for best practices. The team also used these interviews to get targeted feedback on strategies and implementation challenges. This section provides a gap assessment of treatments and discusses the process for the prioritization of the treatments for Phase II.

Section 2.1 – Identification and Categorization of Treatments for Better Serving Non-Motorized Users at Signalized Intersections

Thirty-four treatments were identified as methods of improving service to non-motorized users at signalized intersections. A few of them carry the double sense of a treatment and a policy. For example, having protected-only left turns so that crossing pedestrians and bikes don't face a conflict from left-turning vehicles is a well-known treatment; the tool that makes a difference in some cities is a policy that in certain contexts, left turns should be protected only.

These treatments were grouped into six categories. The categories and the treatments belonging to each are shown in Table 1.

Section 2.2 – Qualitative Assessment for Prioritization

Each treatment identified showed potential for improving either service or safety for non-motorized users. Because of the large number of treatments and limited project resources, there is a need to strategically prioritize and select treatments for the Phase II work plan. The prioritization will ensure that the resources will be used most effectively, and that the final toolbox will offer the greatest possible contribution toward meeting the needs of non-motorized users at signalized intersections.

For the prioritization of treatments, the following factors were considered in the assessment:

- **Guidance gaps:**
    - Whether there are guidance gaps in the state of practice related to each treatment. The assessment for guidance gaps was performed based on the obtained information through literature review (Task 1) and agency engagement (Task 2). While some treatments (e.g., Walk Countdown) have already been explored extensively and implemented frequently by agencies, some treatments (e.g., leading through interval, LTI) lack good information and agencies need guidance to implement these treatments.
- **Expressed agency need:**
    - This assessment indicates the degree to which U.S. agencies directly expressed interest in a treatment and / or expressed a need for guidance on how or when to apply it. This information was obtained based on agency interviews and feedback collected through the agency engagement task (Task 2).
    - Expressed agency need often coincided with (objective) guidance gaps, but there are also many cases in which they diverge. This is because certain treatments (e.g., adaptive walk intervals) may not be a particular interest for agencies, either because they are relatively unknown or because they involve significant implementation challenges.
- **Opportunity for improved safety/service:**
    - The degree to which, in the project team's opinion, the treatment provides opportunity for improved operations and safety for non-motorized users at signalized intersections. This assessment favors treatments that apply in common situations as opposed to those that apply in relatively rare, specialized situations. It also favors treatments that involve either a clear safety benefit or a significant reduction in pedestrian or bicycle delay or inconvenience.

Table 1 shows the team's qualitative assessment of each treatment with respect to the three factors listed above. In general, qualitative ratings for the factors are given "High" for larger perceived gaps or needs or opportunities.

Table 1: Treatments and their Qualitative Assessment for Prioritization for Phase II

	Treatment Name	Guidance Gaps	Expressed Agency Need	Opportunity for Improved Safety/Service
Improving Pedestrian/Bicycle Crossing Experience	Walk countdown	Low	Low	Medium
	Red period countdown	Low	Low	Low
	Independently mounted pushbuttons	Low	Low	Medium
	Accessible signals without push button actuation	Medium	Medium	Medium
	Call indicators	Medium	Low	Medium
	Pedestrian Detection	Medium	Low	Low
	Bicycle Detection	Medium	Medium	Medium
	Bicycle Indications	Medium	Medium	Medium
Reducing Pedestrian Delay	Evaluating pedestrian delay	Medium	Low	High
	Short cycle length	Medium	Medium	Medium
	Maximizing walk interval length	Medium	Medium	High
	Pedestrian recall versus actuation	High	High	High
	Adapting minimum green to demand	High	Low	Medium
	Adaptive walk intervals	Medium	Low	Medium
	Permissive periods for pedestrian actuation	Medium	Low	Low
Reducing Potential Conflicts with Parallel Traffic Turns	Leading pedestrian interval (LPI)	Medium	High	High
	Leading through interval (LTI)	High	Medium	High
	Flashing right turn yellow arrow for permitted conflicts	Medium	Medium	Medium
	Flashing pedestrian/bicycle indicator for permitted conflicts	Medium	Low	Medium
	Early right turn release	Medium	Low	Low

	Treatment Name	Guidance Gaps	Agency Needs	Opportunity for Improved Safety/Service
Eliminating Conflicts with Parallel Traffic Turns	No turn on red	Medium	High	High
	Exclusive pedestrian and bicycle phases	Medium	Medium	Medium
	Protected left turns to address non-motorized conflicts	High	High	High
	Concurrent yet protected crossings	Medium	Medium	Medium
	Delta islands for non-motorized crossings	Medium	Low	Medium
Special Phasing Techniques Favoring Pedestrian and Bicycles	Multi-stage crossings with pedestrian overlaps with left turn phases	High	High	Medium
	Pedestrian phase overlaps with each other, with bicycle phases, and with vehicular holds	Medium	Medium	High
	Pedestrian/bicycle phase reservice	Medium	Medium	Medium
	Two-stage left turn progression for bicycles	Medium	Low	Low
	Pedestrian hybrid beacons (PHB) at intersections with minor streets	Low	Medium	Medium
Bicycle Phases and Special Bicycle Needs	Bicycle phases with simple applications: contraflow, with exclusive ped phase, with LPI and LTI	Medium	High	High
	Diagonal bicycle crossing phases	Medium	Low	Low
	Single-stage bicycle crossings (where crossing islands are too small for bicycle queuing)	Medium	Low	Medium
	Minimum green and change interval settings for bicycles	Medium	Medium	Medium

Section 2.3 – Opportunities

In the table, several knowledge and guidance gaps, expressed agency needs, and opportunities for improved safety and operations are identified. Each of these needs present opportunities for additional efforts. To address these needs, two activities provide the greatest opportunities to strengthen industry practice as well as expand recent research innovation.

Practice Synthesis and Continued Agency Engagement

Similar themes are highlighted in the Task 2 (Agency Engagement) memorandum with several agencies undertaking individual efforts to define decision-making guidance, public engagement, and evaluations on treatments for non-motorized users at signalized intersections. Due to overlapping and similar agency endeavors, there is an opportunity to synthesize the work into a cohesive body of information and potential guidance. Additional agency engagement, discussions, and potential site visits will be considered as part of the work plan as well as aggregating any documented case studies or completed analysis.

Additionally, supplemental engagement with agencies during the Phase II work plan will provide additional insights to refining the Toolbox and guidance on how to use this research project's products. The Toolbox Vision is based on initial interactions, literature review, and interviews. Follow up discussions and expanded and targeted interactions with agency staff regarding the Toolbox will provide valuable insights to improve usefulness and effectiveness.

Automated Traffic Signal Performance Measures

Automated Traffic Signal Performance Measures (ATSPM) is an integration of detector and signal state data to quantify a range of signalized intersection performance measures. Kittelson is the prime consultant on NCHRP 03-122 (Performance-Based Management of Traffic Signals) and the final report and guidebook is nearing completion. The project synthesized opportunities to leverage high resolution data from signal system equipment to produce performance measures. Figure 1 provides a summary of performance measures that can be produced through ATSPM. Figure 2 shows detection requirements for performance measures.

Figure 1: Preliminary ATSPM inputs and outputs

	Required Inputs										Potential Outputs																			
	Data Source				Detection						Applications					Related Users														
Performance Measure	High-Resolution	Central System	Traffic Control System	AVI / Segment Speed / AVL	None	Unmapped	Stop Bar Presence	Stop Bar Count	Advance	SPECIAL	Organizational	Planning	Design and Construction	Operations	Maintenance	System Operator	Vehicle Delay	Pedestrians	Bicycles	Various User Safety	Vehicle Progression	Rail	Emergency Vehicles	Transit	Trucks
Communication and System Status	X	X			X						X		X		X	X									
Flash Status	X	X			X								X		X	X									
Power Failures	X	X			X								X		X	X									
Detection System Status	X	X	X			X							X		X	X									
Phase Termination	X	X				X								X	X	X	X								
Volumes	X		X					X	X			X		X	X	X	X		X		X				
Pedestrian Volumes	X		X							X		X		X	X	X		X							
Split Monitor	X				X									X		X	X								
Split Failures	X						X					X		X		X	X								
Estimated Delay	X			X			X					X		X			X		X						
Estimated Queue Length	X								X																
Oversaturation Severity Index	X								X					X			X								
Pedestrian Phase Actuation and Service	X					X								X				X							
Pedestrian Delay	X					X								X	X	X		X							
Yellow/Red Actuations	X						X							X		X				X					
Red-Light-Running (RLR) Occurrences	X		X				X							X						X					
Pedestrian Conflicts	X							X																	
Effective Cycle Length	X	X			X									X							X				
Progression Quality	X								X					X							X				
Purdue Coordination Diagram	X								X					X							X				
Cyclic Flow Profile	X		X						X					X							X				
Offset Adjustment Diagram	X								X					X											
Travel Time and Average Speed	X			X						X	X			X							X				
Time Space Diagram	X	X		X	X									X							X				
Preemption Details	X					X								X								X	X		
Priority Details	X		X			X								X										X	X

Figure 2: Detection requirements for performance measures (Mackey 2016)

Level of Detection		Performance Measures
	None	• Communication and System Status • Flash Status • Power Failures • Split Monitor • Effective Cycle Length • Time-Space Diagram
	Unmapped Detection	• Detection System Status • Phase Termination • Pedestrian Phase Actuation and Service • Pedestrian Delay • Preemption Details • Priority Details
Mapped Detection (Lane-by-Lane or Lane Group)	**Stop Bar Presence**	• Split Failures • Estimated Delay • Yellow/Red Actuations • Red-Light Running (RLR) Occurrences
	Stop Bar Count	• Volumes
	Advance Detection	• Volumes • Estimated Delay • Oversaturation Severity Index • Progression Quality • Purdue Coordination Diagram • Cyclic Flow Profile
	Radar Speed Detection	• Average Speed

The use of ATSPM is an opportunity for this project to leverage high-resolution data to assess the impacts of signal timing strategy changes. ATSPM will be dependent on intersection and corridor configuration and it will require preliminary investigation to confirm system configuration and reporting capabilities. These preliminary efforts will be incorporated as part of the work plan activities. A number of agencies, including City of Portland, Oregon, City of Charlotte, North Carolina, and Arlington County, Virginia noted ATSPM deployment within their signal system and the ability to create performance measure reports to assist with the project.

SECTION 3.0 – WORK PLAN

Section 3.1 – Overall Plan

The research plan provides a balanced approach to developing a comprehensive knowledge base to support the Toolbox and project-related materials. While many gaps, needs, and opportunities are identified through the research team's preliminary assessment, the overall goals for the research plan is to synthesize industry practice in a consistent manner and focus on opportunities of shared interest. Three work plan categories are used to frame relative "levels of effort" for Phase II activities for each treatment. The first work plan activity type, Complete Information Summary, addresses the first research plan goal of synthesizing industry practice while the second, Agency Synthesis including Case Studies, and third categories, Original, Additional Research, focus on activities where multiple agencies have common interests to expand knowledge in the treatments.

Section 3.1.1 – Constraints

The primary constraints of the Phase II work plan consist of time and budget. For any activities to be conducted as part of this research project in Tasks 6 through 8 will require completion within approximately seven (7) months and $200,000. This does not include the final toolbox production or the final report.

Developing potential work plan tasks requires iterative assessment balancing the level of effort, time to conduct the data collection and analysis, amount of partner agency and research team resources, and the qualitative value of the outcomes for each of the planned activities.

Section 3.1.2 – Work Plan Activity Types

Given the opportunities and constraints within this research project, three distinct work plan activity type were developed to assist with a "level of effort" assessment for work plan prioritization. In increasing "level of effort", the categories are listed as "*Information Summary*", "*Agency Synthesis including Case Studies*", and "*Original, Additional Research*".

Information Summary

At the lower end of "level of effort" is the Information Summary activity type. While much of the treatment information has been gathered through work completed to date, additional efforts to cohesively distill and summarize information and findings are still required. The importance of this activity type efforts is to provide a consistent minimum level of content for each treatment as part of the toolbox. Additional details and research will be conducted on select treatments, however the intent for efforts within this activity type is to develop a uniform information base for each identified treatment.

As described in the Toolbox Vision outline, each treatment will have information on "Core Treatment Attributes" and "Supporting Treatment Information". Details are provided as follows.

1. **Core Treatment Attributes**
    a. Treatment name
    b. Other or alternative names
    c. Description (includes equipment components, phasing diagrams, geometrics, and supporting systems)
    d. Variations and relationship to Relevant Treatments
    e. Problems addressed
    f. Operational detail and other considerations
    g. Context and operating environment
    h. Documented impacts (where there is no documentation available, expected impacts on motorized and non-motorized users will be presented)
2. **Supporting Treatment Information**
    a. Application Examples
    b. Guidance
    c. Other considerations
    d. References

Agency Synthesis including Case Studies

Agency Synthesis including Case Studies is the next work plan activity type with a focus on synthesizing agency practice with supporting information from documented case studies. The intent for this activity type is to compile agency experiences on select treatments and highlight their respective decision-making processes. A number of agencies have developed their own policies, tools, and guidance for selecting and implementing a number of non-motorized treatments at signalized intersections. Efforts within this work plan activity type will focus on synthesizing these practices and coalescing industry perspectives. Additional details for this activity type is provided in Section 3.2.2.

Original, Additional Research

The last work plan activity type is Original, Additional Research. Efforts within this work plan activity type are targeted efforts to expand existing knowledge on select treatments and addressing known gaps to elevate industry practice. With the project constraints, a select number of treatments will be selected for Original Research. For treatments that are selected for this work plan activity type, the level of effort will range from 150 to 300 hours per treatment. Expected activities as part of this work plan activity type may include:

- Conducting field observations and studies at select locations to document and analyze operational changes,
- Conducting simulations with adjustments to variables including traffic signal phasing and timings, vehicular demand, and geometrics,
- Engagement with agency staff for further interviews and document reviews, and

- Utilizing signal performance measures to assess intersection and corridor performance measures relative to treatments for non-motorized users.

Section 3.2 – Work Plan Activity Prioritization

Each of the treatments and identified key gaps are assessed with a perspective of level of effort for a potential research plan.

Table 2 : Prioritization of Treatments and Action Items for the Phase II Work Plan

Improving Non-Motorized Crossing Experience	Reducing Pedestrian Delay	Reducing Potential Conflicts (with Parallel Traffic Turns)	Eliminating Potential Conflicts (with Parallel Traffic Turns)	Special Signal Phasing Techniques Favoring Non-Motorized Traffic	Bicycle Phases and Special Bike Needs
Walk countdown	Evaluating pedestrian delay	Leading pedestrian interval (LPI)	No turn on red*	Multi-stage crossings with pedestrian overlaps with left turn phases	Bicycle phases with simple applications: contraflow, with exclusive ped phase, with LPI and LTI
Red period countdown	Short cycle length	Leading through interval (LTI)	Exclusive pedestrian and bicycle phases	Pedestrian phase overlaps with each other, with bicycle phases, with vehicular holds	Diagonal bicycle crossing phases
Independently mounted pushbuttons	Maximizing walk interval length	Flashing right turn yellow arrow for permitted conflicts	Protected left turns to address non-motorized conflicts	Pedestrian/bicycle phase reservice	Single-stage bicycle crossings (where crossing islands are too small for bicycle queuing)
Accessible signals without push buttons	Pedestrian recall versus actuation	Flashing pedestrian/bicycle indicator for permitted conflicts	Protected yet concurrent right turns	Two-stage left turn progression for bicycles	Minimum green and change interval settings for bicycles
Call indicators	Adapting minimum green to demand	Early Right Turn Release	Delta islands for non-motorized crossings	Pedestrian hybrid beacons (PHB) at intersections with minor streets	
Pedestrian detection	Adaptive walk intervals				
Bicycle detection	Permissive periods for pedestrian actuation				
Bicycle indications					

* No turn on red is identified as a treatment that would largely benefit from additional guidance and address agency needs, however not prioritized for additional research due to the active NCHRP 03-136 Project: Evaluating the Performance of Right-Turn-On-Red Operation at Signalized Intersections

Complete information summary (see Section 3.2.1 for more details)

Conduct agency synthesis including case studies (see Section 3.2.2 for more details)

Perform original, additional research during Phase II (see Section 3.2.3 and Section 3.3 for more details)

Section 3.2.1 – Complete Information Summary

The research team identified the treatments listed in Table 3 for the Information Summary activity type. Efforts for these twenty-five (25) treatments will focus on summarizing and documenting existing information, guidance, and examples in a consistent and cohesive structure.

For each of the identified treatments that are solely selected for this work plan activity type, the anticipated level of effort is less than 50 hours per treatment. A total estimate for is approximately six-hundred (600) hours. Expected activities as part of this work plan activity type may include:

- Identification of additional treatment locations and application examples,
- Illustration of signal timing phasing strategy variations,
- Documentation of additional case studies, papers, and/or agency practices, and
- Expansion of defining context and operating environment.

Table 3 : Identified Treatments in the Complete Information Summary Activity Type for Phase II Work Plan

Category	Treatment Name
Improving Pedestrian/Bicycle Crossing Experience	Walk countdown
	Red period countdown
	Independently mounted pushbuttons
	Accessible signals without push button actuation
	Call indicators
	Pedestrian Detection
	Bicycle Detection
	Bicycle Indication
Reducing Pedestrian Delay	Evaluating pedestrian delay
	Short cycle length
	Adaptive walk intervals
	Permissive periods for pedestrian actuation
Reducing Potential Conflicts with Parallel Traffic Turns	Flashing right turn yellow arrow for permitted conflicts
	Flashing pedestrian/bicycle indicator for permitted conflicts
	Early right turn release
Eliminating Conflicts with Parallel Traffic Turns	No turn on red
	Concurrent yet protected crossings
	Delta islands for non-motorized crossings (includes guidance on dealing with them as well as potentially removing them)
Special Phasing Techniques Favoring Pedestrian and Bicycles	Pedestrian phase overlaps with each other, with bicycle phases, and with vehicular holds
	Pedestrian/bicycle phase reservice
	Two-stage left turn progression for bicycles
	Pedestrian hybrid beacons (PHB) at intersections with minor streets
Bicycle Phases and Special Bicycle Needs	Diagonal bicycle crossing phases
	Single-stage bicycle crossings (where crossing islands are too small for bicycle queuing)
	Minimum green and change interval settings for bicycles

Section 3.2.2 – Conduct Agency Synthesis including Case Studies

The research team identified six (6) treatments listed in in Table 4 for the Agency Synthesis including Case Studies activity type. Efforts for these six (6) treatments will expand upon work completed in Phase I with targeted and focused agency engagement. These treatments are common treatments for non-motorized users at signalized intersections that several agencies have identified as key treatments where individual agencies have developed internal guidance and decision-making documents. The intent of activities within this work plan activity type to gather and synthesize case studies as well as engage with the agency about their information development needs and process. Key findings from these efforts will provide critical information for an effective Toolbox and project deliverables.

Table 4 : Identified Treatments in the Conduct Agency Synthesis including Case Studies Activity Type for Phase II Work Plan

Category	Treatment Name
Reducing Pedestrian Delay	Maximizing walk interval length (including rest in walk)
	Adapting minimum green to demand
Reducing Potential Conflicts with Parallel Traffic Turns	Leading pedestrian interval (LPI)
	Leading through interval (LTI)
Eliminating Conflicts with Parallel Traffic Turns	Exclusive pedestrian and bicycle phases
Bicycle Phases and Special Bicycle Needs	Bicycle phases with simple applications: contraflow, with exclusive ped phase, with LPI and LTI

For treatments that are selected for this work plan activity type, the anticipated level of effort will range from 50 to 150 hours and interactions with up to five (5) agencies per treatment. Expected activities as part of this work plan activity type may include

- Engagement with agency staff for further interviews and document reviews (approximately 5-20 hours),
- Documentation of treatment application with potential site visits (approximately 15-30 hours),
- Review and analysis of available studies/data provided by agency staff (approximately 20-40 hours), and
- Expansion of defining context and operating environment (approximately 10-30 hours).

Section 3.2.3 – Perform Original, Additional Research during Phase II

The research team identified three (3) treatments listed in in Table 5 for the Original, Additional Research activity type. Efforts for these three (3) treatments will expand upon work completed in Phase I as well as address key knowledge and guidance gaps.

Table 5 : Identified Treatments in the Perform Original, Additional Research Activity Type for Phase II Work Plan

Category	Treatment Name
Reducing Pedestrian Delay	Pedestrian recall versus actuation
Eliminating Conflicts with Parallel Traffic Turns	Protected left turns to address non-motorized conflicts
Special Signal Phasing Techniques Favoring Non-Motorized Traffic	Multi-stage crossings with pedestrian overlaps with left turn phases

Details of the proposed work plan and task descriptions for the identified treatments are provided in the following section.

Section 3.3 – Task Descriptions for Original, Additional Research

This section discusses the research team's work plan for the treatments identified for the original, additional research activity type. These treatments are listed below:

- Pedestrian recall vs. actuation,
- Protected left turns to address non-motorized conflicts, and
- Multistage crossings with pedestrian overlaps with left turn phases.

Section 3.3.1 – Pedestrian Recall vs. Actuation

Research Need:

Pedestrian phases can be configured as recall or actuated (typically using pushbuttons). With pedestrian phases on recall, a call for pedestrian service is placed automatically every phase. This eliminates the need for pedestrian actuation and results in pedestrian phases getting realized every cycle. Pedestrian actuation, on the other hand, typically requires a pedestrian to manually activate a WALK signal.

Agencies typically prefer using pedestrian recalls in high pedestrian volume areas (e.g. downtown) where the pedestrian phase is needed every cycle. These areas often have pretimed signals, allowing agencies to provide longer WALK intervals along with the pedestrian recall, reducing pedestrian delay.

For intersections with low pedestrian volumes (e.g., pedestrians are present less than 10% of all cycles), agencies typically prefer using pedestrian actuation with a short WALK interval in order to limit the impacts of pedestrian timings on vehicular operations. The impact is especially more pronounced when crossing requires a long FDW (e.g., when pedestrians cross a wide major arterial) since the time that would be needed for the crossing may be considerably greater than the green time needed for the concurrent traffic, reducing intersection capacity. In addition, pedestrian recall requires embedding pedestrian timings within the ring-barrier structure, which may lead to longer cycle lengths.

For crossings with an intermediate level of pedestrian demand, agencies are interested in guidance as to whether or not the pedestrian phase should be on recall. The decision involves a tradeoff between impact on operations (traffic delay, capacity, progression, and possibly cycle length) and impact on pedestrians. Research shows that at coordinated intersections, for which cycle length is fixed, pedestrian recall reduces pedestrian delay, which in turn improves pedestrian safety because reducing pedestrian delay tends to improve pedestrian compliance (Pline 2001[1]). Kothuri found greater pedestrian compliance with intersections on recall than pedestrian actuated intersections (Kothuri 2014[2]).

At fully actuated intersections, pedestrian recall can increase pedestrian delay if running the pedestrian phase results in a longer cycle length. Pedestrian delay is closely related to cycle length, and so at actuated signals, pedestrians may benefit from having no pedestrian in the cycle in which they arrive so that that cycle will be short.

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[1] Pline, J. L. (2001). Traffic Control Devices Handbook, Chapter 13. Institute of Transportation Engineers, Washington, D.C.
[2] Kothuri, S. (2014). Exploring Pedestrian Responsive Traffic Signal Timing Strategies In Urban Areas. National Institute for Transportation and Communities.

Thus, agencies face the challenge of limiting the impact of pedestrian timings on vehicle delay while providing a safe and acceptable level of service for pedestrians, especially with low to moderate pedestrian volumes. The following questions are often asked by agencies to deal with this tradeoff:

- What would be the impact on traffic if pedestrian phases crossing a major street are put on recall? How to judge when setting pedestrian phases on recall would be disruptive to traffic operations?
- Is there a pedestrian volume threshold (or fraction of cycles in which there is a pedestrian call) to determine when to set pedestrian phases on recall vs. actuation?
- How can knowing the green time distribution for the concurrent vehicle phase help determine the pedestrian phase can be put on recall with little impact to traffic operations?
- If pedestrian recall is programmed, should the WALK interval take a minimum length (typically, 7 seconds)? Or, given the green time distribution of the concurrent phase, might there be an opportunity to lengthen the WALK interval with little or no additional delay to traffic?
- Would the impacts be different for pedestrian phases crossing the major street or the side street?

Our research during Phase II will seek answers to these questions. Specifically, we will identify situations in which providing better pedestrian recall (perhaps with an extended WALK interval) would have little or no impact on traffic operations and will provide guidance for helping agencies identify crossings where those opportunities are likely to exist.

Methodology:

The research team proposes utilizing microsimulation using the VISSIM software to evaluate the impact of pedestrian recall and actuation on pedestrian delay and traffic operations including vehicular delay. VISSIM will allow us to vary inputs (please see the analysis section for details) and conduct extensive sensitivity testing on the varying inputs. This will in turn help us cover a wide range of scenarios (something that wouldn't be practical with the field data due to the high cost associated) and provide guidance on the conditions in which pedestrian recall vs. actuation should be considered. To ensure the simulation models provide realistic outcomes, real intersections and volume settings will be used and the models will be calibrated using field data such as saturation flow rate and queue lengths.

Two sets of experimental setups will be designed in VISSIM, as described below:

1. The first experimental setup will focus on an isolated and actuated intersection in which there is no fixed cycle length and both phase green durations and intersection cycle length vary from cycle-to-cycle.
2. The second setup will consider a coordinated-actuated intersection on a corridor to explore the impacts of pedestrian recall vs. actuation on progression. Therefore, a stretch of corridor with upstream and downstream intersections will be modeled in VISSIM to capture the progression effects on the subject intersection under varying inputs and timing settings.

Data Collection:

As noted above, simulation models will be developed with realistic intersections/networks and traffic patterns. The research team already developed and calibrated numerous signalized intersections/arterials in VISSIM on different projects. These readily available and calibrated modes will be used as the basis. If required, further field data will be collected for calibration such as saturation flow rate, queue lengths, and pedestrian walking speeds.

Analysis:

In order to analyze potential impacts of varying volume and timings, a detailed sensitivity analysis will be performed. Table 6 highlights key sensitivity parameters that will be involved in the analysis. It should be noted that two separate groups are created for isolated and coordinated intersections.

Table 6: Proposed Key Sensitivity Parameters to be Used in the Simulation Testing

Intersection Type	Key Sensitivity Parameters
Isolated Intersection	• Road width and corresponding length of FDW interval • Length of WALK interval (to explore the impact of lengthening WALK interval) • Pedestrian volumes (or fraction of cycles in which there is a pedestrian call) • Traffic demand (or volume to capacity ratio) by approach (both for the side street and the main street) • Presence of left turn lanes and, with them, protected left turn phases
Coordinated-actuated intersection	• Sensitivity parameters listed for the isolated intersection (see above) • Traffic signal progression designed to favor peak direction • Traffic signal progression designed to favor both directions • Intersection spacing

Through extensive simulation testing, we will obtain various performance metrics from VISSIM to explore impacts of various pedestrian timing strategies. Some of these performance metrics will include:

- Fraction of cycles where pedestrians were present,
- Approach green time distribution under various testing scenarios,
- Pedestrian delay,
- Vehicle travel time and delay, and
- Arrivals on green (applicable only to the coordinated-actuated scenario)

Anticipated Outcomes:

The expected outcomes for this research effort are explained as follows:

- For isolated intersections, we will demonstrate various volume and timing scenarios in which providing pedestrian recall would improve pedestrian service (and safety indirectly) considerably with only marginal impacts to traffic operations.

- For coordinated-actuated intersections, we will show the potential impacts of setting pedestrian phases on recall instead of actuation. We will present the effects of different type of timing plans (e.g., recall with a minimum WALK interval, recall with longer WALK interval, etc.), coordination schemes, and intersection spacing on traffic operations.

For both types of intersections, we will highlight cases for agencies in which enhancement opportunities exist for pedestrians with little to no impact on vehicle operations.

Section 3.3.2 – Protected Left Turns to Address Non-Motorized Conflicts

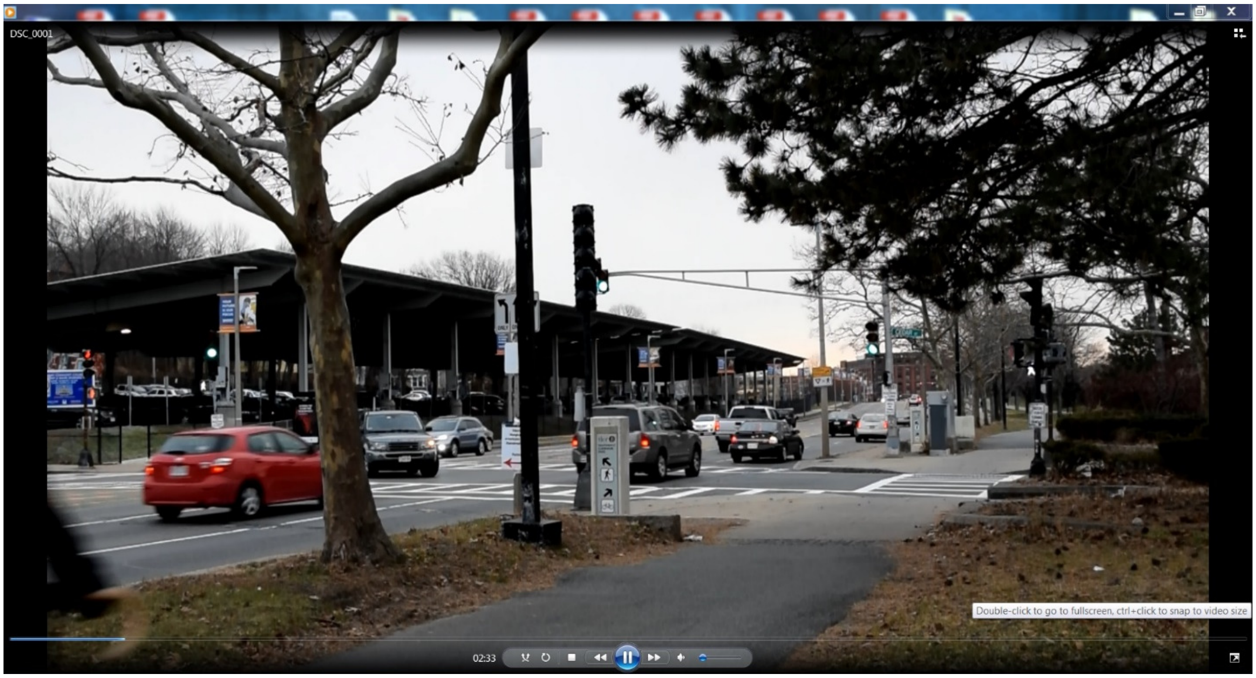
Research Need:

Bicycle safety research has identified conflicts with left-turning vehicles as one of the most prevalent and severe crash types. The potential for crashes is greater when cyclists are in separated bike lanes or sidepaths that are offset from the carriageway, making cyclists less conspicuous. European cities with extensive experience with separated bike lanes tend to have stricter policies than American cities limiting the use of permitted left turns across separated bike paths, based on their crash experience. Because the U.S. has far less experience with separated paths, evidence of the likely safety impact of permitted versus protected left turns across a separated bike path will be valuable for helping American cities establish policies in this regard.

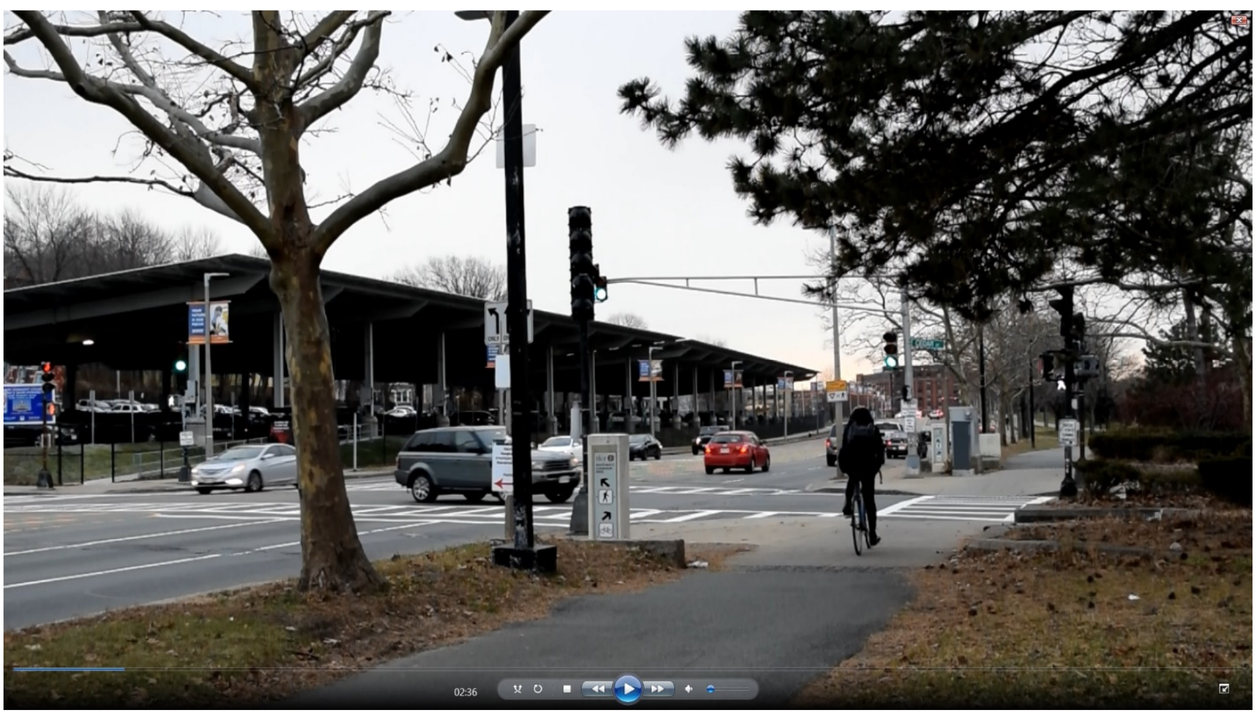
Methodology:

The team proposes a video-based before-after study of two intersections in Boston that are expected to be converted from protected-plus-permitted to protected-only left turn phasing between April and July of 2019. The intersections are Columbus Ave. @ Cedar Street and Columbus Ave. @ Heath Street, both of which are along the Southwest Corridor bike path, a two-way sidewalk-level bike that, approaching the intersections, are offset about 10 ft from the carriageway.

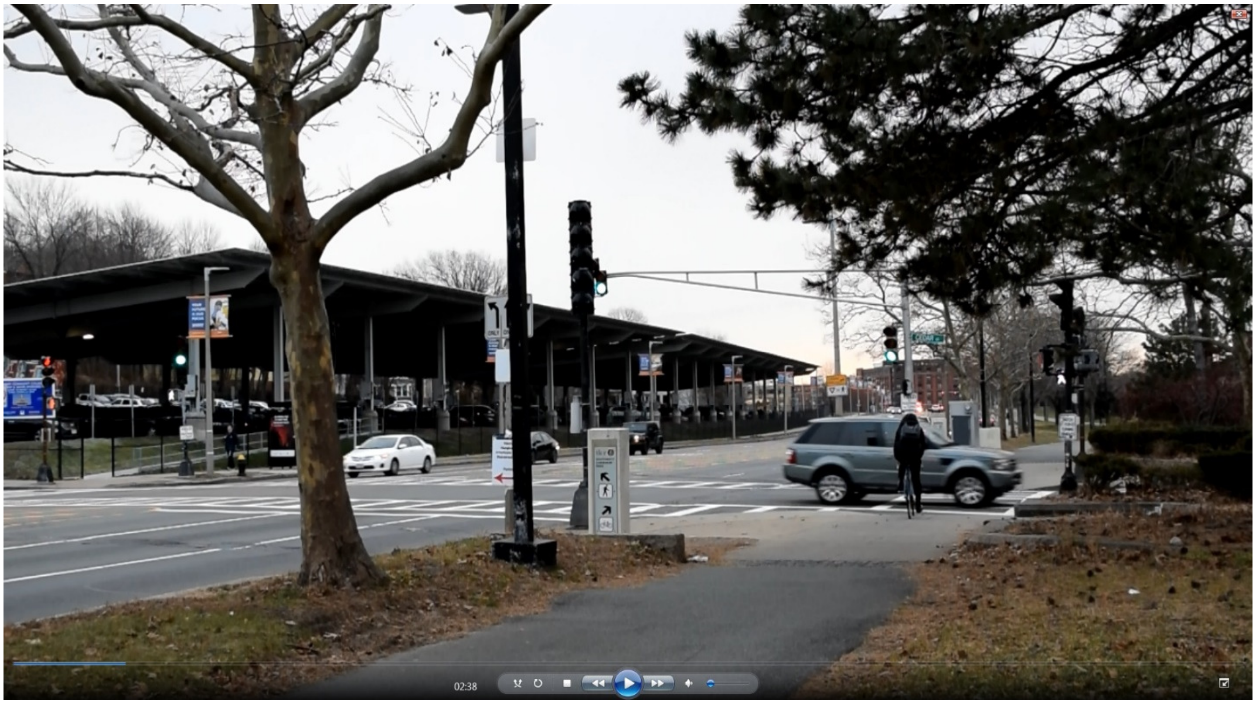
A set of videos taken during Fall of 2018 has proven that camera vantage points can be found that capture the relevant conflicts. The photo sequence below shows an example conflict. In frame (b), the last car preventing the jeep from turning passes, and in frame (c) one can see that the jeep advanced without regard for the approaching bike, who makes an emergency stop to avoid a collision even though the bike has the right of way.



(a) As a cyclist approaches (part of the handlebars and cyclist's arm are visible at the left edge of the frame), an SUV, angled in preparation to make a left turn, waits for an opposite direction red car to pass.



(b) The red car has passed, and the SUV starts to turn, on a collision course with the cyclist.



(c) The cyclist makes an emergency stop to avoid collision, even though the signals (both WALK and green) indicate that the cyclist has right of way.

Data Collection:

We propose to use video to observe 9 hours of before data and 9 hours of after data at each intersection, collected in 1.5 hour sessions in three a.m. peak periods and three p.m. peak periods at each intersection. Observations will be made during peak hours only because the lower bike volumes outside of peak hours makes the frequency of potential conflicts too low.

Analysis:

The before-after study will capture safety-related behaviors and events including bikes and motor vehicle braking or taking other evasive action to avoid a collision, compliance with signals. When left-turning motor vehicles under a permitted condition yield to crossing bikes or pedestrians, we will note whether they do so in their turn pocket or advance to a position in which they are blocking the opposing travel lanes, exposing themselves to a broadside collision. Events involving multiple crossing cyclists or multiple left-turning cars will be coded so as to capture their interaction. Each relevant event will be coded (recorded), along with a timestamp so that, if necessary, the video can be easily reviewed. Traffic and bike counts will also be analyzed so that event frequencies can be normalized by exposure.

Anticipated Outcomes:

We hypothesize that, when the signal phasing is changed from protected-plus-permitted to protected only:

- Conflict rates (conflicts per bike) requiring avoidance maneuvers will significantly decline.
- cyclist compliance will not be significantly different, even though cyclists will have a longer red time.
- That queues will continue to dissipate with every cycle, indicating sufficient traffic capacity and therefore no major increase in vehicular delay.

We also anticipate that video analysis will offer insight into conflict mechanisms involving more than one cyclist and more than one turning vehicle. To the degree that conflicts involve either multiple crossing cyclists ore multiple turning vehicles, risk can be related to traffic volumes.

Section 3.3.3 – Multi-Stage Crossings with Pedestrian Overlaps with Left Turn Phases

Research Need:

Signalized intersections sometimes involve multi-stage pedestrian crossings, particularly where a wide street is crossed. In a multi-stage crossing, pedestrians cross to an island (that is wide enough to provide a safe waiting area for pedestrians), and then wait there for a WALK signal to resume crossing. Two-stage crossings are common, three- and even four-stage crossings are also known, although less frequent.

While crossing islands almost always benefit pedestrians, making a crossing two-stage or multi-stage in time is usually done to benefit vehicular traffic. This is because for long crossings, the time that is needed for a single-stage crossing is sometimes considerably greater than the concurrent vehicular phase. As a result, allowing a single-stage crossing increases lost time and reduces intersection capacity, resulting in longer vehicle delays.

Regulations, such as those in MUTCD, ensure that crossing stage meets minimum safety standards. For example, they must include a minimum length WALK interval and clearance time long enough for a relatively slow pedestrian to get to the next island. However, those regulations offer no protection against designs that result in long delays for pedestrians. In addition, while the Highway Capacity Manual (HCM) offers a simple method for evaluating delay for single-stage crossings, there is no guidance in HCM for multi-stage crossings. The lack of an accepted method for evaluating pedestrian delay at multi-stage crossings sometimes leads to intersection designs with multi-stage crossings resulting in excessive delays for pedestrians (e.g., more than 100 seconds). Sometimes, practitioners have no choice but to use a multi-stage crossing solution. Therefore, there is a need for practitioners to have the tools for evaluating delay at multi-stage crossings and develop and describe techniques to serve pedestrians well, or at least keep pedestrian delay to a tolerable level, while satisfying traffic capacity needs.

Methodology:

The team proposes conducting a field study at an intersection with multi-stage crossing and testing various signal timing strategies to evaluate effect on pedestrian and vehicular operations. One way to improve pedestrian delay at multi-stage crossings through signal timing is to run some crossing stages concurrently with a left turn phase through phase overlaps. By carefully choosing the phasing sequence for left turns (i.e., leading left or lagging left) and allowing left turn phases to overlap, progression opportunities for multi-stage crossings can be created for pedestrians, reducing pedestrian delay with little to no impact on vehicular operations. Our team proposes using two separate sources to quantify operational impacts of left turn overlaps at multi-stage crossings, as discussed below in details:

- To evaluate pedestrian delay, we propose using the *Northeastern University Ped & Bike Crossing Delay Calculator*[3] tool developed by Northeastern University, our teaming partner. The figure below shows a screenshot of the tool along with delay calculation and progression graphics at the crossing in Riverway in Boston.

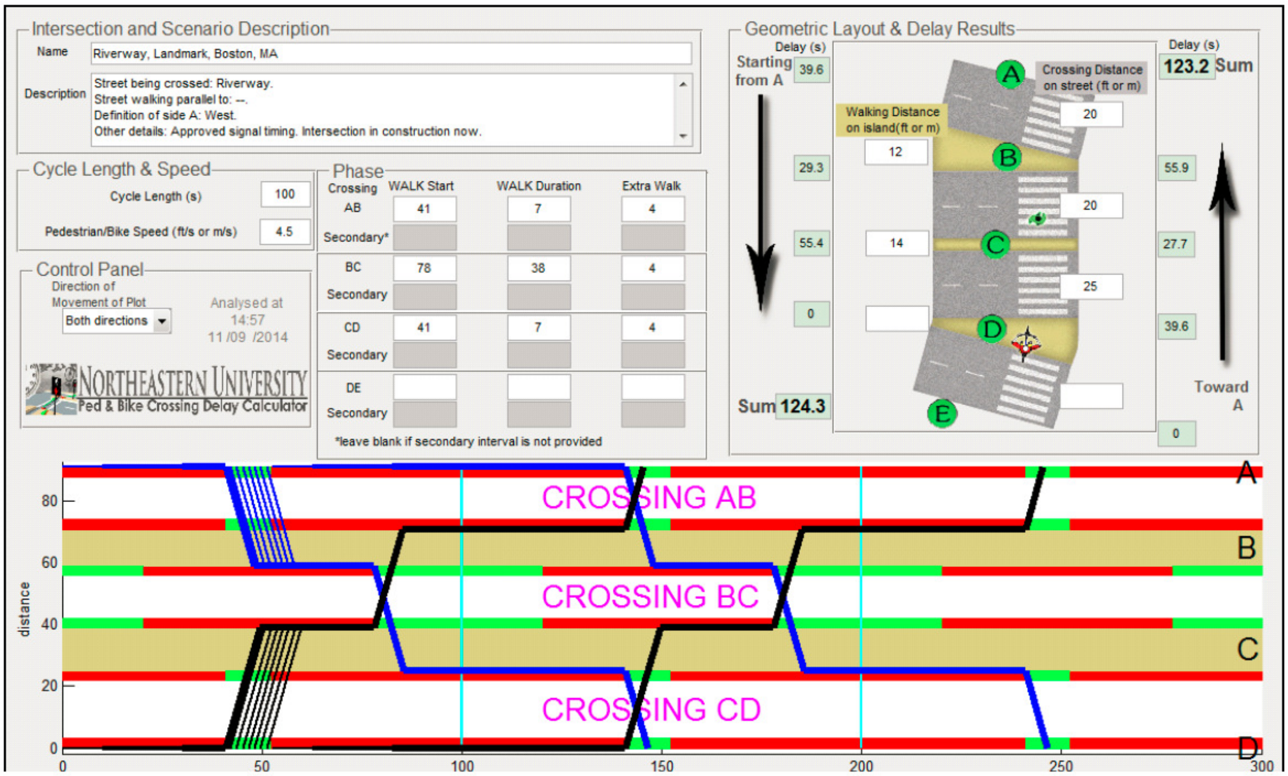


Figure 3: Screenshot from the Northeastern University's Ped & Bike Crossing Delay Calculator Tool

- To assess the impacts on vehicular operations, our team proposes utilizing Signal Performance Measures (SPMs) and high-resolution controller data (signal state and detector state every tenth of a second). Kittelson is currently leading the NCHRP 03-122 Project: Performance-Based Management of Traffic Signals and will leverage our working relationship with agencies to utilize SPMs.

[3] http://www.northeastern.edu/peter.furth/delaycalculator/

Data Collection:

We propose to collect 2 weeks before (without left turn phase overlap) and 2 weeks after (with the left turn phase overlap to reduce delay at multistage crossing) SPM data in the field. The analysis will focus on the weekday AM and PM peak hours since the potential impacts of pedestrian overlaps with left turn phases on intersection capacity will be more pronounced during more congested conditions. As noted previously, several agencies, including City of Portland, Oregon, City of Charlotte, North Carolina, and Arlington County, Virginia noted ATSPM deployment within their signal system and the ability to create performance measure reports to assist with the project. We will work with these agencies to find candidate intersections for testing. We will identify an intersection in which there is a multi-stage crossing and special vehicle detection features (e.g., stop line detection, lane-by-lane detection and advanced count detection) to obtain useful metrics for the analysis. We will then make adjustments in the signal timing plan to reduce pedestrian delay at the multi-stage crossing and collect SPM data to research impacts on vehicular traffic.

Analysis:

The before-after study will capture pedestrian delay improvements at the multi-stage crossing and evaluate the impact of pedestrian overlaps with left turn phases. We will analyze Purdue Split Failure and Purdue Coordination Diagram to research the effects on intersection capacity and progression, respectively. Both for the before and after condition, pedestrian delay will be calculated for pedestrians crossing in both directions since pedestrian progression is influenced by the lead-lag sequencing of the left turns.

Anticipated Outcomes:

Our team hypothesizes that pedestrian overlaps with left turn phases can help reduce pedestrian delay considerably at multi-stage crossings with marginal capacity and delay impacts on vehicular traffic. We anticipate that the analysis through the Ped Delay Calculation tool and SPMs will offer important insights for practitioners and provide signal timing and phasing guidance that can satisfy the needs of both pedestrians and vehicles. In addition, we will demonstrate the feasibility of using a simple numerical method for calculating multi-stage pedestrian delay at signalized intersections and introduce a software tool that can possibly be used by practitioners in the future.

Section 3.4 – Work Plan Summary Estimates

The Phase II work plan described in detail in this memorandum provides a framework for the research team to develop the core content for the Toolbox. It should be noted that the Toolbox production is part of future tasks. The estimates provided in Table 7 summarizes the key activity types as described.

Table 7: Phase II Work Plan Summary Estimates

Work Plan Activity Type	Number of Treatments	Total Labor Hours Estimate (hours)	Total Labor Cost Estimate
Information Summary	25	400 – 600	$55,000
Agency Synthesis w/ Cast Studies	6	500 – 700	$60,000
Original, Additional Research	3	600 – 800	$70,000
Total	**34**	**1,500 – 2,100**	**$185,000**

Section 3.5 – Material Production

The prior sections present the work plan for Tasks 6-7 of the overall project. The purpose for Task 8 is to engage the panel, gather feedback on the Phase II work plan activities and products, and confirmation of the Toolbox vision. Outcomes of Task 8 will serve as a stepping stone for the final phase of the project. A refined plan to produce the Toolbox, outreach materials, and the final report will be completed as a deliverable for Task 8. In addition, based on the outcomes of the proposed work plan, the research team will develop recommendations for future research, highlighting specific treatments, and outstanding issues, and developing a prioritized list of research items. The team will obtain Panel feedback to lay groundwork for future problem statements.

PHASE II REPORT

to the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM (NCHRP)

on

Project 03-133: Traffic Signal Design and Operations Strategies for Non-Motorized Users

Draft 1.0

August 2020

from

Kittelson & Associates, Inc.

In association with:

Northeastern University

Accessible Design for the Blind

Wayne State University

TABLE OF CONTENTS

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Automated Traffic Signal Performance Measures for Pedestrians Using High-Resolution Data

Kittelson & Associates, Inc.

In association with:

Northeastern University
Accessible Design for the Blind
Wayne State University

August 31, 2020

INTRODUCTION

The purpose of this memorandum is to present the findings of the additional research that was conducted to explore any opportunities for utilizing high resolution signal controller data to identify pedestrian and bicycle issues at signalized intersections. Additionally, this document describes a process for agencies to help them identify intersections with opportunities where pedestrian and bicycle treatments can be implemented with little or no impact on traffic operations. It should be noted that while most of this document focused on pedestrian related issues and opportunities, the findings are also applicable for intersections where bicycles also use pedestrian pushbuttons.

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 consists of timestamped 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 Utah Department of Transportation (UDOT) developed an open-source platform that can create a series of visual reports that display the high-resolution data from signal controllers.

Up to date, several research studies have been conducted on the use of high-resolution data to enhance intersection operations. In addition, many agencies adopted ATSPMs to maintain and operate their intersections using high-resolution signal controller data. While ATSPM development has mainly focused on measures related to serving vehicles, they can also be used for measures related to pedestrian service. The objective of this research is to establish a process for agencies to leverage high-resolution data to measure pedestrian service in a more proactive manner. Additionally, the recommended process also includes methods to identify candidate intersections that are suitable for application of certain treatments identified in the toolbox to help improve service for pedestrians. To establish a process for agencies, the research team partnered with the Indiana Department of Transportation (INDOT) to work with their ATSPM data. Detailed information on the data collected from INDOT is discussed below.

INDOT ATSPM DATA DESCRIPTION

Three months of ATSPM data from June 2018 to August 2018 was received from INDOT at over 350 signalized intersections with ATSPM capability. The data included historical raw ATSPM data with the signal state and detector data recorded in one-tenths of a second at each intersection. **Figure 1** displays the location of these intersections.

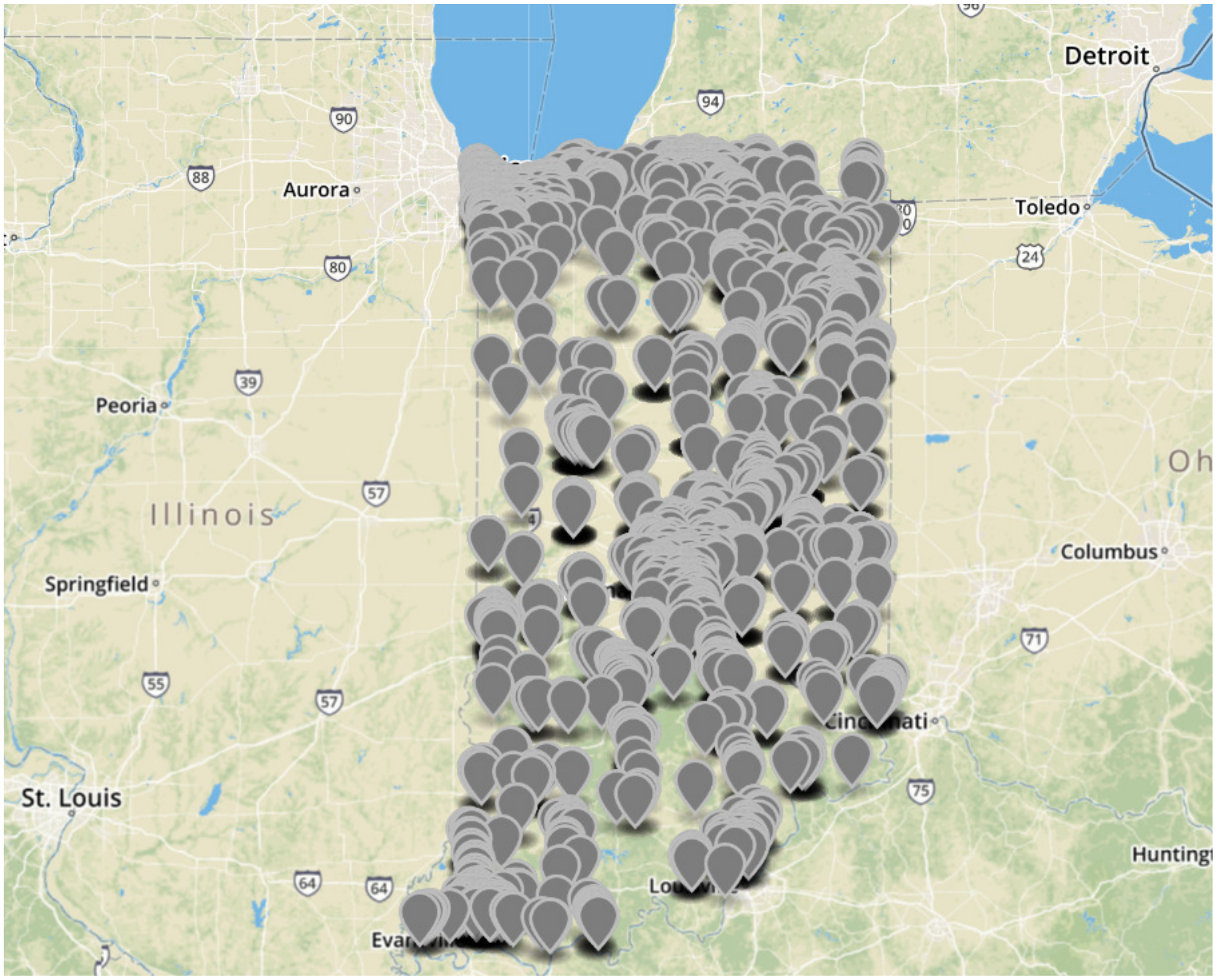


Figure 1: Map of intersections with ATSPM data provided to the research team

After the data was received, the research team filtered the data to only focus on intersections that had some level of pedestrian activity. The filtering used pedestrian actuation enumerations, which resulted in 103 intersections with at least one pedestrian call over the three-month period. **Figure 2** shows those intersection along with the total number of pedestrian actuations received at each location. Detailed discussion on filtering and prioritization of intersections is provided in the following sections.

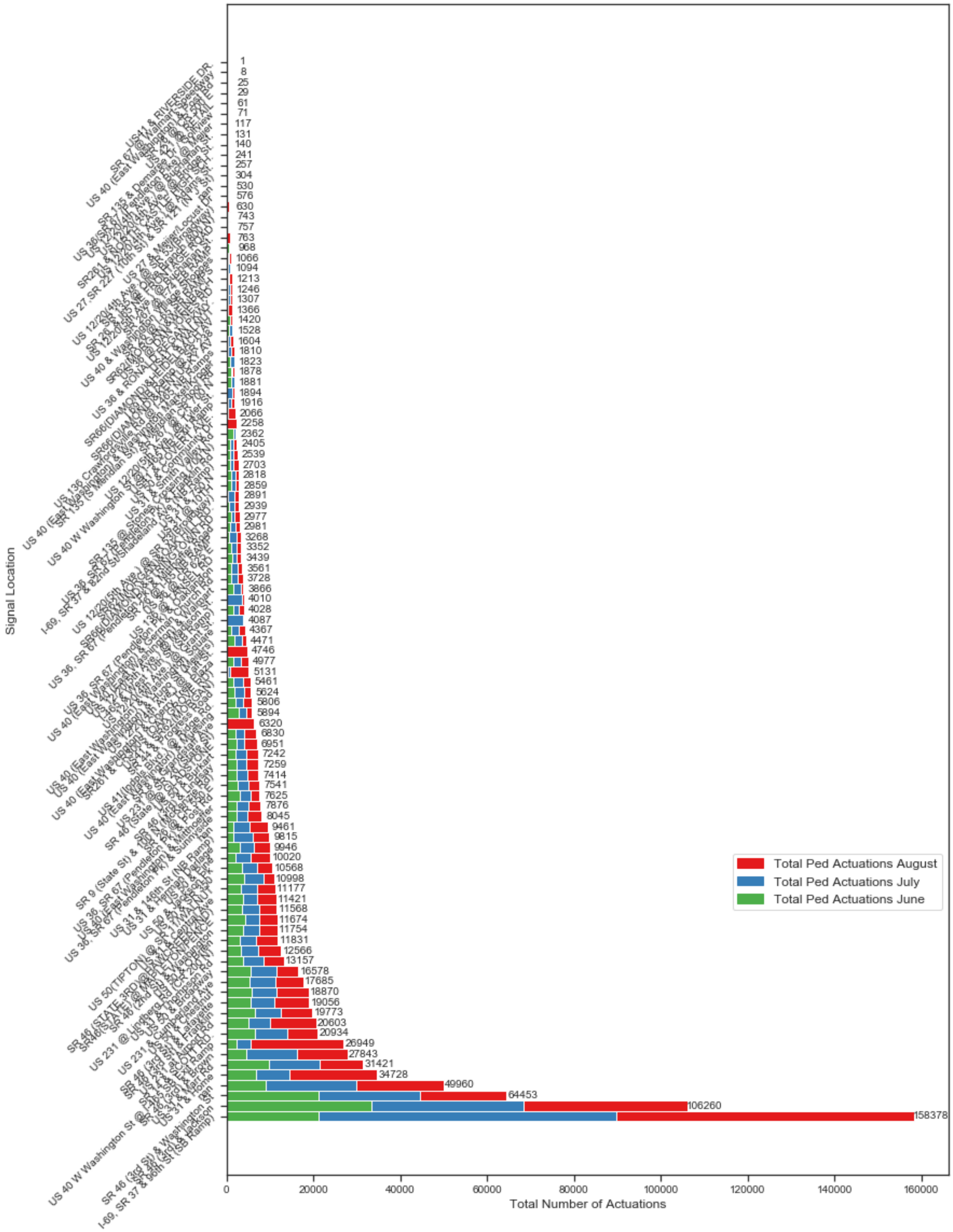


Figure 2: Intersections that had pedestrian actuation over the three months period along with the total number of pedestrian actuations

ESTABLISHING A PROCESS TO LEVERAGE HIGH RESOLUTION DATA FOR PEDESTRIANS

This section describes a proactive process for agencies to leverage ATSPMs to measure pedestrian performance and identify opportunities in which better pedestrian service can be achieved with almost no impact on traffic operations. Next sections describe the recommended steps to follow to integrate ATSPMs for pedestrians.

Filtering and Prioritization of Intersections

For agencies that have high resolution event data at most intersections and all signals connected to a central system, there will be a need to develop a procedure for filtering and prioritizing intersections to determine where it may be best to focus efforts to improve pedestrian conditions. This filtering and prioritization process will allow agencies to conduct a more in-depth analysis for a smaller subset of intersections.

As discussed above, the ATSPM data received from INDOT included over 350 intersections. The initial filtering, shown in **Figure 2**, eliminated intersections with zero pedestrian activity over the three months period. After this initial filtering, the team further refined the data by selecting the top 25 intersections with the most pedestrian activity. **Figure 3** shows these top 25 intersections with the most pedestrian activity. The data grouped by pedestrians crossing the side street (i.e., Phase 2 and Phase 6 actuations, crossings parallel to the mainline movement) vs. crossing the mainline movement (i.e., Phase 4 and Phase 8 actuations, crossings parallel to the side street movement). Pedestrian actuations that occurred only during the AM and PM peak hours were displayed below as well.

While the selection of top 25 was arbitrary and based on the research team's judgment, it allowed the team to focus on intersections that experience high pedestrian activity, and therefore may benefit the most from the pedestrian and bicycle treatments. In particular, the prioritization based on the pedestrian activity is more critical when the goal is to reduce pedestrian delay since these intersections experience high pedestrian volume. For safety improvements, prioritization based on the number of pedestrian actuations may be less relevant (and can be misleading in certain cases) since pedestrians tend to either find alternate routes or switch to a different mode when there are safety issues at intersections, resulting in low pedestrian activity. Therefore, while filtering may be a good starting point to prioritize intersections, especially when the goal is to reduce pedestrian delay, additional filtering methods and field data collection will be required to address safety concerns.

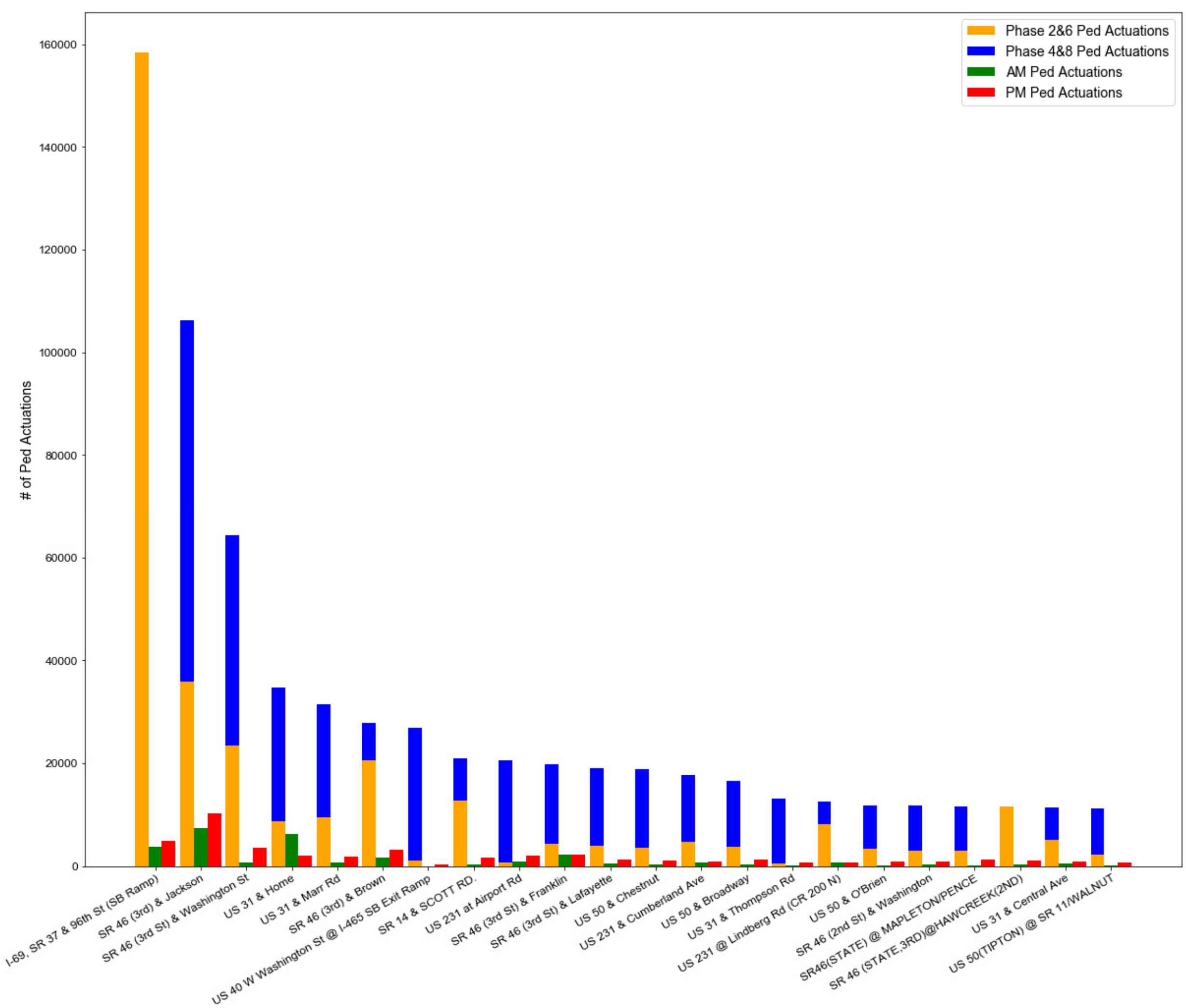


Figure 3: The top 25 intersections with the most pedestrian activity grouped by pedestrians crossing the side street (Phase 2 and 6) versus crossing the mainline movement (Phase 4 and 8)

Identifying Pedestrian Related Issues Using High-Resolution Data

This section presents methods to identify issues experienced by pedestrians utilizing high-resolution controller data.

Pedestrian Delay

Once the intersections with high pedestrian activity are identified, the agencies may consider using the *Pedestrian Delay* report to gain insights into delay experienced by pedestrians. The UDOT's open-source ATSPM 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 is a measure closely related to average pedestrian delay (though 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 total number of pedestrian actuations (**Figure 4**), which is closely related to pedestrian demand (again, however, they are not the same because pedestrians arriving after the pedestrian phase has been called are not counted). Indication of how often pedestrian phases are called can also be helpful in designing signal timing plans. Where the frequency of pedestrian actuations is low, designers may use a cycle length that does not accommodate pedestrian green requirements, and thus shorter than what would be needed to accommodate pedestrian green requirements. With this kind of timing, the cycle will be lengthened whenever a pedestrian phase is served, after which a transition routine is run to recover the extra time added to 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 can be especially valuable when applied to a critical intersection whose cycle length governs the cycle length of a corridor. However, this strategy becomes ineffective if pedestrian actuations are too frequent.

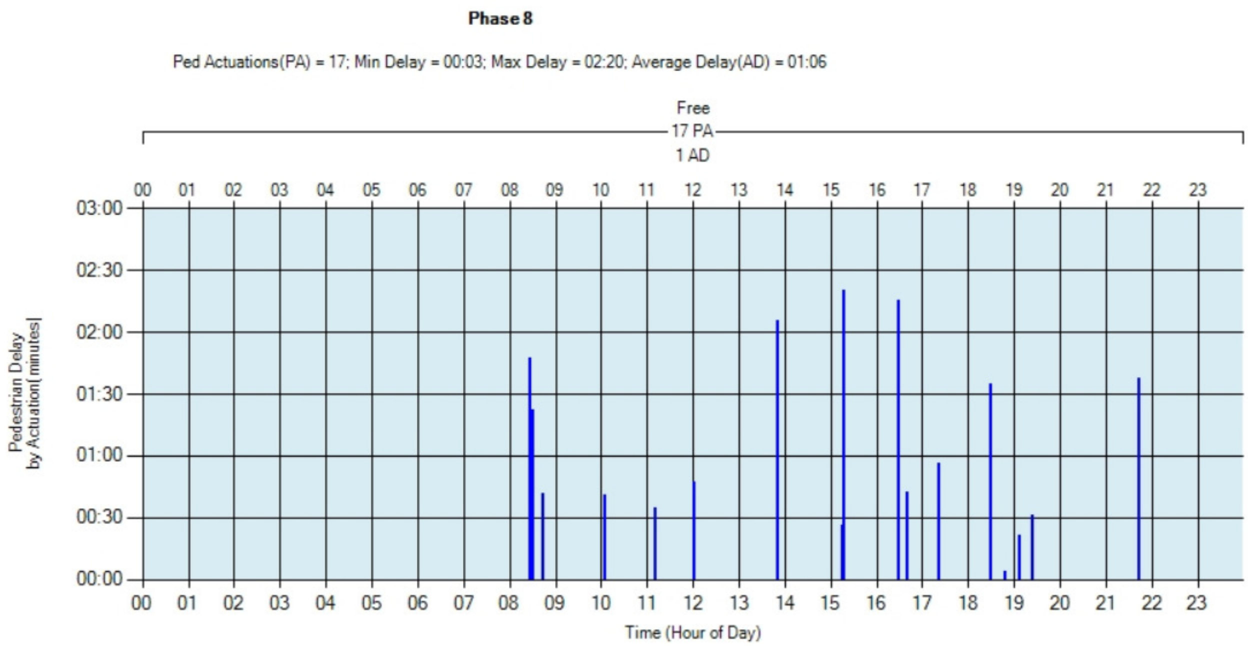


Figure 4: Pedestrian Delay report example generated by the UDOT Open-Source Platform

Pedestrian Conflicts with Permitted Turn Movements

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, permitted turning movements can be counted by cycle. Where the pedestrian phase is actuated, counts during cycles with registered pedestrians can then be isolated. An example in **Figure 5** 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 13th (blue) was one week prior to the start of classes, and August 22nd (red) was during the first week of classes (Hubbard et al., 2008).[1] The data are sorted from largest to smallest flow rate. The increase in right-turn volume after classes began is evident. This analysis showed that after classes began, there were 15 cycles per day with pedestrian activity and in which the conflicting traffic volume was 1200 vehicles/hour or greater, which corresponds to an average headway of less than 3 seconds between vehicles. This analysis helped support a decision to implement an exclusive pedestrian phase.

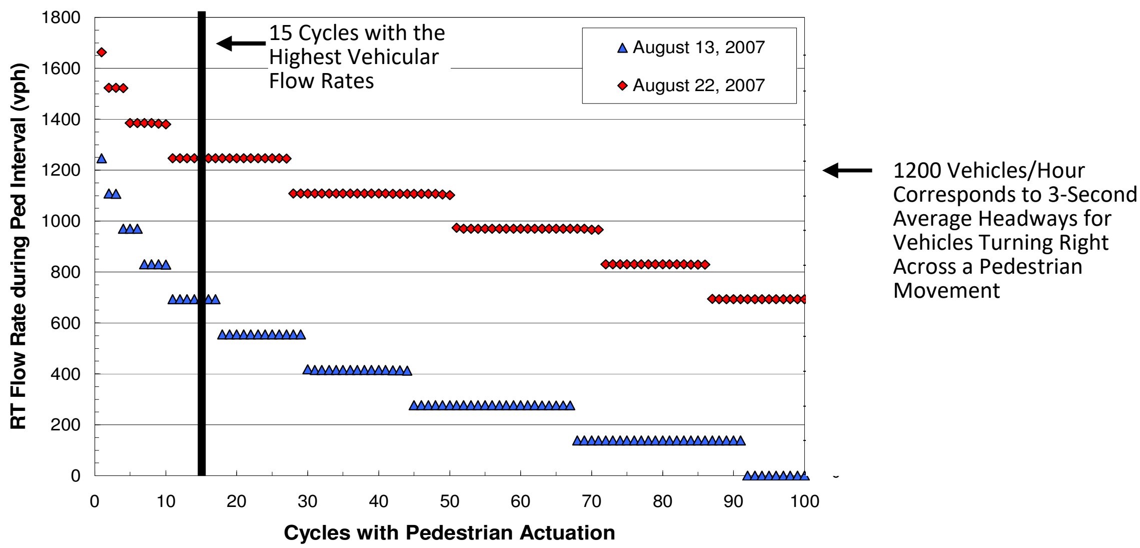


Figure 5: **Pedestrian conflicts example: Right-turn vehicular flow rates during cycles with pedestrian actuations (Hubbard, Bullock, and Day 2008)**

Identifying Candidate Intersections for Treatment Applications

This section discusses a process to identify candidate intersections using high resolution data in which implementing certain treatments to improve pedestrian conditions will have little or no impact on traffic operations.

Maximizing Walk Interval Length

For pedestrian crossings that are concurrent, maximizing the Walk interval length will reduce pedestrian delay and increase compliance. Utilizing high resolution data, this section aims to identify intersections in which a pedestrian phase is terminated well before its concurrent vehicular phase has ended during most cycles. Therefore, this treatment looks for opportunities where the Walk time for pedestrians can be increased without causing longer green times for vehicles. This treatment is generally more applicable for concurrent vehicular phases that are non-coordinated (actuated) because the *Rest in Walk* feature can be

[1] Hubbard, S. M., Bullock, D. M., & Day, C. M. (2008). Integration of real-time pedestrian performance measures into existing infrastructure of traffic signal system. *Transportation research record*, *2080*(1), 37-47.

applied for concurrent phases that are coordinated. Similarly, if intersections are pretimed, the Walk interval length is typically extended to match the end of a green phase, making it less applicable for pretimed intersections.

For intersections with the high resolution data, using certain event codes such as “Phase Begin Green (Event Code 1)” and “Phase Begin Yellow Clearance (Event Code 8)”, agencies can develop phase green time distributions over a certain time period (e.g., AM peak, midday, PM peak etc.). This information can then be used to identify intersections/phases in which Walk time can be increased for a certain time of day without causing any major impacts to vehicular traffic. **Figure 6** provides a hypothetical example of how Walk time for pedestrians can be increased and adapted to vehicular demand. In this example, the Walk time and Flashing Don’t Walk (FDW) time are initially set to 7 seconds and 10 seconds, respectively (therefore a minimum green time of 17 seconds is required to serve pedestrians, showed in the vertical dash line). The green time distribution curve for the concurrent vehicular phase indicates that with the 7 seconds of Walk time, the pedestrian phase was terminated during most cycles (about 90-95% of the cycles) while its concurrent vehicular phase remained green for an extended duration, indicating opportunities for extending the Walk time for pedestrians. According to the green time distribution data, increasing minimum pedestrian green time from 17 seconds to 27 seconds (i.e., increasing Walk time by 10 seconds) would have small impact on traffic operations since the green time for the concurrent vehicle phase remains green for more than 27 seconds during most cycles to serve its vehicular demand.

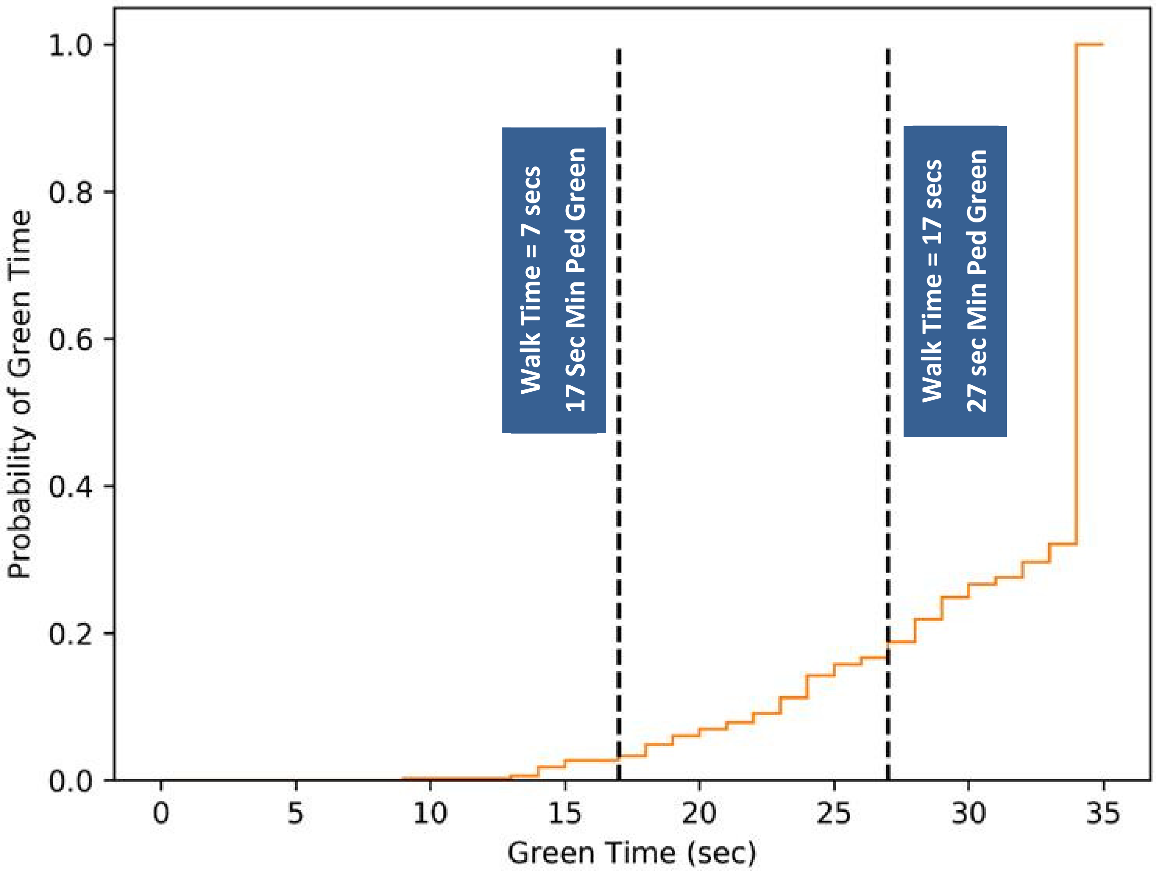


Figure 6: Concurrent vehicular phase green time distribution example to identify candidate intersections for increasing the Walk duration for pedestrians

Following the methodology described above, the research team used the high-resolution data received from INDOT to determine if any opportunities exist to increase the Walk interval based on the vehicle demand. The research team applied the methodology to selected intersections with high pedestrian activity (using the filtering and prioritization process discussed above). One of the intersections that the methodology was applied is the intersection of U.S. 31 and Home Avenue/Westenedge Dr., in Columbus, Indiana (**Figure 7**). All turning movements have a permissive only phasing, leading to two-phase operation (i.e., east-west and north-south), as shown in **Figure 8**. The east-west approach (U.S 31) is the mainline movement carrying higher traffic volumes.

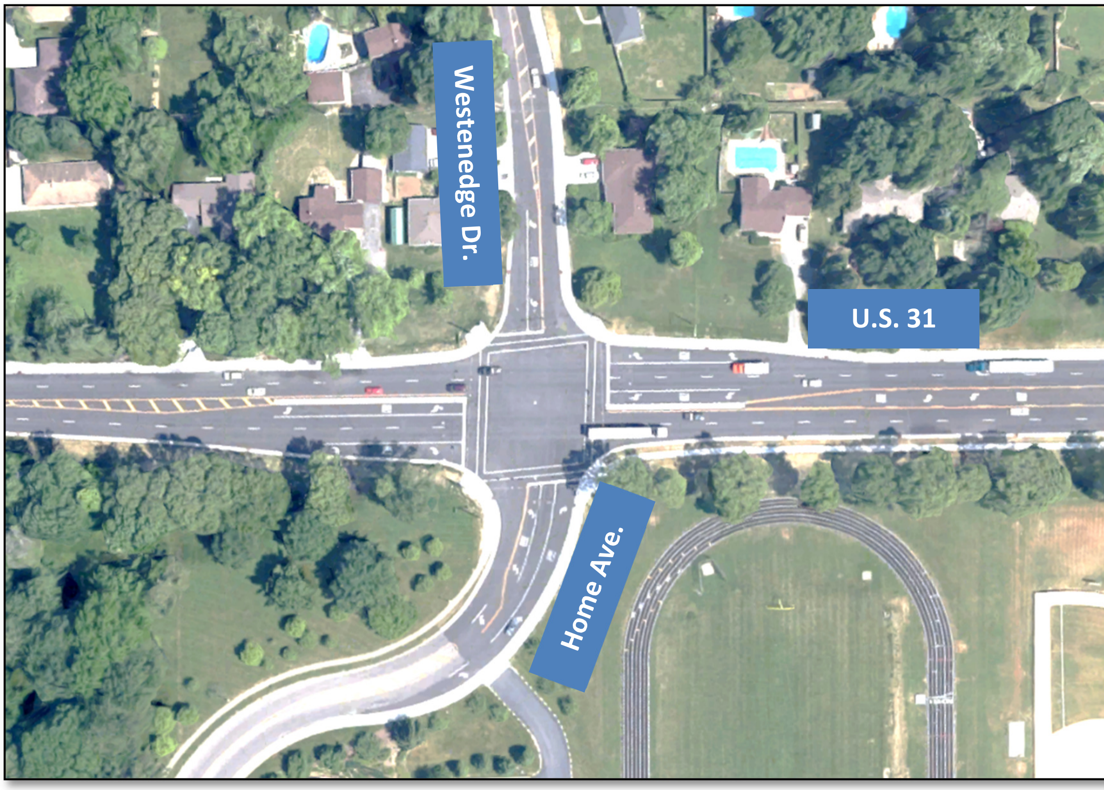


Figure 7: Aerial view of U.S. 31 and Home Avenue/Westenedge Dr., in Columbus, Indiana.

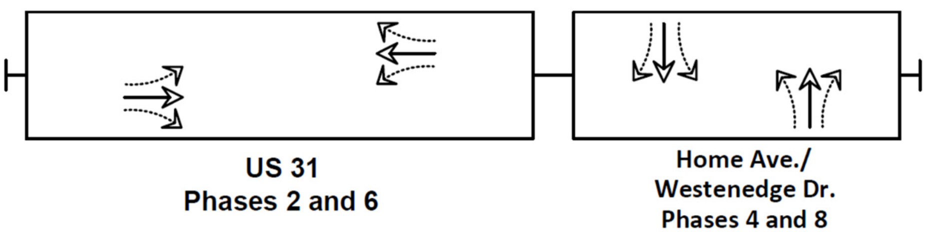


Figure 8: Signal Phasing at the intersection of U.S. 31 and Home Avenue/Westenedge Dr.

Using the high-resolution data, the team extracted Walk time, FDW time, and minimum green intervals for each programmed phase, as shown in **Table 1**. In addition, the data indicated that all pedestrian phases are actuated with push button actuation.

Table 1: Minimum Green, Walk and Flashing Don't Walk intervals for each programmed phase extracted from the high-resolution data

Mode	Phase	Minimum Green/ Walk (s)	Flashing Don't Walk (s)	Change Interval/Buffer (s)	Crossing Distance (ft)
Vehicles	*2*	*10*	*N/A*	*5*	*N/A*
	4	*7*	*N/A*	*5*	*N/A*
	6	*10*	*N/A*	*5*	*N/A*
	8	*7*	*N/A*	*5*	*N/A*
Pedestrians	*2*	*8*	*25*	*5*	*93*
	4	*9*	*30*	*5*	*110*
	6	*8*	*25*	*5*	*93*
	8	*9*	*30*	*5*	*110*

The objective of this analysis was to identify if the Walk duration for the north-south crosswalks that run concurrently with the north-south vehicular movements (i.e. phase 4 and phase 8). As a result, the green time distributions for phase 4 and phase 8 were calculated during weekdays and non-weekdays by time of day (4th of July was excluded from the analysis). **Figure 9** displays the 30th percentile green times for phase 4. Only phase 4 is shown since phase 8 has the exact green time distribution as they both start and end at the same time in each cycle. It should also be noted that the 30-percentile green time was selected based on our discretion so that if the minimum pedestrian green times were set to the 30-percentile green time, the cycles would get elongated only about 30% of the time when there is a pedestrian call.

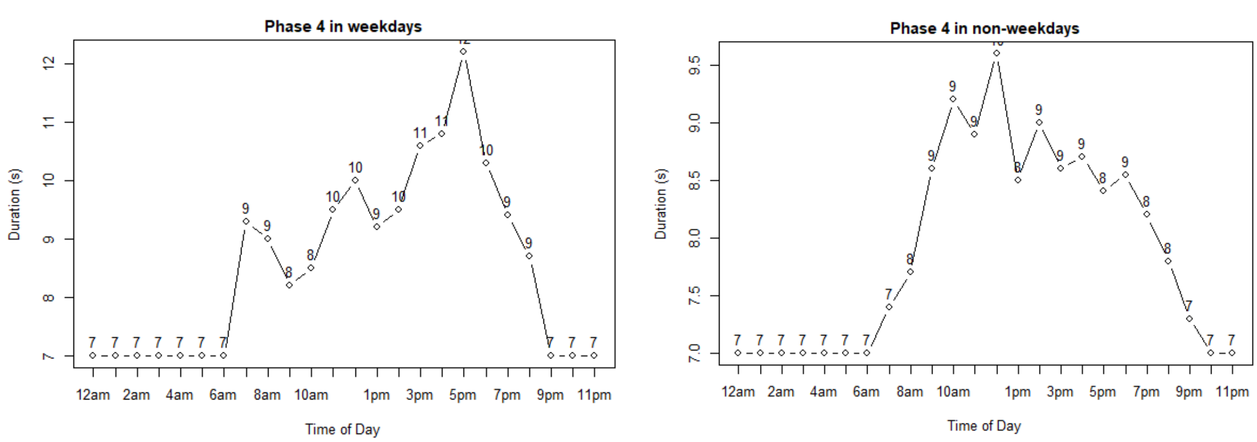


Figure 9: 30th percentile green duration for each phase during weekdays and non-weekdays

The analysis indicated that due to low side street traffic demand, side street green phase durations are low throughout the day. Results show that the 30th percentile green times during the weekday are in the range of 10 seconds, substantially lower than the minimum pedestrian green time required to serve pedestrians (9 seconds of Walk time and 30 seconds of Flashing Don't Walk). As a result, it is found that at this intersection, it is not possible to increase the Walk duration for the side streets without causing any delay to the mainline movement.

It should be noted that only the results from one intersection is shown in this document. The research team applied the same methodology to identify opportunities at other intersections with high pedestrian activity to apply the *Maximizing Walk Interval Length* treatment. The findings, however, were very similar that there were very little opportunities to increase Walk time. This can be explained by two reasons: (1) most intersections have wide crossings across the mainline, which requires long pedestrian clearance intervals, and (2) most intersections with high pedestrian activity have low side street vehicular volumes, which result in short green durations, limiting the ability to extend the Walk duration without causing longer green time for vehicles. Therefore, it is concluded that this treatment can be more applicable at intersections in which crossings are shorter and the green time to serve vehicular demand is long during most cycles.

Pedestrian Recall

When pedestrian phases are set on recall, a call for pedestrian service is placed automatically every cycle. This results in a moderate delay reduction for pedestrians because with recall a pedestrian arriving during the time nominally reserved for the Walk interval will be served immediately, while with pushbutton actuation, pedestrians may not be served until the next cycle. However, pedestrian recall can reduce intersection capacity and increase delay for conflicting traffic, including pedestrians on other crosswalks. The impact is most pronounced when the crossing has a long pedestrian clearance (e.g., crossing a wide arterial).

A companion white paper for this research investigated the effects of setting pedestrian phases crossing mainline movement on recall along a coordinated-actuated arterial (i.e., recall for the crosswalk that runs concurrently with the side street). One of the key findings of the research was when the side street green time required to serve vehicles increases, the impact of pedestrian recall on intersection delay becomes small. This finding suggests that for certain time periods where there is heavy vehicle demand and the side street phase split is often governed by the vehicle needs, setting pedestrian phases on recall may have very little impact on intersection capacity.

For agencies that have the high resolution data logging capability, similar to the *Maximizing Walk Interval Length* treatment discussed above, vehicle green time distribution in the absence of pedestrian calls can be calculated by time-of-day. The green time distribution can then be compared against the minimum green time required to serve pedestrians. For intersections in which the required side street green time for vehicles is longer than the minimum green time to serve pedestrians during most cycles, pedestrian recall can be configured for the side street with little or no impact on vehicle operations and capacity.

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Pedestrian Recall versus Actuation Research

Kittelson & Associates, Inc.

In association with:

Northeastern University
Accessible Design for the Blind
Wayne State University

August 31, 2020

INTRODUCTION

The purpose of this memorandum is to present the findings of the additional research that was performed on "*Pedestrian Recall versus Actuation*" to provide specific guidance for agencies on when to set pedestrian phases on recall.

At signalized intersections, pedestrian phases can be configured as recall or pushbutton-actuated. With pedestrian phases on recall, a call for pedestrian service is placed automatically every cycle, resulting in the controller timing its Walk and pedestrian clearance interval, which begins with the Flashing Don't Walk (FDW) interval and can include several seconds' additional buffer time before a green signal is displayed to conflicting traffic. With pedestrian actuation, the pedestrian phase is omitted from a cycle unless a pedestrian manually places a call to the controller.

Pedestrian recall yields a moderate reduction in pedestrian delay, because with recall a pedestrian arriving during the time nominally reserved for the Walk interval will be served immediately, while with pushbutton actuation, pedestrians may not be served until the next cycle. This effect is not recognized in the *Highway Capacity Manual*'s pedestrian delay formula [1]. Lower pedestrian delay in turn improves pedestrian safety because it tends to improve pedestrian compliance [2] [3]. Kothuri also found that pedestrian recall led to greater pedestrian compliance than pedestrian actuated crossings [4]. In addition, with pedestrian actuation, if pedestrians who do not push a button when they are not first to arrive, when concurrent vehicular phase receives a green display (but without the pedestrian signal since no one pushed the button), pedestrians may start their crossing without the protection of the pedestrian signal, which may leave them partway through their crossing when a conflicting movement receives a green display. Pedestrian recall eliminates this type of conflicts and therefore improves safety.

However, by forcing a pedestrian phase to occur in every cycle, even when no pedestrians are present, the pedestrian recall decision constrains the signal cycle, with impacts other users. It can reduce intersection capacity and increase delay for conflicting traffic, including pedestrians on other crosswalks. The delay impact is most pronounced when the crossing has a long pedestrian clearance (e.g., crossing a wide arterial) and when the intersection is operating close to (or above) capacity. In addition, pedestrian recall requires embedding minimum pedestrian timings within the ring-barrier structure, which may lead to longer cycle lengths, which can increase delay to both vehicles and pedestrians and can interfere with arterial progression [5].

Agencies are looking for more specific guidance on when to set pedestrian phases on recall. Available guidance tends to be qualitative, calling for engineering judgment on a case-by-case basis. For example, the Signal Timing Manual (STM) indicates that pedestrian recall may be used at locations and/or times with high pedestrian volumes [6]. The National Association of City Transportation Officials (NACTO) Urban Street Design Guide recommends using pretimed signals in urban areas, which results in pedestrian phases being on recall [7]. Some cities and states have developed their own guidelines regarding pedestrian recall. For example, the City of Boston, Massachusetts recommends that pedestrian pushbuttons be considered at intersections where pedestrians are present for less than 50% of the cycles during peak hours and at intersections designed to operate with vehicle detection that is actuated [8]. The City of Portland, Oregon implements pedestrian recall on the mainline phases to ensure that pedestrian crossings concurrent with the mainline gets served each cycle [4].

Existing guidance recognizes the obvious conclusion that pedestrian recall is appropriate in high pedestrian volume areas (e.g. downtown) where pedestrian demand is present virtually every cycle. Most cities such as New York City, Washington, D.C., and San Francisco regularly use pedestrian recall. These areas often have pretimed signals, allowing agencies to provide longer Walk intervals along with pedestrian recall, further reducing pedestrian delay. Likewise, for crossings with very low pedestrian demand (e.g., pedestrians are present less than 10% of all cycles), existing guidance clearly supports pedestrian actuation with a limited Walk interval (e.g., 7 seconds) in order to limit the impacts of pedestrian timings on vehicular operations. For crossings with an intermediate level of pedestrian demand, however, agencies are interested in guidance as to whether the pedestrian phase should be on recall.

One of the main limitations of current practice is that the pedestrian recall decision generally considers only the pedestrian volume without considering vehicular demand or, more precisely, green time demand for the concurrent vehicular phase. If the green time required to serve the concurrent vehicular phase is longer than the minimum green duration needed to serve pedestrians during most cycles, setting pedestrian phase on recall should have almost no impact on traffic operations. Under those conditions, pedestrian recall may be appropriate even with low pedestrian volumes.

Research is therefore needed to address the following questions related to the recall-actuation tradeoff:

- What would be the impact on traffic if pedestrian phases crossing a major street are put on recall?
- How to judge when setting pedestrian phases on recall would be disruptive to traffic operations?
- Is there a pedestrian volume threshold (or fraction of cycles in which there is a pedestrian call) to determine when to set pedestrian phases on recall vs. actuation?
- How can knowing the green time distribution for the concurrent vehicle phase help determine whether the pedestrian phase can be put on recall with little impact to traffic operations?
- Would the impacts be different for pedestrian phases crossing the major street or the side street?

The objectives of this research were to seek answers to these questions. Specifically, the research team identified situations in which providing pedestrian recall would have little or no impact on traffic operations. The outcomes of this research can provide guidance for agencies to help them identify pedestrian crossings where those opportunities are likely to exist.

This research focused on the effects of pedestrian recall for pedestrians crossing the main arterial (i.e., running concurrently with the side street) since the impact of putting a side street on pedestrian recall has more impacts on traffic operations due to the longer crossing times required. With coordinated-actuated operation, a traffic signal control strategy that is commonly used in the U.S., setting the mainline phases on pedestrian recall usually has no impact on intersection performance since the coordinated phases are served every cycle and are usually guaranteed enough green time to serve the pedestrian phase.

METHODOLOGY

In this research, VISSIM microsimulation software was utilized to model the impacts of pedestrian recall versus actuation. A base model was developed using a real network in Fairfax County, Virginia. All the data required for the development of the model were gathered from the field. Maintaining the same roadway geometry, vehicle and pedestrian volumes were adjusted to create and test various scenarios (see below for details). The following sections provide a detailed description of our methodology.

Base Model Development

Five signalized intersections were chosen from the Richmond Highway (U.S. Route 1) corridor in Fairfax County, Virginia, as shown in **Figure 1** (*indicates the intersection). Russell Road was selected as the analysis intersection in which pedestrian recall and actuation were tested under various scenarios. This intersection was selected as it is a noncritical intersection with slack capacity whose cycle length is controlled by another intersection on the arterial. Therefore, providing pedestrian recall here will not cause oversaturation.

(*indicates the subject intersection that was analyzed)

Figure 1: Richmond Highway Simulation Network in VISSIM and Study Intersections

Base signal timings were obtained from Virginia Department of Transportation (VDOT) for the Richmond Highway corridor. However, since only a subset of intersections was considered for this analysis, cycle lengths and splits were re-optimized using Synchro, maintaining the existing phase sequences and the coordinated-actuated operation mode. This led to a corridor cycle length of 110 seconds (shorter than the existing cycle length).

At our test intersection (i.e., Russell Road), two crosswalks were modeled and analyzed in our model:

i. Pedestrians crossing the mainline (i.e., Richmond Highway), concurrent with the side street vehicular movement. As discussed earlier, pedestrian recall versus actuation was tested only for this crossing. The Walk interval was limited to 7 seconds; the pedestrian clearance interval consists of 20 seconds of FDW. By Virginia DOT policy, pedestrian clearance interval must be completed before the vehicular change interval (yellow and red clearance) begins. Therefore, the yellow and red clearance intervals are considered as part of the buffer time.

ii. Pedestrians crossing the side street (i.e., Russell Road), concurrent with the coordinated mainline movement. This crossing was set to recall and operate in Rest in Walk mode. With the Rest in Walk mode, a controller dwells in the Walk interval while the concurrent vehicular phase is green, starting FDW at the moment when the necessary pedestrian clearance will end simultaneously with the scheduled end of vehicular green. No experimentation was done with this crossing; it was modeled only to measure the effects of pedestrian recall versus actuation on the other crossing.

Scenario Testing and Variables

Sensitivity runs were performed at the test intersection/crosswalk by varying pedestrian demand, and thus the probability of pedestrian calls in a given cycle. The side street volume, and thus average green time required to serve side street demand was also varied in the experiments. This was expressed as a fraction of minimum green time needed to serve a pedestrian phase (calculated as Walk + FDW). **Table 1** summarizes all the scenarios analyzed in our research. A total of 60 scenarios were modeled and analyzed in VISSIM {5 pedestrian probability scenarios * 6 side street scenarios * 2 pedestrian mode settings (ped recall and ped actuation)}.

Table 1: Simulation Scenarios Considered for the Analyses

Probability of pedestrian demand in a given cycle (henceforth denoted as "PP")
0.1 (4 peds/hr)*
0.3 (12 peds/hr)*
0.5 (24 peds/hr)*
0.7 (42 peds/hr)*
0.9 (80 peds/hr)*

Side street green time required as a fraction of minimum pedestrian green time needed (hencefore denoted as "SSG")
0.5
0.6
0.7
0.85
1.0
1.2

*values in parentheses indicate hourly pedestrian volumes corresponding to each pedestrian probability

The probability of pedestrian demand in a cycle (PP) is related not only to pedestrian volume, but also to the Walk interval and cycle length. For the experimental site, pedestrian volumes for each PP scenario were calculated assuming a Poisson arrival process for pedestrians, which leads to the following equation:

$$Hourly\ Pedestrian\ Volume = \frac{-\ln(1-PP)}{[C-(PP*W)]}*3600 \qquad (1)$$

where PP = probability of pedestrian demand in a given cycle, C = cycle length (s), and W = Walk interval length (s).

To convert SSG values into hourly vehicular volumes that can be entered as an input to the VISSIM experimental setup, the following formula was first utilized using the lost time concepts identified and described in Furth et al., for the actuated approaches [9].

$$Hourly\ Vehicular\ Volume = \frac{\left[(Walk+FDW)*SSG-L_{start\ up}-L_{end}\right]*SatFlow}{Cycle\ Length} \qquad (2)$$

where $L_{start\ up}$ is the start up lost time, assumed as 2 seconds, L_{end} is the end lost time, assumed as 3 seconds, and Sat Flow is the saturation flow rate, assumed as 1,800 vehicles per hour per lane. It should be noted that after the initial volumes were calculated using equation (2) and entered into the simulation, the actual green times were obtained from VISSIM and compared to SSG values given in **Table 1**. Where there are differences, hourly vehicular volumes were slightly adjusted in VISSIM to match the SSG values.

Base Signal Timing

For all the scenarios tested, a cycle length of 110-seconds was assumed along the corridor and at our test intersection (i.e., Russell Road). For SSG values below 1.0, the side street phase maximum green duration was fixed to 27 seconds to meet the minimum pedestrian green requirements (7 seconds Walk and 20 seconds of FDW, as discussed above). For SSG values of 1.0 and 1.2, the side street phase maximum green duration was increased to accommodate side street vehicle demand, where extra green time borrowed from the coordinated phases in order to maintain the same cycle length.

Selected Performance Measures

The following performance measures were used:

- Average pedestrian delay for pedestrians crossing the arterial
- Average pedestrian delay for pedestrians crossing the side street
- Average intersection vehicle delay
- Average network vehicle delay
- Phase green time distribution, including average green times, for the side street as well as the coordinated phase.

Pedestrian delay measures assume full pedestrian compliance. Reported results are averages of ten simulation runs performed for each scenario and recall setting combination, each with different random seeds. Delay effects associated with each scenario are reported using the measure *Delay Change*, given by:

$$Delay\ Change = Delay\ with\ Ped\ Recall - Delay\ with\ Ped\ Actuation \qquad (3)$$

Therefore, a positive delay change indicates that pedestrian recall increases delay, while a negative value indicates that pedestrian recall reduces delay.

RESULTS

Figure 2 shows delay change for pedestrians crossing the main arterial with pedestrian actuation and recall. Delay change is the same for all SSG values. Results indicate that with low values of PP (e.g., PP = 0.1), the delay change is nearly equal to the length of the Walk interval (7 seconds), because the low probability of pedestrian demand in the previous cycle makes it unlikely that a pedestrian arriving in the first 7 seconds of a cycle will be greeted by a Walk interval. With high values of PP, there is a high chance that another pedestrian arrived earlier in the cycle and pushed the button, giving an arriving pedestrian almost the same effect as if the pedestrian phase were on recall. Therefore, delay reduction is smaller as the PP values increase.

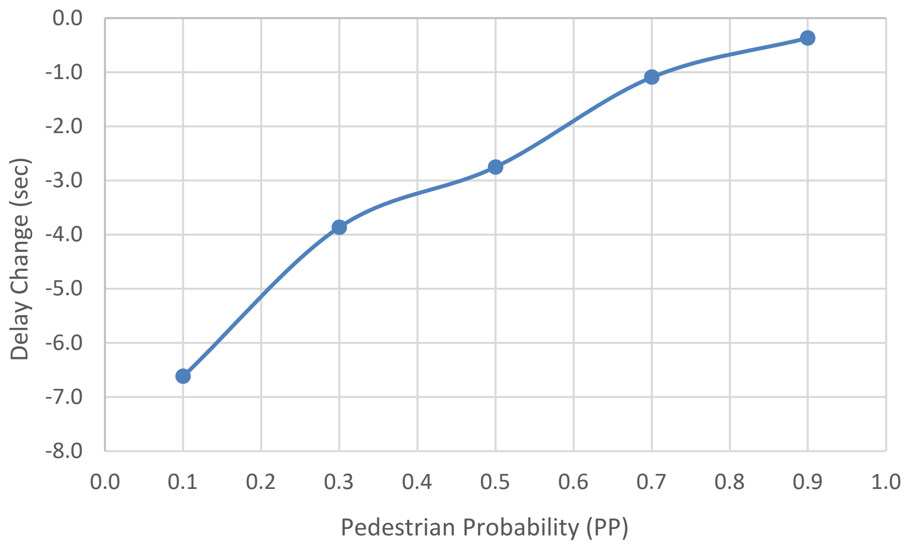


Figure 2: Average Pedestrian Delay Change for Pedestrians Crossing the Main Arterial under Various Probability of Pedestrian Call (PP) Scenarios

Figure 3 shows delay change for pedestrians crossing the side street. Recall that for this crossing, the pedestrian phase is assumed to be on recall with the Rest in Walk feature. Therefore, the change in green duration for the mainline movement also affects delay for pedestrians. For pedestrians crossing the side street (running concurrently with the coordinated mainline movement), however, pedestrian recall increases delay, resulting in negative delay change. This is because the mainline movement was set to Rest in Walk. With pedestrian recall on side street, average mainline phase green time is reduced since there is no early return to the coordinated phases. This also leads to a shorter Walk interval for pedestrians, resulting in an increase in average pedestrian delay. For example, results show that with PP = 0.1 and SSG = 0.5 (the highest impact scenario), average pedestrian delay is increased by almost five seconds. Another important finding is that with high SSG scenarios (e.g., SSG $\geq$ 0.85), regardless of the PP values, the impact of pedestrian recall becomes small. This is because putting side street on recall does not increase side street phase green time as much since the side street vehicular demand already requires long green times, limiting the impact of pedestrian recall on the phase green time for the mainline movement.

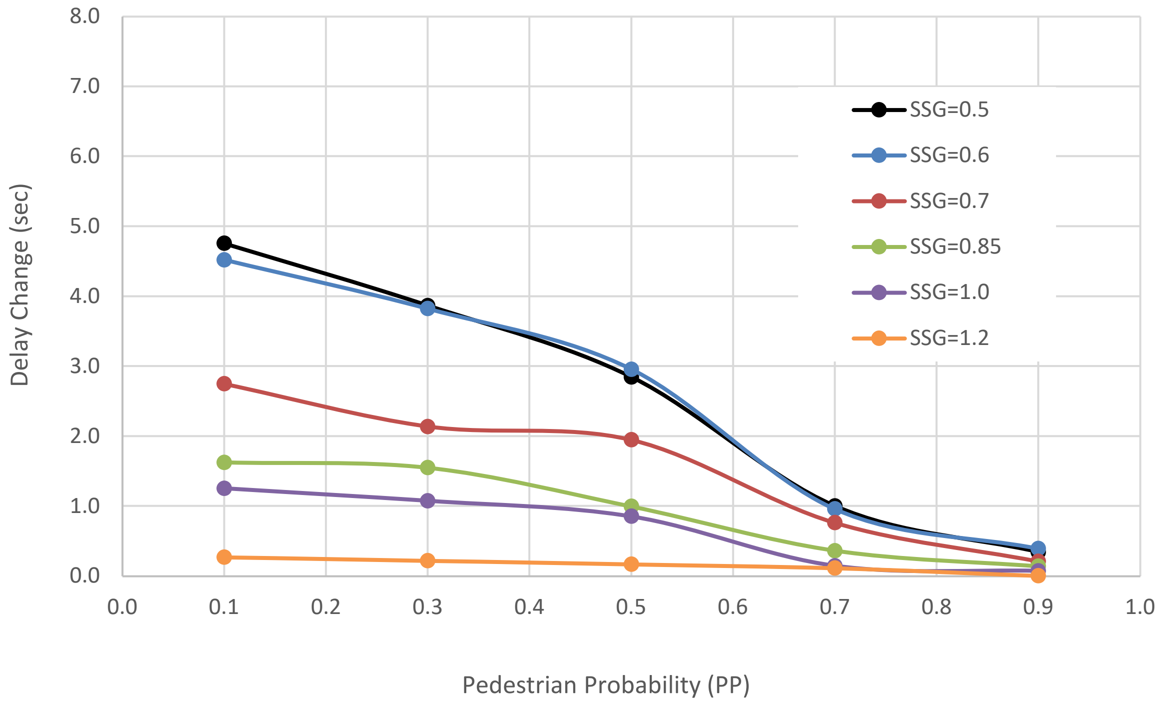
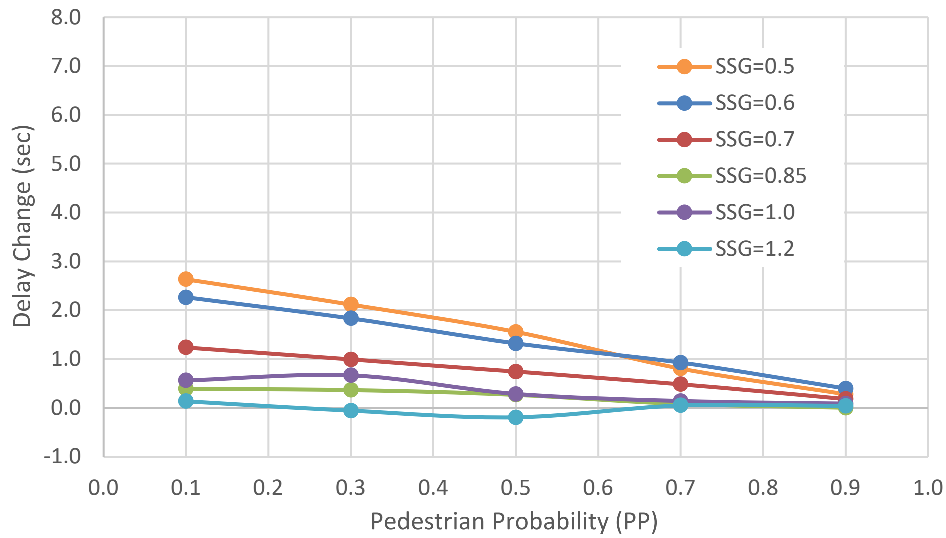


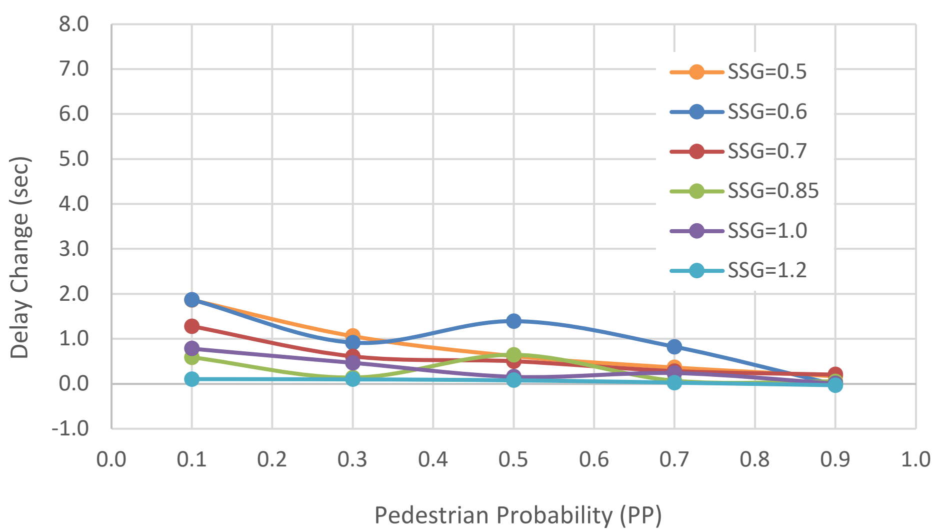
Figure 3: Average Pedestrian Delay Change for Pedestrians Crossing the Side Street under Various Probability of Pedestrian Call (PP) and Side Street Green Ratio (SSG) Scenarios

It is worth highlighting that for agencies that do not use the Rest in Walk feature, pedestrian recall would have no delay impact for pedestrians crossing the side street since the Walk duration would remain the same. Furthermore, from a pedestrian delay perspective, while the change in pedestrian delays almost offset each other for the low SSG scenarios, reducing pedestrian delay for crossing the main arterial from 59 seconds to 52 seconds with PP = 0.1 is likely a much bigger benefit than increasing pedestrian delay for crossing the side street from 8 seconds to 13 seconds. This is due to the potential safety benefit of reducing a large delay through increased compliance that is not captured in this research. In addition, with no pedestrian recall and pedestrians facing a large delay, there is a high risk of pedestrians illegally crossing and getting caught in the middle of a crossing when the green signal transitions to a conflicting phase. This likely safety benefit is also not captured in this research.

Figure 4 displays overall intersection and network delay change for vehicles under various PP and SSG scenarios. Intersection delay results indicate similar findings where the impact of pedestrian recall on average intersection delay is negligible when SSG $\geq$ 0.85. With lower SSG and PP scenarios, the increase in intersection delay becomes more pronounced, though still the increase is still less than three seconds for all the scenarios. This is partly because the results are obtained from a scenario in which platoons from upstream intersections arrive at the study intersection towards the middle of the green phase. As a result, while pedestrian actuation allows returning to the coordinated phase early in the absence of a pedestrian call, the effect of pedestrian recall is generally small since platoons arrive later during the green phase. In this case, the main benefit of pedestrian actuation is for the turning vehicles from side streets onto the mainline at upstream intersections since starting the mainline green phase early would reduce their delay. To explore the effects of pedestrian recall on intersection delay under different coordination patterns and progression bands, additional sensitivity runs were performed, as discussed in detail in the next section.



a. Intersection vehicle delay



b. Network vehicle delay

Figure 4: Vehicle Delay Change under Various Probability of Pedestrian Call (PP) and Side Street Green Ratio (SSG) Scenarios

Network delay change also shows similar results where the impact of pedestrian recall is very limited under high SSG scenarios. One interesting finding is that the network delay impact is slightly smaller than intersection impact. This can be attributed to the effect of coordinated control system along an arterial. With pedestrian recall, while some vehicles may be getting stopped at the subject intersection, these vehicles could have been stopped at the next intersection without pedestrian recall, which results in a lower network delay impact compared to the intersection impact.

In addition to the intersection and network delay results, phase green time distributions including average green duration for the side street and the mainline were recorded to provide further insights into the results. **Figure 5** presents green time distributions for each SSG scenario when there are no pedestrians crossing the mainline at the study intersection. The minimum pedestrian green duration (27 seconds) to serve pedestrians is also shown on the graph in vertical dashed line to provide reference. Results support the findings discussed above. With high SSG scenarios, it can be observed that phase green duration was longer than the minimum pedestrian green time in most cycles, indicating that setting pedestrian recall would have little to no impact. For example, when SSG = 1.0, less than 30% of the cycles had a green duration that is less than 27 seconds and when SSG = 1.2, only about 18% of the cycles required green duration that is less than 27 seconds.

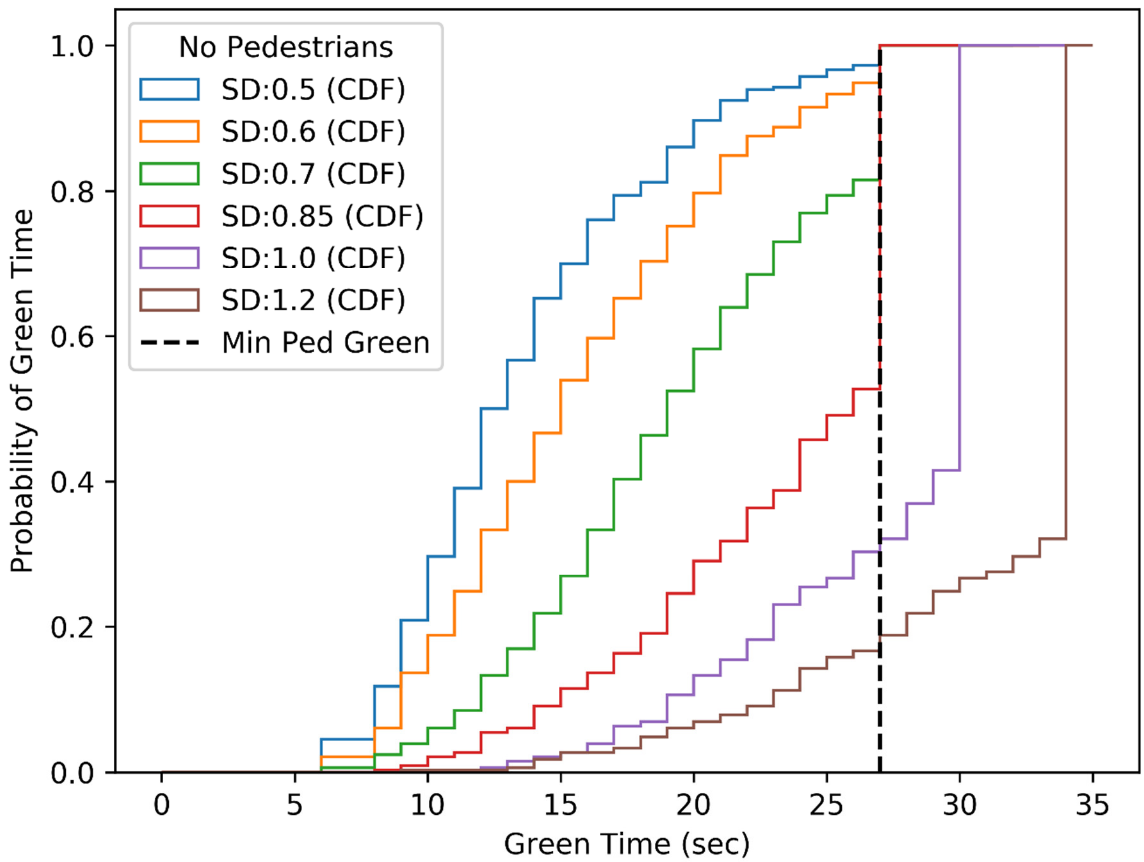


Figure 5: Green Time Distributions and Cumulative Distribution Functions (CDF) for each SSG Scenario When Pedestrian Volume Crossing the Mainline is Zero (i.e., No Pedestrian Calls)

Progression Band Sensitivity Scenarios

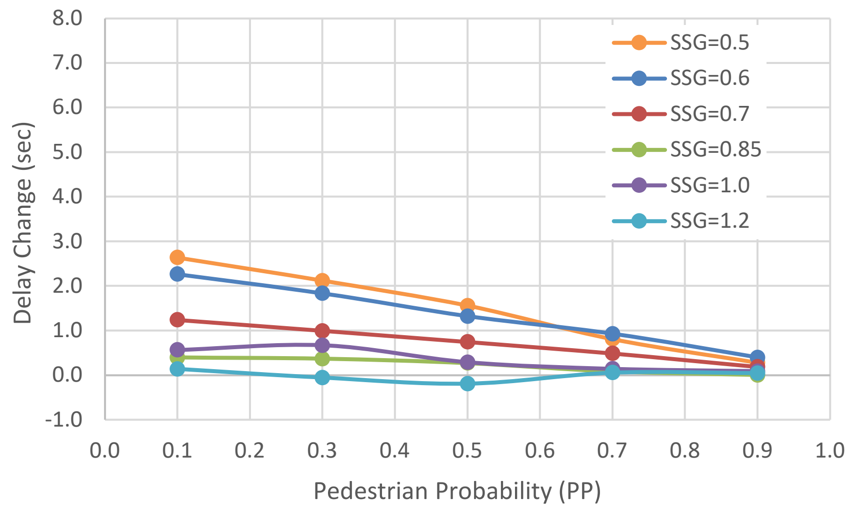
As discussed above, additional sensitivity scenarios were performed to measure the impacts of pedestrian recall on intersection delay under different coordination patterns and progression bands, which was achieved by changing the intersection spacing in the model. With the sensitivity runs, the cycle length and splits were maintained, but intersection spacing in both directions and offsets were adjusted such that platoons are arriving at different points of the mainline green phase at the subject intersection. **Table 2** describes the sensitivity runs performed.

Table 2: Experiment Details for the Progression Band Sensitivity Scenarios

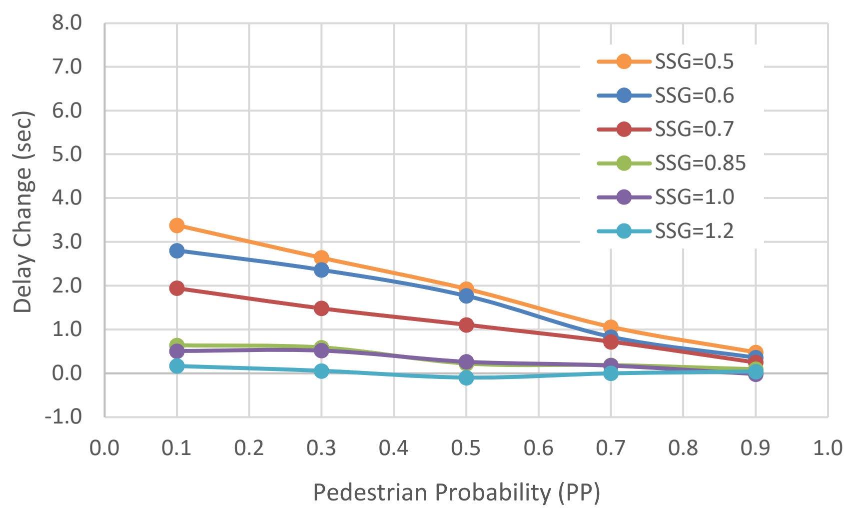
Sensitivity Scenario and Description	Platoon Arrival Pattern
Left-Skewed (i.e., the subject intersection is closer to Mohawk Lane intersection). This is the original scenario discussed above.	• Eastbound platoon arrives towards the middle of the green phase • Westbound platoon arrives towards the middle of the green phase
Middle-Skewed (i.e., the subject intersection is in the middle of Mohawk Lane and Janna Lee Avenue intersection)	• Eastbound platoon arrives towards the middle of the green phase • Westbound platoon arrives towards the start of the green phase
Right-Skewed (i.e., the subject intersection is closer to Janna Lee Avenue intersection)	• Eastbound platoon arrives before the green phase starts • Westbound platoon arrives towards the middle of the green phase

Results of the sensitivity scenarios for the average intersection vehicle delay are displayed in **Figure 6.** The original results that were previously discussed above for the left skewed scenario are also provided for comparison purposes. It should be noted network delay results were very similar to the intersection delay results, and thus not included.

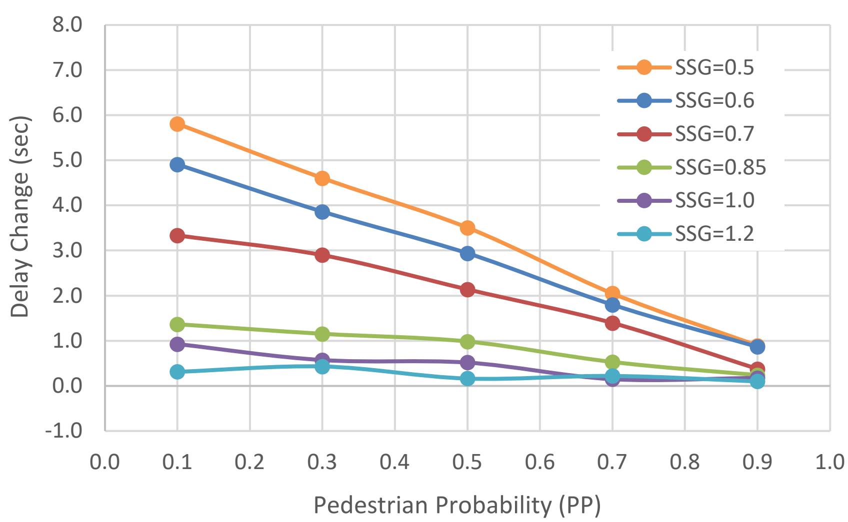
Results show that for the middle-skewed scenario, the findings are almost identical to the left skewed scenario with an increase in average intersection delay is less than 0.5 seconds. This is because platoon arrival patterns for these two scenarios are similar. The impact of pedestrian recall on intersection delay for the right-skewed scenario, however, is considerably higher. This is because with the right-skewed scenario, platoon arrivals are non-ideal since the eastbound platoon arrives before the green phase starts for the mainline. This, in turn, causes larger vehicle delays when the side street is set to pedestrian recall because recall eliminates the early return to the coordinated phase, adding additional delay for the mainline movements. As a result, the sensitivity runs conclude that, for coordinated arterials, the impact on pedestrian recall on vehicle delay may be different depending on the progression bands and arrival patterns and results can be site-specific.



a. Left-Skewed (Original) Results



b. Middle-Skewed Results



c. Right-Skewed Results

Figure 6 Progression Band Sensitivty Results: Intersection Vehicle Delay Change under Various Probability of Pedestrian Call (PP) and Side Street Green Ratio (SSG)

SUMMARY AND CONCLUSIONS

This research investigated the effects of setting pedestrian phases on recall along a coordinated-actuated arterial to identify situations in which providing pedestrian recall would have little or no impact on traffic operations. The research studied the effects of pedestrian recall for pedestrians crossing the main arterial because the impact of putting side street on pedestrian recall has more impacts on intersection capacity due to the longer crossings required. The impacts of pedestrian recall were analyzed by varying probability of pedestrian calls in a given cycle (by changing pedestrian demand) and the green time required to serve the side street vehicular phase as a fraction of the minimum green time required to serve pedestrians.

Results show that with low pedestrian volumes, the delay reduction is nearly equal to the Walk duration. This is because with pedestrian actuation, the low probability of pedestrian demand in the previous cycle makes it unlikely that a pedestrian arriving during the Walk interval will have the Walk indication. With high pedestrian values, delay reduction with pedestrian recall is almost zero because there is a high chance that another pedestrian arrived earlier had already placed a call.

Another important finding is that when the side street green time required to serve vehicles increases (as a fraction of the green time required pedestrians), the impact of pedestrian recall on intersection delay becomes small. In particular, when the fraction is higher than 0.85, there is negligible impact on intersection delay. This finding suggests that for certain time periods where there is heavy vehicle demand and the side street phase split is governed by the vehicle needs, setting pedestrian phases on recall may have very little impact on intersection capacity. To eliminate confusion for pedestrians when recall was applied based on the time of day, it is recommended for agencies to use call indicators for pedestrian pushbuttons to provide real-time feedback for pedestrians confirming that their call for service has been registered, and illuminating the call indicator by default (automatically) when pedestrian phases are on recall.

Finally, the sensitivity analysis conducted for this research showed that progression patterns and the arrival of platoons (e.g., platoons arriving towards the beginning of a green phase vs. middle of a green phase) might have different impacts on intersection delay when the side street phase split is governed by pedestrian minimum green requirements. As a result, for coordinated arterials, the impact of pedestrian recall can vary, and results can be site-specific.

REFERENCES

[1] "The Highway Capacity Manual 6th Edition," TRB, 2016.

[2] S. C. Otis and R. B. Machemehl, "An analysis of pedestrian signalization in suburban areas," Center for Transportation Research, Bureau of Engineering Research, the University of Texas at Austin., 1999.

[3] R. Van Houten, R. Ellis and J. L. Kim, "Effects of various minimum green times on percentage of pedestrians waiting for midblock “walk” signal," *Transportation Research Record,* pp. 78-83, 2007.

[4] S. M. Kothuri, "Exploring Pedestrian Responsive Traffic Signal Timing Strategies in Urban Areas.," National Institute for Transportation and Communities, 2014.

[5] S. E. Chowdhury, S. A. S. and N. Mitrovic, "Estimating pedestrian impact on coordination of urban corridors.," *Transportation Research Record,,* vol. 2673, no. 7, pp. 265-280, 2019.

[6] T. Urbanik et al., Signal Timing Manual - Second Edition, The National Academies Press, 2015.

[7] National Association of City Transportation Officials, Urban Street Design Guide, 2013.

[8] CIty of Boston, "Boston Complete Streets Design Guidelines," 2013.

[9] P. G. Furth, B. Cesme and T. H. J. Muller, "Lost Time and Cycle Length for Actuated Traffic Signal," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2128, no. 1, pp. 152-160, 2009.

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Task 8 –Stakeholder Engagement

Kittelson & Associates, Inc.

In association with:

Northeastern University
Accessible Design for the Blind
Wayne State University

August 31, 2020

SECTION 1 – INTRODUCTION

The objective of panel and stakeholder engagement is to gather feedback on traffic signal design and operations strategies for non-motorized users. The project team conducted three in-person workshops with agency stakeholders in Lansing, Michigan; Tampa, Florida; and Portland, Oregon. The workshops focused around four (4) key learning objectives:

- Directly engage public agencies, with a mix of planning and engineering staff, on existing practices for signal design and control for non-motorized users.
- Identify success stories, best practices, and lessons learned in the following areas: signal design and control in the project development process, signalized intersection performance management, institutional policies on non-motorized user safety
- Focus dialogue around basic and/or systemic solutions, with an emphasis on how collaboration and clear communication can be used to improve the odds of project success
- Create a high-level proceedings document with links to resources from the peer exchange participants, which can be made accessible as an appendix to the full NCHRP report, as well as individually shared with participants in the workshops.

This feedback expands the written guidance and best practices identified through the Toolbox development and documents implementation challenges experienced by practitioners. This technical memorandum provides an overview of the workshops and describes key findings.

SECTION 2 – WORKSHOP OVERVIEW

Each workshop was organized into three main sections: project overview, local case studies, and a facilitated discussion on innovations and barriers.

Overview of the Research Project:

The Project Team shared the goals of the research project and provided an overview of work done to date. This included an overview of the workshops objectives and the information being requested form participants.

Case Studies

The workshop participates shared case studies about local bicycle and pedestrian treatment or policy implementation. The presenters were asked to address the following questions:

- What data (if any) was used to drive your decision-making? What data would have been useful?
- How did you decide which mode(s) to prioritize at the intersection?
- What performance measure(s) (if any) were used to evaluate the treatment?
- Were than any unexpected barriers to implementation of the treatment?

- Were there any policies or stakeholders that really stood out in helping the project along? If so, how did this specifically make things run more efficiently?

The presentations were followed by a brief time period for questions and discussion before the next presentation. The goal of these presentations was to shift participants from an abstract to a concrete frame of mind with respect to challenges associated with implementing signalized intersection strategies for pedestrians and bicyclists, as well as to make participants more comfortable sharing with one another. The lessons learned from the morning case study presentations also served as a baseline for discussion in the next session.

Facilitated Discussion

The discussion session focused on applying experiences from the case study presentations, along with other experiences raised by the group, to the following thematic areas:

- Increasing accessibility and acceptance of innovative treatments (Raising the Roof)
- Increasing the use of systemic treatments and improving minimum standards (Raising the Floor)
- Improving collaboration and information sharing (Razing Barriers to Implementation)

These questions were used as a starting point. The discussion was then driven by areas of significant participant interest distilled from the case study session.

Questionnaire

In addition to the formal agenda items, a questionnaire was distributed to the attendees during each workshop to collect information on treatments that are more commonly used, and the type of information agencies are seeking to increase their level of comfort to implement certain treatments. The following summarizes the results of the questionnaire:

- The following treatments are commonly used by the agencies at the workshops: walk countdown, pedestrian recall, rest in walk, no turn on red, independently mounted pushbuttons, and short cycle lengths.
- Some agencies have started to use the following treatments: accessible signals without push button actuation, bicycle detection, adaptive walk intervals, permissive periods for pedestrian actuation, protected left turns for non-motorized users, and concurrent yet protective crossings.
- Maintenance was a common reason for not implementing treatments and the need for more guidance on the benefits.

Detailed results are provided in Appendix B.

SECTION 3 – PARTICIPANTS

Three (3) workshops were conducted between July and August 2019 with a total of 35 participants. Each of the workshops were coordinated with local City or DOT staff assisting in workshop logistics. Locations of the workshops and participants are summarized in Table 1. Sign-in sheets are provided in Appendix C.

Table 1. Workshop Participants

Workshop	Participating Agencies	Number of Participants
Lansing, Michigan July 29, 2019	Michigan DOT City of Lansing City of Ann Arbor Southeast Michigan Council of Governments (SEMCOG) City of Grand Rapids	10
Tampa, Florida August 13, 2019	City of Tampa City of Orlando Florida DOT Hillsborough Area Regional Transit Authority (HART) Hillsborough MPO	14
Portland, Oregon August 22, 2019	Portland Bureau of Transportation (PBOT) Oregon DOT Washington County Clackamas County Portland State University	11

SECTION 4 – KEY FINDINGS

The following summarizes key findings from the agency workshops.

Common Challenges

Agencies expressed a need to apply a more systematic approach to treatment applications. Relying on crash data for justification can be a barrier and is reactive. Additional documentation on treatment benefits would be helpful. Agencies would also like to be able to communicate the ancillary benefits to communities and drivers to increase support for pedestrian and bicycle improvements.

Among the treatment's agencies have started applying, more guidance is needed for left turn conflicts and cycle length trade-offs. Left turn conflicts with pedestrians are a high crash problem and there is a desire for treatments beyond LPIs. Additional guidance is needed on how to balance cycle length and level of protection from turning conflicts.

Maintenance Responsibilities & Responses

Maintenance cost and responsibilities are often shared between the local jurisdiction and state DOT. Local agencies often maintain signals on the state road with reimbursement from the state DOT. In some cases, this allows local agencies more flexibility to implement treatments through routine maintenance. It can also create challenges when local and state agency standards differ. Smaller jurisdictions often partner with their county or state agency to maintain signals in their jurisdiction.

A specific challenge that was brought up by several agencies is detection technologies. There are challenges related to the reliability and accuracy of detection for pedestrians and bicycles and the ongoing maintenance requirements associated with it.

Institutional Barriers

A common sentiment among participants was the desire to do more for non-motorized users, but there are institutional barriers that can prevent of hinder progress and innovation. One of those challenges is the need to update manuals. Some state and local agencies are starting to see multi-modal integration into policy documents and manuals, but not all policies are documented. There was also a desire for more national guidance that can be incorporated in to state and local manuals.

One specific area that could benefit from additional guidance and documentation is ADA considerations. There is generally a lack of uniformity when considering ADA. Some agencies have dedicated staff, while others are more reactive to customer complaints.

Performance Measures

Several jurisdictions rely on crash data to rank and prioritize projects. Because crashes are rare and random events, there is a need for additional ways to understand the quality of service for non-motorized users. Some agencies have started using level of traffic stress and are shifting toward substantive safety approaches.

Level of service (LOS) remains a primary performance measure for signal evaluation, even though agencies have started shifted away from LOS standards. Agencies recognized the needs to take a more comprehensive approach to performance measurement but do not currently have the tools to evaluate service for non-motorized users. Some agencies have started using pedestrian delay and high-resolution traffic data, but this is done on a case-by-case basis.

Staff and Training

Participants were asked about the current training available to staff at all levels, from project managers to technicians. Training documents, job shadowing, and mentoring were the common methods that are used to train new hires. In some cases, vendors and consultants are hired train personnel on equipment, in conjunction with an equipment implementation or as a standalone request.

With the lack of documented practices, there are many unwritten rules related to non-motorized user treatments. This creates a challenge will staff turnover. Retention of qualified employees was mentioned as a concern due to funding and a lack of competitiveness against private entities and companies. Having proper documentation for standard practices will help ease challenges with staff turnover.

Data/Data Needs

Crash data and counts were the most common data sources currently being used by agencies. These data sources however often to do not capture the true needs and demand of non-motorized users. Participants expressed desire to start using additional sources including scooter data and Strava. There is also a need to better understand desire lines and directional information – where people are and where they are going. These additional sources would help agencies identify issues and implement solutions and treatments.

Some agencies have started conducted before and after studies, but this is not consistent. Consistent use of before and after studies would provide more information to help agencies evaluate treatments, understand where they are most effective, and feel more comfortable implementing the treatment at additional locations.

APPENDIX A – WORKSHOP AGENDA

SIGNAL TIMING FOR NON-MOTORIZED USERS
WORKSHOP AGENDA

Location: Sleeping Bear Conference Room, VanWagoner Building — 425 West Ottawa Street, Lansing, MI 48909

Date: Monday, July 29th

Agenda Items

09:00am – 09:15am	Welcome and Introduction of Participants	*Steven Lavrenz, Wayne State University*
09:15am – 09:30am	Overview of NCHRP 03-133 project • Work completed to date • Next steps & goals of workshop	*Kevin Lee, Kittleson & Associates*
09:30am – 10:45am	Case Studies • US24 & Garner – Suburban access management • M-85 Fort Street – Suburban access management • M-5 Grand River – Streetscape Redesign • SEMCOG – Policy & Regional Partnership Experiences	All *Facilitated by Wayne State University*
10:45am – 11:00am	Break	
11:00am – 12:00pm	Case Studies	All *Facilitated by Wayne State University*
12:00pm – 01:00pm	Lunch	
01:00pm – 02:00pm	*Planning, policy, and operations strategies* for implementation: innovations and barriers	All *Facilitated by Wayne State University*
02:00pm – 02:15pm	Break	

SIGNAL TIMING FOR NON-MOTORIZED USERS
WORKSHOP AGENDA

Location: THEA Board Room

1104 E Twiggs St
Tampa, FL 33602

Date: Tuesday, August 13th

Agenda Items

10:00am – 10:15am	Welcome and Introduction of Participants	*Kittelson & Associates, Wayne State University*
10:15am – 10:30am	Overview of NCHRP 03-133 project • Work completed to date • Next steps & goals of workshop	*Kevin Lee, Kittelson & Associates*
10:30am – 12:00pm	Case Studies	
	• Jackson St Cycle Track – Project Development Process	*FDOT, Alex Henry*
	• Cass St Cycle Track – Bike Signals • Smart Paint – Crossing treatments for pedestrians with visual disabilities	*City of Tampa, Vik Bhide*
	• LPI Policy	*FDOT, Ron Chin*
12:00pm – 1:00pm	Lunch	
1:00pm – 2:30pm	*Planning, policy, and operations strategies* for implementation: innovations and barriers	*Facilitated by Wayne State University*
2:30pm – 3:00pm	Discussion Wrap-Up & Closing	*Kittelson & Associates*

SIGNAL TIMING FOR NON-MOTORIZED USERS
WORKSHOP AGENDA

Location: 2nd Floor Conference Room

851 SW 6th Avenue, 2nd Floor
Portland, Oregon 97204

Date: Thursday, August 22

Agenda Items

	09:00am – 09:15am	Welcome and Introduction of Participants	*Kittelson & Associates,*
	09:15am – 09:45am	Overview of NCHRP 03-133 project • Work completed to date • Next steps & goals of workshop	*Kevin Lee, Kittelson & Associates*
	09:45am – 11:30am	Case Studies • Oregon DOT • Washington County • PBOT	*Portland Area Agencies*
	11:30am – 12:30pm	Lunch and survey	
	12:30pm – 1:45pm	Discussion: Planning, policy, and operations strategies for implementation (innovations and barriers)	*Facilitated by Northeastern and Kittelson*
	1:45pm – 2:00pm	Discussion Wrap-Up & Closing	*Kittelson & Associates*

Learning Objectives

- Directly engage public agencies, with a mix of planning and engineering staff, on existing practices for signal design and control for non-motorized users.
- Identify success stories, best practices, and lessons learned in the following areas: signal design and control in the project development process, signalized intersection performance management, institutional policies on non-motorized user safety
- Focus dialogue around basic and/or systemic solutions, with an emphasis on how collaboration and clear communication can be used to improve the odds of project success
- Create a high-level proceedings document with links to resources from the peer exchange participants, which can be made accessible as an appendix to the full NCHRP report, as well as individually shared with participants in the workshops.

APPENDIX B – WORKSHOP QUESTIONNAIRE

PLEASE USE THE FOLLOWING SCALE TO ANSWER QUESTIONS 1 & 2 BELOW:

0 = NOT AT ALL 1 = TO A SMALL EXTENT 2 = TO SOME EXTENT 3 = TO A MODERATE EXTENT 4 = TO A GREAT EXTENT 5 = TO A VERY GREAT EXTENT

Treatment Category	**Treatment Name**	**Treatment Description**	**Q1: How frequently do you use this treatment?**	**Q2: What is your willingness to test and/ or expand this treatment?**	**Q3: What would you need to increase your level of comfort to implement this treatment? If you need more space, please use the margins.**
Improving Pedestrian and Bicycle Crossing Experience	Walk countdown	Indications typically designed to begin counting down at the beginning of Flashing Don't Walk signal (some agencies also used Countdown from the begging of Walk signal)	**Avg Response:** 4.1	**Avg Response:** 4.5	Generally standard for countdown for FDW. Need funding to retrofit. Countdown during walk disrupts transit signal priority
	Independently mounted pushbuttons	Pushbutton actuations that are placed at the edge of roadway (e.g., next to the curb ramp) to provide easier access for pedestrians and cyclists. They prevent cyclists from dismounting to activate and provide better accessibility for people with disabilities.	1.5	2.6	Maintenance - knocked down by vehicles and snow plows Cyclists shouldn't have to push button
	Accessible signals without push button actuation	On signals with recall and signals with non-intrusive detection, pedestrians do not need to push a button to call the signal	1.3	2.7	Maintenance, detection challenges
	Bicycle detection	Technologies such as loop, active infrared, and video detection at or in advance of stop bars to allow signals to detect the presence of bicycles.	1.1	3.2	Better tech/reliability
	Bicycle indications	Provides confirmation to cyclists that their presence has been detected (e.g., through the illumination of a small blue light near the bicycle signal)	0.2	3.2	Working Bike Detection

PLEASE USE THE FOLLOWING SCALE TO ANSWER QUESTIONS 1 & 2 BELOW:

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Treatment Category	**Treatment Name**	**Treatment Description**	**Q1: How frequently do you use this treatment?**	**Q2: What is your willingness to test and/ or expand this treatment?**	**Q3: What would you need to increase your level of comfort to implement this treatment? If you need more space, please use the margins.**
			Avg Response:	**Avg Response:**	
Reducing Pedestrian Delay	Short cycle length	Reducing the length of a signal cycle usually means lower pedestrian and bicycle delay, which also tends to improve compliance, and therefore non-motorized safety.	2.5	3.1	Vehicle delay/data driven decision Ped clearance Interagency cooperation
	Rest in Walk	For pedestrian crossings that are concurrent, Rest in Walk makes the Walk interval last as long as will fit within the green time of its concurrent phase	2.3	3.1	Preemption Pedestrian expectations Some agencies are fully actuated
	Pedestrian recall	Places a continuous call for pedestrian service, without the need for actuation, and results in ped phases getting realized every cycle	3.1	3.5	Context Dependant Overnight
	Adapting Walk time to vehicular demand	If the green time required to serve the concurrent vehicular phase is consistently longer than the minimum green duration to serve pedestrians, then Walk time can be increased with almost no impact on vehicular traffic	1.5	3.6	Context Dependant
	Permissive periods for pedestrian actuation	A permissive window is the range of time in a cycle within which a call will trigger that phase being served in the current cycle; calls received after the end of the window will be served in the next cycle.	1.1	2.7	Driver expectation/ consistency controller programming

PLEASE USE THE FOLLOWING SCALE TO ANSWER QUESTIONS 1 & 2 BELOW:

0 = NOT AT ALL 1 = TO A SMALL EXTENT 2 = TO SOME EXTENT 3 = TO A MODERATE EXTENT 4 = TO A GREAT EXTENT 5 = TO A VERY GREAT EXTENT

Treatment Category	Treatment Name	Treatment Description	Q1: How frequently do you use this treatment?	Q2: What is your willingness to test and/ or expand this treatment?	Q3: What would you need to increase your level of comfort to implement this treatment? If you need more space, please use the margins.
Reducing Potential Conflicts with Parallel Traffic Turns	Flashing right turn yellow arrow (FYA)	FYA is displayed when a phase involves a permitted conflict with crossing pedestrians and bicycles. FYA can be used for permitted right turns and for permitted left turns from a one-way street	**Avg Response:** 0.3	**Avg Response:** 3.2	Driver expectation, education effectiveness PSU/OSU safety research concern
	Flashing pedestrian/bicycle indicator	A flashing is displayed to a phase that involves turns that have a permitted conflict with crossing pedestrians or bicycles	0.1	2.4	Context dependent Experimentation
Eliminating Conflicts with Parallel Traffic Turns	No turn on red (NTOR)	Restricts right turn on red movements to eliminate conflicts	2.0	2.8	Policy direction and case study of benefits
	Exclusive pedestrian/bicycle phases	During an exclusive phase, all traffic movements are held and pedestrians (in some cases, also bikes) are allowed to go on all crosswalks	0.9	2.4	Context dependent Ped compliance
	Protected left turns for non-motorized users	Provides a green arrow for left turn vehicles while stopping both oncoming traffic and parallel pedestrian crossings to eliminate conflicts	1.8	3.1	Guidance on context and benefits
	Concurrent yet protected crossings	Separates crossing pedestrians and cyclists in time from right turning traffic, while pedestrians and cyclists cross concurrently with through vehicles	1.3	2.8	Guidance on contexts

PLEASE USE THE FOLLOWING SCALE TO ANSWER QUESTIONS 1 & 2 BELOW:

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Treatment Category	Treatment Name	Treatment Description	Q1: How frequently do you use this treatment?	Q2: What is your willingness to test and/ or expand this treatment?	Q3: What would you need to increase your level of comfort to implement this treatment? If you need more space, please use the margins.
Special Phasing Techniques Favoring Pedestrians and Bicycles	Multi-stage crossings with ped overlaps with left turn phases	With multi-stage crossings, pedestrians cross to an island and then wait there for a WALK signal to resume crossing. With ped overlaps with left turn phases, progression opportunities for multi-stage crossings can be created, reducing pedestrian delay	**Avg Response:** 0.7	**Avg Response:** 2.4	Pedestrian education Context dependent
	Ped/bike phase reservice	This treatment serves pedestrians and bicycles twice in a given cycle, reducing non-motorized delay substantially as it roughly halves the length of red period	0.5	1.9	Context dependent More non-motorized users
Bicycle phases and special bicycle needs	Bicycle signal phases	Bicycle signals include separate signal heads that indicate bicycle phasing and separate bicycle movements from other conflicting traffic. Bicycle signals are traffic signal heads used at intersections with conventional traffic signals to specifically control the movement of bicyclists to improve bicycle safety at intersections.	0.4	2.7	More bikes Less impact to network
	Minimum green and change interval settings for bicycles	Minimum green and change interval settings should be designed to serve the needs of bicyclists, particularly at signalized intersections where bicycles use vehicular phases (e.g., intersections with bike lanes but without exclusive bike phases). This increases the comfort and safety for bicycles.	0.8	3.3	Guidance on where to implement Longer clearances can foster undesirable driver behavior

APPENDIX C – WORKSHOP PARTICIPANTS

Michigan Workshop Attendees	
Name	**Agency**
Carissa McQuiston	MDOT
Nathan Bouvy	MDOT
Joe McAttee	MDOT
Andy Kilpatrick	City of Lansing
Josh Carey	MDOT
Nathan Schilling	MDOT
Cynthia Redinger	City of Ann Arbor
Jenya Abramovich	SEMCOG
John Bartlett	City of Grand Rapids
Tonya Doyle-Bicy	MDOT

Tampa Workshop Attendess	
Name	**Agency**
Stephen Benson	City of Tampa
Vik Bhide	City of Tampa
Chris Cairns	City of Orlando
Brandon Campbell	City of Tampa
Ron Chin	FDOT D7
Cal Hardie	City of Tampa
Alex Henry	FDOT D7
Danni Jorgenson	City of Tampa
Milton Martinez	City of Tampa
Nicole McCleary	HART
Wade Reynolds	Hillsborough MPO
William Porter	City of Tampa
Matt Nance	FDOT D7
Julie Scanlon	FDOT D7

Portland Workshop Attendees	
Name	**Agency**
Peter Koonce	Portland Bureau of Transportation
Stefan Bussey	Portland Bureau of Transportation
Gabriel Graff	Portland Bureau of Transportation
Adam Moore	Portland Bureau of Transportation
Michelle Marx	Portland Bureau of Transportation
Mark Haines	Portland Bureau of Transportation
Kate Freitag	Oregon Department of Transportation
Shaun Quayle	Washington County
Shelley Oylear	Washington County
Bikram Raghubansh	Clackamas County
Sirisha Kothuri	Portland State University

NCHRP Project 03-133

Traffic Signal Design and Operations Strategies for Non-Motorized Users

Policy and Practice Recommendations

Kittelson & Associates, Inc.

In association with:

Northeastern University
Accessible Design for the Blind
Wayne State University

August 31, 2020

SECTION 1.0 – INTRODUCTION

The purpose of this memorandum is to present opportunities for updates to guidance documents such as the Manual of Uniform Traffic Control Devices (MUTCD) and identify opportunities for future research. These recommendations were compiled through agency engagement that included a series of agency interviews and three full-day workshops in Lansing, Michigan, Tampa, Florida, and Portland, Oregon and through research into individual treatments.

SECTION 2.0 – POLICY RECOMMENDATIONS AND OPPORTUNITIES FOR FUTURE RESEARCH

Table 1 summarizes a broad set of recommendations to ease the implementation of treatments for non-motorized users at signalized intersections. These recommendations range from changes to warrants to analysis methods and additional guidance to support treatment decision-making. Where recommendations are focused on specific treatments, a reference is provided to the Guidebook. **Table 1** also provides information on what manuals or domains may need to be updated to address the recommendation including the following:

A. Manual on Uniform Traffic Control Devices (MUTCD)
B. Highway Capacity Manual (HCM)
C. Design Manuals
D. Signal Timing Manual, 2nd Edition (STM2)
E. Technology Systems (Hardware and Firmware)
F. Intersection Analysis Software
G. State and Local Law
H. State and Local Signal Operating Policy
I. Intersection Analysis Policy / Practice
J. Bikeway Design Guidance

The recommendations are further discussed in the following subsections.

Table 1. Policy and Research Recommendations

Proposed Policy or Guidance	Application Domain									
	MUTCD	**HCM**	**State and Local Law**	**Design Manuals**	**STM2**	**Technology Systems**	**Analysis Software**	**Operating Policy**	**Analysis Policy/Practice**	**Bikeway Design Guidance**
Signal Warrant Procedure	x									
Bicycles Exempt from NTOR *(See Section 6.8)*	x		x					x		x
Bicycle Use of WALK signal			x					x		x
Pedestrian Delay and Level of Service *(See Section 3.1.3)*		x					x		x	
Pedestrian Delay for Full Multistage Crossings *(See Section 3.1.3.3)*		x					x		x	
Pedestrian Progression with Multistage Crossings *(See Section 10.1)*					x					
Two-stage Left Turn Progression *(See Section 9.3)*					x					x
Two-stage Left Turn Delay *(See Section 9.3)*		x			x		x			x
Pedestrian Phases Free from Parent Vehicular Phase *(See Section 6.7)*					x	x				
Pedestrian and Right Turn Phase Running Free at Channelized Right Turns *(See Section 6.4)*					x	x				
Pedestrian Clearance Interval Requirements *(see Section 7.4)*	x				x					
Pedestrian Phase End Buffer as a Parameter *(see Section 7.4)*	x				x	x		x		
Pedestrian Speed as a Measure of Service *(See Section 4.1.1.2)*		x			x				x	
Flashing Pedestrian and Bicycle Crossing Warnings *(See Section 6.9)*	x									
Pushbutton Placement for Bicycle Use *(See Section 8.3)*	x			x						x
Default to Rest in Walk for Coordinated Phase *(See Section 7.3)*						x		x		
Uniformity of Red Arrow and No Turn on Red *(See Section 6.8)*			x							
Control Vehicles			x	x					x	
Context Sensitive Design Policies				x						
Funding			x							
Permitted vs Protected Turns *(See Section 6.1)*								x	x	
Detection *(See Section 9.4)*										
Accessibility when Changing Signal Timing				x			x	x		
Pedestrian Signal Changes that Require Installation of APS *(See Section 4.4)*				x				x		

Signal Warrant Procedures

The Manual on Uniform Traffic Control Devices (MUTCD) includes eight traffic signal warrants to investigate the need for a traffic control signal. It is required for an engineering study to justify installing a traffic signal with the eight warrants as an initial framework for guidance. Three of the eight warrants focus solely on vehicle volumes and number of vehicular lanes at the intersection. Engineers can also use pedestrian volumes, crash experience, and the role of the intersection in the network to warrant a signal; however, these warrants can be difficult to meet. Based on experiences with agencies, interviews with professionals, and feedback from the workshops, the following section provides a summary of insights on signal warrant procedures.

Pedestrian Volume Warrant

The pedestrian volume warrant requires at least 75 pedestrians to cross the street for four hours of the day or 93 pedestrians in one hour of the day. These thresholds only apply if the posted speed exceeds 35 mph and the vehicles per hour on the major street (total of both approaches) reach approximately 1,000. If the speed is 35 mph or less, or there are few vehicles on the major street, the pedestrian crossing thresholds are even higher. Without a traffic control device, it is unlikely that number of pedestrians would feel comfortable crossing the street, even if there is pedestrian demand. Pedestrians may space themselves out along the corridor as they look for a gap in traffic, find another route, or use another mode to make the trip. There is an opportunity to provide additional guidance so agencies can review factors such as land use mix and intensity, transit use and location of transit stops, and out of direction travel to justify a traffic a signal, rather than requiring the high pedestrian counts. Additionally, the standard that the pedestrian warrant shall not be applied at locations where the distance to the nearest traffic control signal or STOP sign controlling the street that pedestrians desire to cross is less than 300 feet limits the ability to provide frequent, safe crossings for non-motorized users, especially in urban areas.

Coordinated Signal System Warrant

The coordinated signal system warrant is intended for use when progressive movement in a coordinated signal system necessitates installing traffic control signals at intersections where they would not otherwise be needed in order to maintain proper platooning of vehicles. The warrant includes guidance that the warrant should not be applied where the resultant spacing of traffic control signals would be less than 1,000 feet. This prohibits the use of the coordinated signal system warrant in urban areas where signals are often spaced a few hundred feet apart.

Crash Experience Warrant

The crash experience signal warrant conditions are intended for application where the severity and frequency of crashes are the principal reasons to consider installing a traffic control signal. One of the criteria that must be met is an adequate trial of alternatives with satisfactory observance and enforcement has failed to reduce the crash frequency. This requires agencies to invest time and money to test other treatments when a signal may immediately improve the safety performance of the intersection and create additional benefits for non-motorized users.

Bicycles Exempt from NTOR

No Turn on Red (NTOR) refers to a restriction on right turns during red intervals that seeks to eliminate conflicts between turning vehicles and other users (vehicles, pedestrians, and bicycles) crossing the street, thereby increasing safety. When bicyclists are traveling in the road, they must obey the traffic laws as if they were a vehicle. NTOR restrictions increase delay for these bicyclists, who pose a more limited threat to other conflicting pedestrians and bicyclists. Exempting bicyclists from NTOR and allowing them to make the right turn, after bicycles first come to stop and yield to other users crossing the street, would reduce conflicts from motorized users and reduce bicycle delay. Allowing cyclists to move more quickly through intersection may have additional benefits for motorists queued behind them who would not have to wait for the bicyclist when the light does turn green.

Recommendation: Additional research on intersection operational and safety effects of exempting cyclists from No Turn on Red.

Bicycles Allowed to Use Walk Signal

When treatments including leading pedestrian intervals are implemented, bicyclists may see the Walk sign before their signal turns green or the Walk indication extended beyond the vehicle green. In most places, bicyclists are not legally allowed to proceed through the intersection if their signal is red, even if the pedestrian Walk is on, unless they are using the pedestrian signal to cross. This can create confusion and unnecessary delay for bicyclists. Some local laws have been updated to allow bicyclists to proceed through the intersection on red, after coming to a complete stop. A similar approach could be taken to allow bicyclists to legally follow the pedestrian signals and proceed through the intersection during Walk, so long as turning cyclists yield to conflicting pedestrians in the crosswalk.

Recommendation: Additional research on intersection operational and safety effects of allowing bicycles to use the Walk signal for pedestrians.

Pedestrian Delay and Level of Service

American intersection design practice has typically not included measurement or reporting of pedestrian delay. For pedestrian delay to be optimized and prioritized – as vehicular delay is – it is vital that it 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.

Furthermore, when designers want to report pedestrian delay, software commonly used for intersection analysis does not calculate or report pedestrian delay, even though pedestrian timing information is part of the analysis. That means that designers and planners have to calculate pedestrian delay as a separate process. The *Northeastern University Pedestrian and Bicycle Crossing Delay Calculator* is currently available for free (http://www.northeastern.edu/peter.furth/delaycalculator/) and can handle up to four crossing stages and partial crossing phases that are served twice in a cycle. If pedestrian delay were integrated into more common intersection analysis software it would remove a barrier to measurement and streamline reporting.

Lastly, many state and local agencies have adopted level of service (LOS) standards for vehicles. These standards encourage the optimization of roadways for vehicles and leave little room to understand tradeoffs to improve service for non-motorized users. Some agencies, such as the Florida Department of Transportation, have replaced LOS standards with LOS targets, leaving room for multimodal evaluations. California was the first state to switch from LOS to Vehicle Miles Traveled, measuring how well a project reduces greenhouse gas emissions, develops multimodal transportation, preserves open spaces, and promotes diverse land uses and infill development.

Recommendation: Additional promotion of available pedestrian performance measures as part of agency decision-making process and integration of pedestrian delay calculation into traditional traffic analysis software.

Pedestrian Delay for Full Multistage Crossings

Where crossings have to be made in two or more stages, pedestrian delay can be deceptively long and complex to calculate. Common tools only calculate delay for individual stages and simply adding the stages together does not account for the effect of signal progression for pedestrians between partial crossings (e.g., with poor progression, average pedestrian delay for multistage crossings can be more than double the delay of a single stage crossing). Two kinds of numerical methods can be used to calculate the true crossing time including wait times: deterministic and stochastic. These methods are detailed in Section 3.1.3.3 of the Guidebook. The analysis currently requires specialized tools, such as the Northeastern University Pedestrian and Bicycle Crossing Delay Calculator, or microsimulations. This creates additional barriers for agencies. If multistage crossing delay was incorporated into traditional analysis software it would be easier to report and make it easier to fully understand the tradeoffs of various intersection configurations for motorized and non-motorized users.

Recommendation: Additional promotion of available pedestrian performance measures as part of agency decision-making process and integration of pedestrian delay calculation for multistage crossings into traditional intersection analysis software.

Pedestrian Progression with Multistage Crossings

By breaking a long crossing into parts, multistage crossings can improve pedestrian safety and comfort, and make crossings more accessible to pedestrians with walking disabilities. Multistage crossings can improve intersection efficiency by providing a shorter crossing time for pedestrians, 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 one partial crossings to the next are given to pedestrians.

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.” 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.

Recommendation: Additional research in analyzing, modeling, and applying pedestrian progression opportunities with multistage crossings to explore the effects on intersection operations and pedestrian delay.

Two-Stage Left Turn Progression

When traversing an intersection to make a left turn either on separated bike lanes or conventional bike lanes, bicyclists have the choice to make a vehicle-style turn, which typically involves shared use of the vehicular travel lanes, or that of a pedestrian-style turn, where the bicyclists cross one approach at a time. The National Association of City Transportation Officials (NACTO) has included guidance in their Urban Bikeway Design Guide on two stage queuing boxes, also known as bicycle turn boxes, that adorn the corners of intersections and provide a designated and safe space in the intersection for bicyclists to wait to complete their movement. However, if two stage turns are not explicitly considered while developing signal timing plans, cyclist delay involved in making a two-stage left turn can be large. One way to reduce delay is to provide progression for bicycles from the initial crossing to the second. This can typically be achieved by carefully designing leading or lagging left turns based on the primary direction of bicycle traffic making the two-stage left turn.

Recommendation: Additional research to investigate the operational effects of two-stage left turn progression for bicycles on vehicle and bicycle delay under varying intersection characteristics such as vehicular turn volumes or unidirectional bicycle crossings.

Two-Stage Left Turn Delay

Similar to multistage pedestrian crossings, there is a lack of analytical tools to efficiently calculate and report two-stage left turn delay. Without adequate reporting, it is cumbersome for agencies to truly consider this operational strategy, optimize its effectiveness, and understand potential tradeoffs. A similar method to the multistage crossing method developed by Furth et al., (2015) can be applied to bicycle two stage turns. By carefully sequencing left turn phases (e.g., leading left on one street and lagging left on other street to provide through phases in succession) and providing shorter cycle lengths, researchers showed that two stage left turn delay results are comparable to average delay for a single stage crossing. If integrated into traditional intersection software analysis tools, this treatment could be more widely understood and implemented.

Recommendation: Additional promotion of available bicycle performance measures as part of agency decision-making process and integration of two-stage left turn delay calculation for cyclists into traditional intersection analysis software.

Pedestrian Phases Free from Parent Vehicular Phase

In U.S. practice, 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. Freeing pedestrian phases from being a child to a vehicular parent would allow them to overlap with each other. In 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, providing pedestrian progression opportunities at multi-stage crossings or shortening cycle lengths in low traffic periods when pedestrian minimum timing needs may dominate.

Recommendation: Additional research and collaboration with technology vendors and signal controller manufacturers to develop, test, and implement alternate phase structures, timings, and displays for flexible pedestrian applications.

Pedestrian and Right Turn Phase Running Free at Channelized Right Turns

Where channelized right turns are signalized, it makes the pedestrian crossings, and sometimes bicycle crossings as well, multi-stage, which can result in long delays unless signals are timed for good progression for crossing pedestrians and cyclists. When the right turn and its crossing have no conflicts except 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, Tremont Street turning onto Melnea Cass Blvd. The right turn will end whenever the pedestrian pushbutton is actuated and 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. This can help improve progression and reduce delay for multi-stage pedestrian crossings.

Recommendation: Additional research to develop, test, and implement alternate phase structures, timings, and displays for flexible pedestrian applications at channelized right turns.

Pedestrian Clearance Interval Requirements

The MUTCD specifies a clearance need for pedestrians who begin crossing at the start of the Walk interval. The combined duration of the Walk, Flashing Don't Walk (FDW), and phase end buffer should be long enough for a person to cross the street at a speed of 3.0 feet per second, beginning at the pedestrian pushbutton or, if there is not a pushbutton, 6 feet from the edge of the curb. The latter requirement could be simplified to requiring additional 2 seconds. The MUTCD calculation currently does not limit how much of the pedestrian phase end buffer can count against the needed crossing time, and where the pedestrian pushbutton is closer than 6 feet from the curb, it does not guarantee 2 seconds for pedestrians to begin their crossing.

Recommendation: Additional guidance on pedestrian clearance interval requirements and phase end buffer at intersections with slower pedestrians.

Pedestrian Phase End Buffer as a Parameter

The pedestrian phase consists of three intervals: Walk, FDW, and the pedestrian phase end buffer, during which steady Don't Walk is displayed but conflicting traffic may not be released. 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 about to end imminently.

The MUTCD states that the pedestrian phase end buffer should be at least 3 seconds. No maximum is specified. From experience, most pedestrians know that when FDW ends – which is also when the countdown reaches zero – pedestrians typically 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 that portion of the pedestrian phase end buffer that pedestrians can reasonably rely on to finish their crossing in comfort. The Guidebook proposes that effective buffer be limited to 3 or 4 seconds, freeing FDW end from start/end of yellow and promoting uniformity in phase end buffer duration. 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.

Recommendation: Additional research to gain better understanding on how varying phase end buffers affect pedestrian crossing behavior as well as their impact on cycle length and vehicle operations.

Pedestrian Speed as a Measure of Service

Currently, pedestrian walking speeding is an input into signal design and operations. MUTCD guidance states pedestrian must be able to walk at 3.5 feet per second between curb and opposite curb during pedestrian clearance interval and walk at 3 feet per second between push button (or a location 6 feet from the face of the curb) and opposite curb during walk plus pedestrian clearance interval. Any additional time that is required to satisfy the condition of the 3 feet per second guidance should be added to the Walk interval. In practice, however, often agencies follow the first guidance and calculate pedestrian clearance time using walking speed of 3.5 feet per second. At intersections with many slower pedestrians (e.g., elderly people crossing), this results in potential safety issues as slower pedestrians may not have enough time to finish their crossing.

Walking speed distribution could be used as a performance measure to quantify the quality of service for pedestrians, especially for pedestrians who walk slower than 3.5 feet per second, or pedestrians who use wheelchairs. Practitioners would report the slowest speed or low percentile speeds (e.g., 5th percentile) at which a pedestrian could cross the street during the pedestrian phase. This may help incentive treatments that increases the Walk duration such as Rest in Walk, which would allow slower moving pedestrians to clear the intersection within the pedestrian phase more easily.

Recommendation: Additional case studies with agencies to gather information on if and how pedestrian speed is utilized while developing pedestrian timing intervals and tradeoffs involved.

Flashing Pedestrian and Bicycle Crossing Warnings

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 along with a yield sign for turning vehicles. Various flashing warnings have been tested across the world and have been found to reduce right turn conflicts and the severity of conflicts and increase yield compliance for pedestrians in the crosswalk. Currently, the flashing yellow arrow is the only flashing warning routinely used in the US with right turns and left turns from a one-way street.

Recommendation: Some flashing warnings that have been tested have been shown to cause driver confusion. Additional research (e.g., pilot implementation or using driver simulator) could investigate driver behavior and compliance with flashing warnings, which will in turn could help standardize flashing warning for non-motorized conflicts at signalized intersections.

Pushbutton Placement for Bicycle Use

Independently mounted pushbuttons can be especially valuable where bicyclists use a pushbutton. Bicyclists have less lateral mobility than pedestrians and therefore need a pushbutton reachable from their queuing position. And if a pushbutton is too close to the curb, a bicyclist may not be able to reach it without their front wheel encroaching on the street. The U.S. currently has no standards for pushbutton location for serving bicyclists. More stringent limitations on pushbutton location would aid bicyclists where they are expected to use one. This includes sufficient longitudinal setback and minimal lateral offset.

Recommendation: Additional promotion of independently mounted pushbuttons based on the European practice at intersections where bicycles are required to use pushbuttons so that a cyclist can reach them without dismounting.

Default to Rest in Walk for Coordinated Phases

Rest in Walk is a controller setting that applies to coordinated phases. With this setting, the concurrent pedestrian signal dwells in the Walk interval until the end of vehicular green minus the time specified for FDW. This way, if the concurrent vehicular green phase runs longer than scheduled, the Walk interval will be longer as well. Without Rest in Walk, the pedestrian signal will only display Walk for a fixed amount of time, after which it will run the FDW and then, if the concurrent phase is still running, Rest in Don't Walk.

Rest in Walk maximizes the Walk interval, reducing pedestrian delay and thereby increasing compliance without significantly constraining the signal cycle. At some intersections, the pedestrian phase ends long before its concurrent vehicular phase; in such a case, the Walk interval could have been longer without affecting the signal cycle, giving pedestrians more opportunities to cross the street, improving compliance and accessibility for slower pedestrians.

Recommendation: Additional information dissemination and outreach to agencies to highlight the benefits of Rest in Walk feature for coordinated phases with little or no impact on vehicle operations.

Uniformity of Red Arrow and No Turn on Red (NTOR)

The NTOR treatment is widespread throughout the United States but the state laws regarding NTOR and red arrows are inconsistent. While the MUTCD indicates that right turn on red 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 sign NTOR in conjunction with red arrows as well as with circular red indications.

Recommendation: Additional research to better comprehend and account for the expected driver response to the red arrow display for right turning vehicles and working with state agencies to develop uniform legislation that would enforce NTOR with the red arrow display.

Control Vehicles

The design vehicle is a frequent user of a given street and dictates the minimum required turning radius. While designs must account for the challenges that larger vehicles, especially emergency vehicles, may face, these infrequent challenges should not dominate the safety or comfort of a site for the majority of daily users. Large turning radii lead to higher vehicle speeds, adversely affecting non-motorized user safety, and longer crossing distances and therefore cycle lengths. Use of a control vehicle, or infrequent large user, allows practitioners to better design for non-motorized users rather than the largest possible vehicle. While a design vehicle is expected to use one incoming and one receiving lane, the control vehicle can turn using multiple lane spaces. This keeps turning radii and crossing distances smaller for non-motorized users while still accommodating infrequent larger vehicle movements.

Agencies can adopt both a design vehicle and a control vehicle based on the land use context and transportation function of the roadway. In the Urban Streets Design Guide, NACTO recommends adopting a delivery truck (DL-23) as the design vehicle in urban areas and relying on designated freight routes and control vehicles to accommodate larger freight traffic.

Recommendation: Additional research and documentation on current practices for agencies on identifying and designing for control vehicles in their roadway network. Additionally synthesis on how agencies adjust built environments to "right-size" intersections to meet shifting user needs.

Context Sensitive Design Policies

State-level design guidance can apply Federal recommendations for more context-based design practices. State roadway design manuals drive many design decisions and impact many projects. Allowing agencies to use discretion and context-sensitive approaches can improve the ease with which agencies are able to implement treatments for non-motorized users.

In many States, design standards were created to address specific safety concerns related to vehicle travel. Traffic signal spacing requirements, for example, were encouraged on suburban arterials to minimize conflict points and maintain regular, predictable traffic flow. But as suburban arterials mature into places with many destinations, these spacing requirements can become an impediment to safety. It is difficult to serve these land uses that create multimodal travel demand in midblock locations with a signal because of these design controls.

In recent years, State DOTs have recognized the importance of understanding land use context when making roadway design decisions. Context-sensitive designs recognize differing street design needs in different places. Some States have identified areas within their boundaries where pedestrian and bicycle demand is likely. Additional flexibility can be given to implement non-motorized user treatments in these areas without costly and time intensive studies. For example, FDOT recently update the Traffic Engineering Manual to allow implementation of Leading Pedestrian Intervals without a study in their urban contexts.

Recommendation: Additional research to observe non-motorized safety benefits of context-sensitive design using data from agencies who have adopted context-sensitive design policies, and dissemination of findings through outreach and education materials.

Funding

When agencies or projects are competing for funding, the scoring process should include pedestrian and bicycle-related prioritization criteria and/or weight projects differently when they include multimodal elements. This helps multimodal projects compete on a more level playing field with other infrastructure projects.

Another challenge for small pedestrian and bicycle projects is that to receive Federal funds, projects must be identified in the statewide transportation improvement program/transportation improvement program (STIP/TIP), in addition to meeting requirements for the specified funding program. For a small project, the effort (staff time and cost) of programming a project can seem out of proportion with the amount of project funds allocated. Grouped listings aggregate individual projects of a similar project type into one fundable package within the STIP/TIP, providing flexibility to fund small scale projects as they become ready for funding and does not require the additional time to gain an individual spot on the STIP/TIP.

Permitted versus Protected Turns

Guidelines found in the Traffic Signal Timing Manual Second Edition 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 related crashes, more than roughly 5 per year per left turn movement. Apart from the crash experience criterion, those are conditions that relatively few intersections meet. It also stands out that those guidelines make very limited consideration for pedestrian or bicycle use. Guidance should be updated to include considerations for non-motorized users such as presence of a bicycle facility and visibility of approaching bicyclists to turning vehicles.

Some American communities with high pedestrian and bicycle use have adopted policies that more strongly favor protected only left turns. For example, in Cambridge, MA, permitted turns are allowed at smaller intersections. However, at larger intersections, the City has been converting permitted left turns to protected only left turns to provide a safer operation for pedestrians, bicycles, and other vehicles. The City of 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 website). New York City has also recently converted several intersections to protected only phasing.

In Amsterdam and other Dutch cities, protected only phasing is used by policy at all multilane intersections and wherever left turns cross a two-way bike path. Permitted left turns are allowed on streets with one lane per direction; however, in practice, protected left turns are more common except from minor street approaches that are too narrow to have left turn lanes.

Recommendation: Revisiting the current permitted vs. protected left turn phasing guidance to incorporate the needs of pedestrians and bicycles based on the presence and type of a bicycle facility, the number of lanes, pedestrian activity, etc.

Detection

A common concern heard from agencies interviewed was the lack of reliable detection options. There were concerns over maintenance requirements and the accuracy of detection. Detection is required for several treatments including pedestrian actuation and extended green phases for bicycles. At signalized intersections that have separate bicycle phases that are actuated or on low volume streets in which bicycles and vehicles follow the same signal phase, bicycle detection will ensure that a call will be placed to the controller to serve the bicycle phase. This reduces the impact on vehicle capacity by not providing a green phase when there is no bicycle detection. Similarly, bicycle detection can help provide longer red clearance for bicycles when only they are detected, limiting the impact on intersection operations. Detection technology continues to improve and needs to start being integrating back into pedestrian and bicycle timings. Signal timing for pedestrians and bicycles do not need to be absolute and detection can be used for passive actuation and to adjust the length of interval based on demand.

Recommendation: Additional research to synthesize the existing detection technology used by agencies for pedestrians and bicycles at signalized intersections to document their benefits, limitations, and operational and safety effects.

Accessibility when Changing Signal Timing

Changes to signal timing and functioning can affect the accessibility of the crossing to individuals with disabilities. Often changes are made without consideration of those effects. The Americans with Disabilities Act requires facilities to be “accessible to and usable by individuals with disabilities” and requires communication with individuals with disabilities to be as effective as communication with those without disabilities. Procedures to review changes with consideration of the effect, particularly for those who are blind or who have low vision and cannot see the pedestrian signal, need to be explicitly added to the design manuals, operating policy and analysis policy/practice. Multi-stage crossings, if not well-designed, can be a barrier.

Recommendation: Additional information dissemination through outreach and training to agencies to incorporate accessibility needs into agencies’ design manuals and policy documents.

Pedestrian Signal Changes that Require Installation of APS

Certain signal timing changes particularly affect the safety of individuals who are blind or who have low vision, where accessible pedestrian signals (APS) are not installed. Those include LPIs, exclusive pedestrian phases, and protected intervals. As such pedestrian safety features are installed, APS need to be also installed. The MUTCD has standards for the features and installation of APS, but these can be hard to understand and interpret for those who are not familiar with the equipment, leading to poor or unusable installations. Design manuals and policies need to be updated, with installation details, to provide clear guidance to designers and engineers, and municipalities for the appropriate use of APS when signal modifications are made.

Recommendation: Additional information dissemination through outreach and education to inform practitioners regarding the unintended accessibility consequences of certain signal timing changes to improve pedestrian conditions.

REFERENCES

Furth, P. G., Wang, Y. D., & Wang, Y. D. (2015). Delay Estimation and Signal Timing Design Techniques for Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Left Turns. In Transportation Research Board 94th Annual Meeting (No. 15-5365).

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TRAFFIC SIGNAL DESIGN AND OPERATIONS STRATEGIES FOR NON-MOTORIZED USERS

FINAL

Prepared for:
National Cooperative Highway Research Program
Transportation Research Board
National Research Council

By:
Kittelson & Associates, Inc.

In association with:
Northeastern University
Accessible Design for the Blind
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NCHRP

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Chapter 1 Introduction

Transportation agencies across the country are paying increasing 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 many strategies to improve service for pedestrians and bicycles at signalized intersections, many of them remain poorly understood. A lack of national guidance, coupled with a dearth of analytical tools and performance measures, limit 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 guidance to help agencies design and operate signalized intersections in a way that improves safety and service for pedestrians and bicycles, 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 issue arise.

There is a spectrum of approaches, shown in **Exhibit 1-1,** that agencies have taken with respect to addressing the needs of pedestrians and bicycles at signalized intersections, from complying only with minimum standards to a practice of integration in which pedestrians and bicycles are considered in all aspects of signal control. This Guidebook moves beyond accommodating pedestrians and bicycles at traffic signals, and towards 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 bicycles, while at the same time 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*, helping agencies move closer to full integration.

Exhibit 1-1: Approaches for Non-Motorized User Planning and Design

Practitioners designing for motorized and non-motorized users have traditionally been siloed, with one group having a limited understanding of traffic signal operations and the other 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 in which the needs of non-motorized users are fully integrated. The Guidebook creates connections between the technical subject matters of planning, design, operations, safety, and implementation to create an easily accessible and understandable toolbox for practitioners. Its guidance is tailored to serve a wide range of stakeholders and to address diverse operating environments and intersection characteristics, resource levels, and system components.

1.1 Guidebook Contents

This Guidebook presents a variety of treatments to address non-motorized user needs at signalized intersections and guidance on how to select, implement, and evaluate those treatments. Accessibility considerations are integrated throughout the treatments. The Guidebook is organized in 10 sections. The key questions addressed in each section include:

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 bicycle needs at signalized intersections? What priority should pedestrian and bicycle needs have 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 Pedestrian and Bicycle Service

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 is available for calculating performance measures?*

Chapter 4: Signal Timing Basics

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

Chapter 5: Introduction to Treatments

Considering the various 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 Delay

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: project based or site-oriented and 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, one can find in the introduction to treatments in **Chapter 5** that there is 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) chosen for the site.

In a ***policy-oriented approach***, an agency may be seeking a more systemic way to integrate pedestrians and bicycles into their signalized intersection design and operations. It may start with goals such as to improve pedestrian safety, to improve bicycle safety, or to minimize pedestrian and bicycle delay. Based on its chosen goals and objectives, agencies can use Error! Reference source not found. to determine which strategies best suit their needs, and use the detailed treatment descriptions to add specific treatments to their best-practice portfolio. They 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, agencies can initiate a program of proactively applying the chosen best practices systemwide.

Chapter 2 Understanding User Needs and Establishing Priorities

In the U.S., traffic signal timing is traditionally developed to facilitate motor vehicle delay at signalized intersections, with minimal attention to the needs of pedestrians and bicycles. Too often, the unintended consequence is often diminished safety and mobility for pedestrians and bicycles. The issue is exacerbated by practitioners relying on software tools designed to optimize signal timing by minimizing motor vehicle delay with no consideration of pedestrian delay or safety beyond meeting minimum standards such as for 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 bicycles' needs.

The second edition of the Signal Timing Manual (STM2) 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, a first step is to identify the types of users present in an environment, understand their needs and how signal timing and intersection design affect them, and prioritize those needs.

Identifying and Prioritizing Non-Motorized Users

As a rule, pedestrians and bicycles should be considered as intended users of an intersection 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 where they are more frequent users, on routes critical for their mobility, and where there is a safety issue. The following data sources can help determine the degree to which pedestrians and bicycles 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 is certainly important in helping determine the priority that they should be afforded in intersection design. Third part data sources and probe data can be used to supplement traditional counts and, in some cases, can provide a broader perspective versus manual counts, by providing information over longer time periods, for example.
- **Field Visits and Observations:** Observing the study area can reveal the types of users present at various times of the day (peak and off-peak) and day 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. Road safety audits may also be considered 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 push buttons. Care must be taken when evaluating this kind of data, however, since pedestrian volumes may or not be strongly related to pushbutton actuation counts.
- **Crash History:** Practitioners can obtain historical crash data, typically three to five years, 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 of 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 bicycle demand.

- **Conflict Analysis:** Conflicts at signalized intersections are addressed through dedicated phasing and separating conflicting movements, however oftentimes not all conflicts are eliminated. This includes turning movement conflicts, both left and right-turning movements. Crash history provides insights into outcomes of these conflicts but the near-misses and uncomfortable pedestrian experiences are not always reported. Identifying and assessing conflict analysis is becoming more common, especially with advancements in technology. It 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 the 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 youth or seniors 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 multi-use path nearby? Is it a pedestrian or bicycle an access route to shopping, employment, or recreational destinations? And 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 by virtue of having a concentration of elderly or low-income residents, or households without access to automobiles. For example, children and elderly 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 a non-motorized user need through public involvement activities and customer requests. Other sources on the list can help validate the request or concern.

2.2 Pedestrian and Bicycle Needs

Pedestrians and bicycles have the same basic needs of intersection users who are in motor vehicles: 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 disabilities and people with 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 low 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 and 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 taken to reduce it.

Comfort in this context 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 objectively speaking, they are safe; however, if signals are timed so that the pedestrian display goes to steady Don’t Walk and the countdown timer goes blank when the pedestrians are still 8 s from finishing their crossing, with still two more 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 safety *and* in 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. By rules of the road, those turning motorists are supposed to yield the right of way. But where intersection geometry allows high speed turns, or where turning traffic volume is high, turning motorists can be less likely to yield, creating an asymmetric and uncomfortable challenge over who is going 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 bicycles value their time and therefore want to minimize delay. In fact, compared to motorists, waiting can be more onerous for pedestrians and bicycles because they are exposed to the weather. And importantly, it is well known that pedestrian and bicycle 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), with little to no attention to minimizing pedestrian delay. The current framework of traffic signal timing design needs to be changed to one that aims to minimize pedestrian delay and bicycle delay 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 delay to vehicles.

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

Perhaps the greatest reason that pedestrian-unfriendly signal timing plans proliferate is that in typical American practice, while vehicular delay has been the key performance measure in intersection evaluation, neither pedestrian nor bicycle delay are measured or reported at all. 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.

Agencies wishing to improve service for pedestrians and bicycles at traffic signals can consider establishing a policy requiring that any intersection analysis that reports vehicular delay must also report pedestrian and bicycle delay, along with a level of service rating that allows a direct comparison with vehicular level of service 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 delay by crossing and, for multistage crossings, by direction, because long delay for any crossing movement can indicate a safety issue. A commonly used scale for determining a level of service (LOS) based on pedestrian delay is from the 2000 edition of the Highway Capacity Manual (HCM), reproduced below as Table 1. For bicycles, no standard scale for their delay-based LOS has been established, but the same scale used for pedestrians may be appropriate because, like pedestrians, they are exposed to weather and exhibit significant non-compliance when waiting times are long.

Table 1. Level of Service for Pedestrian Delay at Signalized Intersections

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: Highway Capacity Manual 2000, Exhibit 18-9

2.2.3 IMPROVING EASE OF USE AND INFORMATION

Pedestrians and bicycles want the crossing experience to be easy, and to receive information that lets them know how the system is going to serve them, reducing 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 lights that illuminate when they push a button, so pedestrians and bicycles want to see confirmation that they have been detected. Countdown displays help assure pedestrians, as they cross, that they'll have enough time to finish, and for faster pedestrians, help them decide based on their own walking speed whether it's safe to begin crossing. **Chapter 8** describes treatments related to added information and convenience.

2.2.4 ACCESSIBILITY

Intersection crossings should be accessible to all pedestrians, including those with disabilities. Persons with vision impairments rely especially 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 strict, legal meaning, but 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 the time to begin crossing – the intersection design should ensure that audible cues are provided. In general, Accessible Pedestrian Signals are needed wherever visual pedestrian signals are installed so the status of the signal is positively conveyed to individuals with vision disabilities and 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 the green, such as Leading Pedestrian Interval, Accessible Pedestrian Signals (APS) are particularly needed to let pedestrians with vision disabilities know that the WALK is not concurrent with the traffic and to help cue all pedestrians to the nonconcurrent signal timing. Pushbutton detectors and accessible pedestrian signals 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 seniors, young children, and people 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; otherwise, wide streets become impassable barriers for people on foot, which can not only make walking infeasible as a mode of transportation, but also transit, which generally requires crossing the street either when going or coming. 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 to positively *optimizing* accessibility by slower pedestrians, including evaluating signal timing plans by a performance measure that indicates the lowest pedestrian speed that it 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 the toolbox.

2.3 ESTABLISHING OBJECTIVES AND PRIORITIES

Broadly speaking, the 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, e.g., to minimize pedestrian and bicycle collisions as well as auto collisions, to maximize pedestrians' and bicyclists' sense of security, to minimize pedestrian and bicycle delay as well as vehicle delay, to be an industry leader in providing information to pedestrians and bicycles, 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 guide design and provide a means for evaluating current unmet need as well as the success of a treatment.

Objectives for signalized intersection design will sometimes conflict with each other or at least involve a tradeoff, such as when improving pedestrian and bicycle safety involves treatments that increase vehicle delay, or when a treatment that would benefit pedestrians or bicycles would 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, for example, 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.

Reasons to assign greater priority to pedestrians and bicycles 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, planners have designated priority networks for auto, bicycle, 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 mean doing nothing more than meeting minimum standards on their behalf. Many of the treatments described in this Guidebook offer substantial improvement in service or safety to pedestrians and bicycles with no or little detriment to vehicle capacity or delay, and many 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 effort or ongoing operational support. Treatments that are experimental or have only interim approval may require staff effort or additional support to apply to the FHWA for permission to experiment. With each treatment description in the toolbox, a *Considerations* and *Implementation Support* section provides pertinent information on its likely maintenance and staff support demands.

Equipment and Software Costs and Constraints. Many of the treatments described in the toolbox require additional equipment, such as new signal heads. And while most of the treatments can be supported with standard signal control equipment and software, some may require upgraded or specialized equipment or 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 the operation of their signals (e.g., the length of Walk interval, upper and lower limits for cycle length, etc.) 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., agency policy that does not allow flashing operation), practitioners may need to consider whether or how that conflict can be resolved.

The Federal Highway Administration (FHWA) provides additional resources for agencies wising to gain a better understanding of their current capabilities and the effect on traffic management.

2.5 References

Federal Highway Administration website. https://ops.fhwa.dot.gov/tsmoframeworktool/index.htm [Accessed July 1, 2020].

Furth, P.G. and M. Wagenbuur (2017). Systematic Safety: The Principles Behind Europe's Vision Zero (video). YouTube.

Chapter 3 Performance Measures Related to Serving Pedestrians and Bicycles

In the outcome-based approach introduced in the previous section, the next step after defining and prioritizing user needs is to define performance measures, also known as measures of effectiveness 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, they can be used to optimize and compare alternatives; and after improvements are made, they can be used for before/after analysis. An outcome-based approach can also help document decisions, emphasizing agency priorities and community values when considering tradeoffs in decision making.

This outcome-based approach is well established as pertains to vehicular intersection users, with intersection design paying careful attention to performance measures such as volume/capacity ratio, average vehicular delay, and level of service. The same attention is needed for pedestrians and cyclists to adequately address their needs.

The following subsections provide detail 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 to assessing intersection performance relative to safety risks and to assist in diagnosing outcomes that a change in intersection design and/or operations might address. Practitioners can obtain three to five 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 Error! Reference source not found. can help identify trends.

Crash statistics can tell an incomplete story with regard to the safety of pedestrians and cyclists, partly because of their far greater vulnerability leads them to avoid dangerous situations, and partly because 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 an unusually high speed, 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.

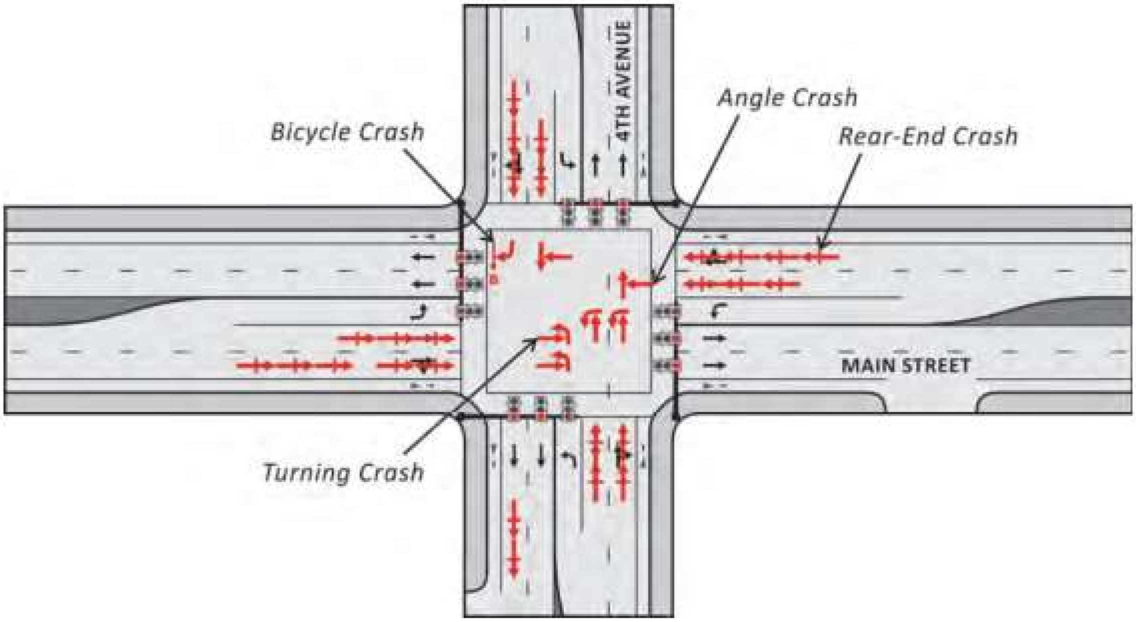


Exhibit 3-1: Example Collision Diagram (source: Signal Timing Manual)

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 crash.

Conflict counts can also be used as a performance measure, both as a surrogate for 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, for example, measured the percentage of compromised pedestrian crossings and found that LPIs reduce the number of compromised crossings.

Compliance counts can also be valuable safety measures. Poor red-light compliance by pedestrians and bicycles can indicate poorly designed traffic control with excessive pedestrian or bike delay, or with signals that tell them not to go even when it's safe to cross. Violations of No Turn on Red restrictions and driver non-yielding when making permissive turns (including when turning on red) can indicate a need for stronger messaging or 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, aggregating 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 protected crossings or a partially protected crossing treatment such as with leading pedestrian interval 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, suppressing 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. Where pedestrian and bicycle counts were made in conjunction with vehicular counts, substitute counts may be needed for bicycles and pedestrians if they were done on days of unusual pedestrian or bicycle demand.

3.3 AVERAGE PEDESTRIAN DELAY

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

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 is vital that it 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 pedestrian signal timing and has all the data needed to calculate pedestrian delay. That means that at present, if agencies require that pedestrian delay be reported, designers will have to calculate pedestrian delay in a separate analysis and report it separately from standard reports produced by intersection analysis software. Agencies that specify or recommend any particular intersection analysis software should consider demanding that its developers add pedestrian and bicycle delay to its calculation and reporting functionality.

3.3.1 PEDESTRIAN DELAY FORMULAS FOR PRETIMED, ACTUATED, AND MULTI-STAGE CROSSINGS

For single stage crossings with pretimed signals, the *HCM* provides a well-established formula for pedestrian delay,

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

where d_p is average pedestrian delay, C is cycle length, and g_{Walk} is the effective walk interval. The HCM 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 interval g_{Walk}, and so

$$g_{Walk} = WALK + AdditionalWalkTime \quad \text{(Equation 3-2)}$$

where *WALK* is the length of the Walk interval. The *HCM* suggests using 4 s as additional Walk time, based on a study that predates pedestrian countdown timers.

Where a pedestrian crossing is pushbutton actuated, the HCM 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 using that crosswalk in a cycle, average delay with pushbutton actuation is given by

$$d_p = \frac{C}{2} \quad \text{(Equation 3-3)}$$

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, and 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. Where demand for a crosswalk is 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 result given by **Equations 3-1** and **3-3**. Let:

vP = demand for a particular crosswalk (both directions) (pedestrians/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)

d = average delay (s)

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

$$d_p = d_{al} \text{ if } vP \le vP_{lo}, \tag{Equation 3-4}$$

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

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

Where crossings have to be made in two or more stages, pedestrian delay can be deceptively long and complex to calculate by formula (Wang and Tian (2010), Ma et al (2011).). Instead, a simple numerical method can be applied that simply tracks pedestrians, arriving every 0.5 s, through the crossing, and averaging the results (Furth et al. (2019)).

This method can be applied using the *Northeastern University Pedestrian and Bicycle Crossing Delay Calculator,* which is available for free (http://www.northeastern.edu/peter.furth/delaycalculator/) (Furth et al. (2019)). The calculator tool can handle up to four crossing stages and can also handle 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 3-stage crossing in Boston. Note that the average delay in the below example is more than 120 s, even though the cycle length is only 100 s.

Exhibit 3-2: Delay report and progression diagram for a 3-stage pedestrian crossing. Source: Furth et al. (2019).

It is also possible to calculate average pedestrian delay using microsimulation models that include pedestrian modeling functionality. However, this method involves considerable time, expertise, and the cost of the software license. If microsimulation is used, it is important to run it long enough that it processes at least 500 pedestrians per crosswalk to reduce variability and capture sufficient sample size, since individual delay varies depending on when in the cycle a person arrives.

3.4 Bicycle Delay and Average Operating Speed

In many cases, bicycle delay closely tracks vehicular delay or pedestrian delay. Where bicycles follow vehicular signals, if signalized intersections are widely spaced, bicycle delay is usually a little less than the delay of the concurrent vehicular movement 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 will usually begin to cross not only during the Walk interval, but also during the Flashing Don't Walk interval.

Nevertheless, bicycle delay should be considered as a key performance measure, along with average operating speed, a performance measure that 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 delay. One is along a street with closely spaced signals, as discussed in **Section 0**. 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 is where bicycles make a two-stage left turn (two square crossings, staying 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 Leading Pedestrian Intervals (see **Section 6.5**) or to turn right on red (see **Section 9.6**).

3.5 Accessibility and Intersection Layout Measures

In addition to the simple question of whether an intersection has accessible signals, there are several indicators that can be measured with regard to the objective of making crossings accessible, including:

- Lowest pedestrian speed designed (see **Section 7.4***, Pedestrian Clearance Interval Settings for Serving Slower Pedestrians*).
- 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***, Accessible Signals without Pushbutton Actuation*).
- Pushbutton offset from a crosswalk's approach path and from the curb (see **Section 8.3***, Accessible Signals without Pushbutton Actuation*; see **Section 9.4**, *Bicycle Detection*).

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

- Crosswalk length and related adequacy of clearance time provided (see **Section 7.4***, Pedestrian Clearance Interval Settings for Serving Slower Pedestrians*).
- Depth of a crossing island and queuing area on an island versus the depth and area needed. In this regard, bicycles' needs are different from those of pedestrians (see **Section 10.1**, *Multstage Crossings – General*).
- Sight distance for permitted turn conflicts when a bicycle path is physically separated from a roadway (See **Section 6.2**, *Protected-Only Left Turns to Address Non-Motorized User Conflicts*).

3.6 Performance Data From Traffic Signal Systems

Where the capability exists, automated data collected from traffic signal systems can also be utilized to generate useful performance measures. The potential exists with any centralized signal system that automatically logs data and is especially promising in systems that have the high-resolution data logging capability from their signal control equipment.

3.6.1 **USING CENTRALIZED SIGNAL SYSTEMS**

Centralized traffic signal systems with the capability to log data automatically and generate reports with various performance measures are available and utilized by many agencies. 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 measures of effectiveness (MOEs). The reports can be predefined, with user selected reporting intervals, or they can be scheduled to run automatically. Some examples of these reports include vehicle detector occupancy, green time distribution, vehicle detector failures, the number of max outs, etc.

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, Washington often programs phase splits that are less than the time required to serve pedestrians to maintain shorter cycle lengths and reduce delay for all users. When there is a pedestrian call, the phase is lengthened to serve it, and the cycle is then forced into a transition period to recover the extra time used by the lengthened phase to return to coordination. Staff are able to 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 disrupts signal coordination, signal timing strategies are reviewed and adjusted to serve the pedestrian timings within the coordinated cycles, thereby limiting transitions, improving service for pedestrians , and reducing the impact on signal coordination.

3.6.2 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 consists of timestamped 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 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 related to serving vehicles, they can also be used for measures related to pedestrian and bicycle service. 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 is a measure closely related to average pedestrian delay, though 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 total number of pedestrian actuations (**Exhibit 3-3**), which is closely related to pedestrian demand (although, again, they are not the same because pedestrians arriving after the pedestrian phase has been called are not counted). By indicating of how often pedestrian phases are needed, it can also be helpful in designing signal timing plans. Where the frequency of pedestrian actuations is low, designers may use a cycle length that is shorter 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, after which a transition routine is run to recover the extra time added to 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 can be especially valuable when applied to a critical intersection whose cycle length governs the cycle length of a corridor. However, this strategy becomes inefficient due to the frequent transitions if pedestrian actuations are too high.

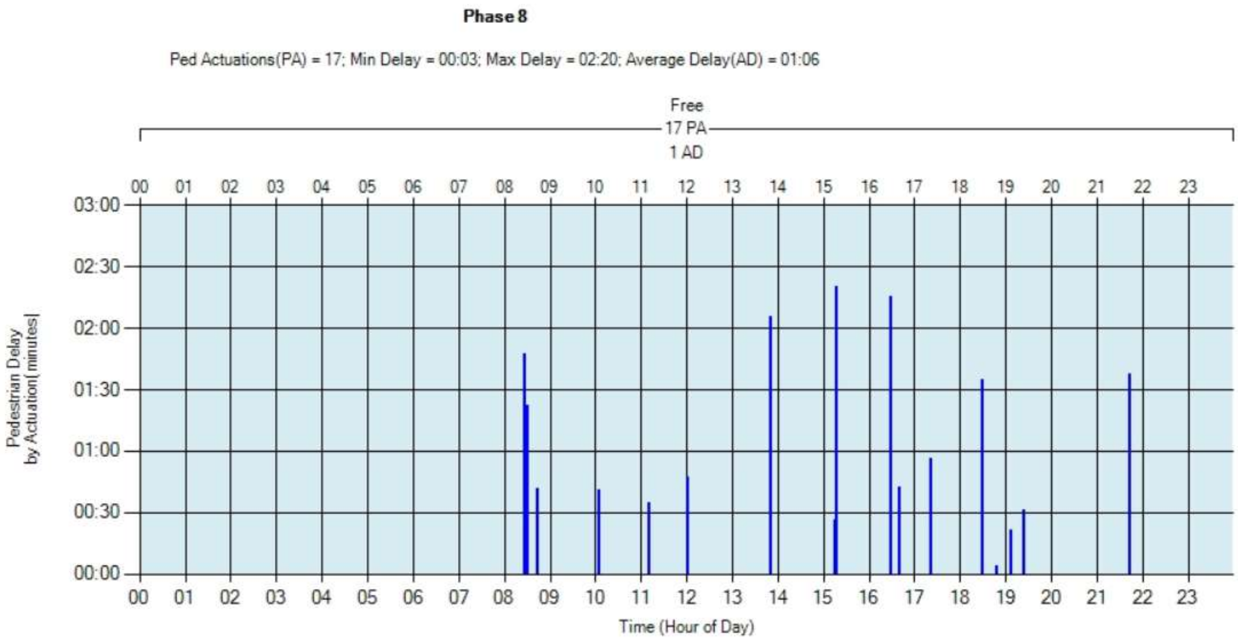


Exhibit 3-3: Pedestrian Delay report example generated by the UDOT Open-Source Platform.

Unfortunately, reports based on pedestrian phase actuation data are unable to measure pedestrian activity or delay where pedestrian phases are on recall, and their accuracy in measuring pedestrian delay and activity declines where 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. Where 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^{th} (blue) was one week prior to the start of classes, and August 22^{nd} (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 showed that after classes began, there were 15 cycles per day with pedestrian activity and in which the conflicting traffic volume was 1200 vehicles/hour or greater, which corresponds to an average headway of less than 3 s between vehicles. This analysis helped support a decision to implement an exclusive pedestrian phase.

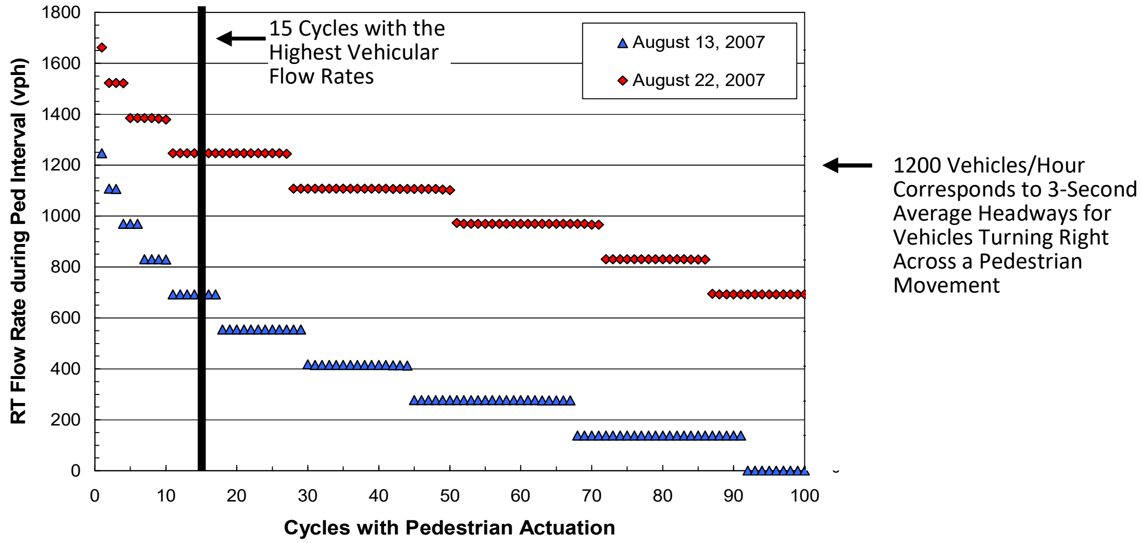


Exhibit 3-4. Pedestrian conflicts example: Right-turn vehicular flow rates during cycles with pedestrian actuations (Hubbard, Bullock, and Day 2008)

3.7 References

Furth, Peter G., Yue Danny Wang, and Michael A. Santos. "Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Turns: Delay Estimation and Signal Timing Techniques for Limiting Pedestrian and Bicycle Delay." *Journal of Transportation Technologies* 9.04 (2019): 489.

Hubbard, S. M., Awwad, R. J., & Bullock, D. M. (2007). Assessing the impact of turning vehicles on pedestrian level of service at signalized intersections: a new perspective. Transportation research record, 2027(1), 27-36

Ma, W., Liu, Y., Xie, H., & Yang, X. (2011). Multiobjective optimization of signal timings for two-stage, midblock pedestrian crosswalk. *Transportation research record*, *2264*(1), 34-43.

U.S. Access Board (2011). Proposed accessibility guidelines for pedestrian facilities in the public right-of-way. *Washington, DC*.

Wang, X., & Tian, Z. (2010). Pedestrian delay at signalized intersections with a two-stage crossing design. *Transportation research record*, *2173*(1), 133-138.

Chapter 4 Signal Timing Basics

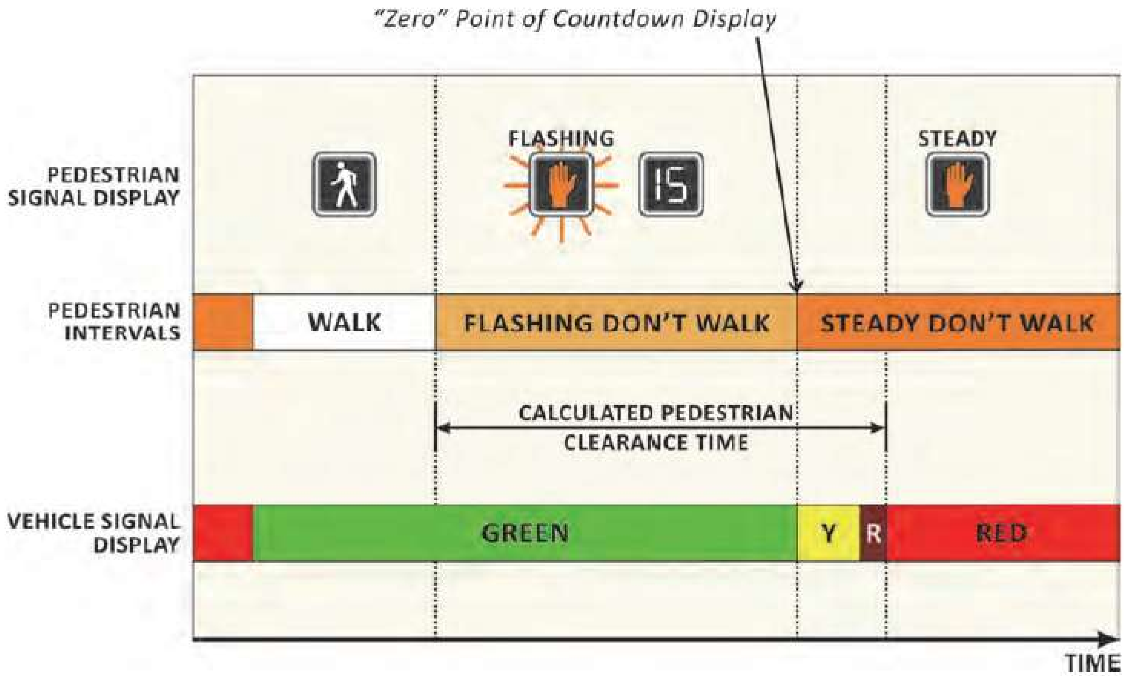
This section first covers signal timing principles for pedestrians and bicycles to provide a better understanding of signal timing fundamentals. Then, it provides a toolbox of signal timing and design treatments to improve pedestrian and bicycle mobility and safety at signalized intersections. Each treatment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

4.1 Signal Systems Understanding

Implementing treatments for pedestrians and bicycles requires an understanding of the principles of the vehicular signal system. Prior to exploring new treatments for non-motorized users, agencies must understand the equipment and controller(s) currently being used and how that influences operations. Existing indications, for example, may create conditions on how the intersection operations 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 **Section 5** notes which treatments are likely to require new equipment. Equipment needs are also summarized for each treatment, when applicable, in the toolbox (**Sections 6-10**). For additional information on vehicular signal systems, refer to the MUTCD and *Signal Timing Manual, 2nd Edition.*

4.2 Pedestrian Intervals

The pedestrian phase consists of three intervals: Walk, Flashing Don’t Walk (FDW), and the pedestrian phase end buffer, during which steady Don’t Walk is displayed but conflicting traffic may not be released. During the rest of the cycle, in which pedestrian phase is inactive, a steady Don’t Walk continues to be displayed, as shown in **Exhibit 4-1** below. 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 about to end imminently; pedestrians are expected to use this interval, along with the FDW interval, to complete their crossing.



Note: The figure assumes clearing through yellow and red clearance

Exhibit 4-1: Pedestrian Intervals [Signal Timing Manual, Second Edition].

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

Where 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*** – *Maximizing Walk Interval)*.

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 feet per second, a speed attainable by more than 90% of the population. Where slower pedestrians routinely use a crossing, a lower pedestrian design speed may be used. The MUTCD also describes an option, rarely implemented, to use a pedestrian design speed of up to 4 feet per second in conjunction with an pushbutton through which slower pedestrians may request a longer clearance time (see **Exhibit 4-2**.).

Exhibit 4-2: Example of Extended Push Button Press Signage.

The MUTCD also specifies a second clearance need, for pedestrians who begin crossing at the start of the Walk interval. The combined duration of the Walk, FDW, and phase end buffer should be enough for a person to cross the street at a speed of 3.0 feet per second, beginning at the pedestrian pushbutton or, if there is not one, 6 feet from the edge of the curb. This requirement is typically constraining only for long crossings. Normal practice is to make a preliminary pedestrian timing ignoring this second clearance need, and then check whether it is satisfied; if not, increase the length of the Walk interval until it is.

Section 7.4, *Pedestrian Clearance Settings for Serving Slower Pedestrians,* offers more detail about pedestrian clearance needs and related pedestrian timing.

4.2.3 FLASHING DON'T WALK INTERVAL AND PEDESTRIAN PHASE END BUFFER

Together, the FDW interval and the phase end buffer supply the pedestrian clearance need. Relative to a concurrent vehicle phase, the FDW interval may end (and the phase end buffer begin) during the green for the concurrent vehicle phase, at the onset of yellow, during the yellow, or at the end of yellow. 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 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 4.1) 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, discussed in greater detail in **Section 7.4**, *Pedestrian Clearance Settings for Serving Slower Pedestrians.*

4.3 PEDESTRIAN CALL MODES: ACTUATED OR RECALL

Pedestrian phases can be on recall or actuated. On recall means that a call for pedestrian service is placed automatically every cycle. If actuated, the controller places a call for the pedestrian phase when a pedestrian is detected. 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*** *Pedestrian Recall vs. Actuation.*

4.4 Accessible Pedestrian Signals

Accessible pedestrian signals (APS) help people with low vision, possibly combined with 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 a standard pedestrian pushbutton and an accessible pedestrian signal. At signals without standard pushbuttons (e.g., pretimed intersections, phases with pedestrian recall), the need for an APS can still be utilized by providing similar pushbutton units without requiring that the pedestrian call mode become actuated. For more detail, see **Section 0** *Accessible Signals without Pushbutton Actuation*).

Exhibit 4-3: Pushbutton integrated APS (Source: www.apsguide.org).

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's Section 4E.08 and 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 (2011) includes a requirement for APS wherever pedestrian signals are installed and referred to the MUTCD standards for APS features and functioning. The Guidelines have not been finalized and adopted by United States Department of Justice and DOTs but may be considered best practice. Several municipalities and states, including Minnesota and Maryland, install APS at all reconstructed or newly signalized intersections. Many also have policies to install APS when requested by a member of the public and when the location meets other requirements (e.g., New York City, Portland, Oregon, Seattle, Washington). These requirements typically include that the location is already signalized.

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 U.S. and used widely in Europe is to have 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 longer time than autos, especially with large intersection crossings, to clear an intersection 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** *Minimum Green and Change Interval Settings for Bicycle Clearance*.

Bicycles 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, with 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 which limits application of bicycle signals is that there must not be any permitted conflict with turning vehicles, including right turns. As of March 2019, there are 480 intersections that are currently using bicycle signal faces across the U.S. (Monsere et al., 2019).

4.6 Traffic Signal Controller Elements Overview

The following section 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.

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 • Signal Progression for Bicycles
Advance Walk	A pedestrian overlap configuration, programmed as a number of seconds, where the pedestrian phase starts before the corresponding vehicle phase.	Advance provides a leading pedestrian interval, allowing pedestrians to enter the crosswalk before conflicting vehicles.	• Leading Pedestrian Interval • Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds
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
Steady Don't Walk	The period of time after the walk and flashing don't walk have completed timing. The duration of the steady don't walk interval is not a programmable parameter in the controller and is simply the length of	Part of the overall pedestrian clearance internal. Must be displayed for at least three (3) seconds before the release of conflicting vehicles, per the MUTCD.	

	the phase minus the walk and FDW intervals.		
Alternate Walk/Ped Clear	The amount of time the Walk indication is displayed when an alternate Walk (for special-needs pedestrian) call 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 Push Button • Maximizing Walk Interval Length
Phase Options			
Pedestrian Recall	Causes the controller to place a continuous call for pedestrian service on a phase, resulting in the pedestrian walk and clearance intervals timing every cycle.	Typically used at locations and/or during times with high pedestrian volumes	• Pedestrian Recall versus Actuation
Rest in Walk (Actuated Rest in Walk)	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 • Pedestrian Recall versus Actuation
Ped Recycle	Allows pedestrian service in the programmed ring to recycle if there is a pedestrian call registered on the phase in service or pedestrian recall is programmed for the phase and there are no serviceable opposing calls.	Reduced pedestrian delay by allowing for late pedestrian service and for pedestrian to reservice if remaining service time allows Can be used under actuated and non-actuated operation	• Reservice
Force Cord Ped Yield Option	Forces a pedestrian phase in walk rest to fully terminate in time for the coordinated phase to yield on-time when there are no conflicting calls.	If used in conjunction with Ped Recycle, the pedestrian phase will serve again if the coordinated phases do not yield (no conflicting calls)	• Reservice
Bicycle Phase	Separate 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 • Minimum Green and Change Interval Settings for Bicycles • Signal Progression for Bicycles
Coordination Features			
Ped Clear in Yellow	FDW terminates at the end of the yellow interval		
Ped Clear in Red Clear	FDW extends into all red interval		

Ped Clear in Trailing Green	FDW extends into overlap trailing green times	Extend the pedestrian phase with leading pedestrian intervals	• Leading pedestrian intervals
Ped NA Plus		Will not serve rest walk in recycle	
Vehicle Based			
Flashing Yellow Arrow (FYA)	A protected-permitted left-turn display that feature a flashing yellow arrow in addition to the standard red, yellow and green arrows. When illuminated, the flashing yellow arrow allows waiting motorists to make a left-hand turn after yielding to oncoming traffic.	FYA can we programmed with a Negative Ped or Not Ped condition. If FYA is on and a pedestrian call comes, the pedestrian waits. The FYA would terminate early if there is time remaining in the through phase or the pedestrian phase would be served in the next cycle without FYA.	• Protected Left Turns to Address Non-Motorized Conflicts
Right Turn Overlaps	Right-turn movements operating in exclusive lanes are assigned to more than one phase that is not conflicting (e.g. nonconflicting 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 a flashing yellow arrow or red arrow instead of the green arrow.	• Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds
Time of Day	Most signals have several timing plans that operate at different times of day.	Use a “dummy phase” to allow different type of operations throughout the day, such as exclusive pedestrian phases during off-peak times.	• Exclusive Pedestrian and Bicycle Phases
Alternate Phases	Phase is served every other even/odd	Typically used for split phase	

4.7 References

Monsere, C. et al. (2019). NCHRP Web-Only Document 273: Road User Understanding of Bicycle Signal Symbol Indications. Transportation Research Board, Washington DC.

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 section introduces the treatments and provides additional guidance 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 sections covers a different intended outcome, organized as follows:

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

Treatments in this section 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 Delay

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

Chapter 10: Techniques for Multistage Crossings

This section 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
- **Application and Expected Outcomes:** National and international use; benefits and impacts

- **Other Considerations:** Accessibility considerations, other guidance, relationship to other treatments, Equipment needs, other signal timing considerations, signage and striping, and intersection layout.

Examples are embedded within each treatment description.

5.2 OVERVIEW OF TREATMENTS

While 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, indicating 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, geometric changes, or specialized software or programming. Requirements indicated in this table are for the most likely anticipated application, recognizing that there may be applications with greater or lesser 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. Reduce or Eliminate Conflicts with Turning Traffic	6.1	Protected-Only Left Turns to Address Non-Motorized 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 Interval (LPI)	Operational	Pedestrians	X			
	6.6	Delayed Turn / Leading Through Interval (LTI)	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. Reduce 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 vs. Actuation	Operational	Pedestrians		X	X	
	7.6	Pedestrian Hybrid Beacons	Geometric/ Equipment	Pedestrians	X	X	X	X

	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 Push Buttons	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 Bicycles	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	
10. Multistage Crossings	10.1	Multistage Crossing	Geometr5ic / 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 Crossing	Operational	Bicycles		X		

Chapter 6 Treatments that Reduce or Eliminate Conflicts with Turning Traffic

This section 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-turning traffic as well	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 (LPI)
	6.6	Delayed Turn / Leading Through Intervals (LTI)
	6.7	Pedestrian Overlaps with Leading Pedestrian Intervals (LPI) and Vehicular Holds
Preventing turns on red	6.8	No Turn on Red
Fostering yielding by turning traffic	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 to 50 percent 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 section 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 delay. This often leads to agencies allowing turn conflicts with pedestrians and bicycles, which can create safety issues, especially for pedestrians and bicycles due to their vulnerability.

Protected-Only Left Turns to Address Non-Motorized User Conflicts (**Section 6.1**) examines the question of 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 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. Its main drawback is its negative impact on traffic capacity, which 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 the 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 signalized, that creates multistage crossings which can entail large pedestrian delays unless carefully timed.

Treatments 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, and no protection from right turns might be appropriate.

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

Delayed Turn / Leading Through Interval **(Section 6.6)**. At the start of a vehicular phase, turning traffic is held for a short time (but typically longer than an LPI) while through traffic, pedestrians, and bicycles for certain cities, get a head start, allowing them to establish their priority in the crosswalk before turning traffic is released.

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

No Turn on Red (Section 6.8) deals with a different kind of turning conflict. This well-known treatment has interactions with many other treatments described in this manual, such as LPI, which aims to give pedestrians a short interval free of turning conflicts.

Flashing Pedestrian and Bicycle Crossing Warnings (**Section 6.9**) 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, used for this purpose in several US cities, and a flashing pictogram used in Amsterdam.

REFERENCES

Lord, D., Smiley, A., & Haroun, A. (1998). Pedestrian accidents with left-turning traffic at signalized intersections: Characteristics, human factors, and unconsidered issues. In *77th Annual Transportation Research Board Meeting, Washington, DC*. Available at https://safety.fhwa.dot.gov/ped_bike/docs/00674.pdf.

6.1 PROTECTED-ONLY LEFT TURNS TO ADDRESS NON-MOTORIZED CONFLICTS

6.1.1 **BASIC DESCRIPTION**

6.1.1.1 ALTERNATIVE NAMES

Not available.

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 involve a left turning vehicle was between 17 and 32 percent (Lord et al., 1998). In Cambridge, MA, 19 percent 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 bicycles fatalities in a 5-year period ending in 2014, 108 were killed by a left turning vehicle (New York City DOT, 2014). Left turns are also a leading cause of vehicle-vehicle injury crashes.

Protected only left turn phasing separates crossing pedestrians and bicycles in time from left turning vehicles. "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 movement, including pedestrian, bicycle, and vehicular movements, runs concurrently. This differs from the 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 left turns

- High speed roads

1. 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 related 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. Still, because 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 their model, 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 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, searching for and anticipating a gap, and 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.

2. 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 (*MassDOT, 2015)*.

3. Limited visibility to approaching bicycles

The AASHTO Green Book recommends that left turns at signalized intersection have permitted phasing only if drivers waiting to turn left have a clear sight line to approaching vehicles to whom they are obligated to yield (that is, 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, approaching bicycles close enough to conflict with a turning vehicle should be visible, or else the left turn should be separated in time from the bicycle movement. The time needed for the left turn maneuver is given by:

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

where t_o is 5.5 s if the design for a left turning passenger car (6.5 s for a single unit truck, 7.5 s for a combination truck), and *C* is the additional distance, in ft, 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 any approaching bicycle is one to whom the left turning driver is obligated to yield; its length is

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

Bicycle design speed may be taken to be 14.7 to 17.6 ft/s (10 to 12 mph) on level ground, 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.

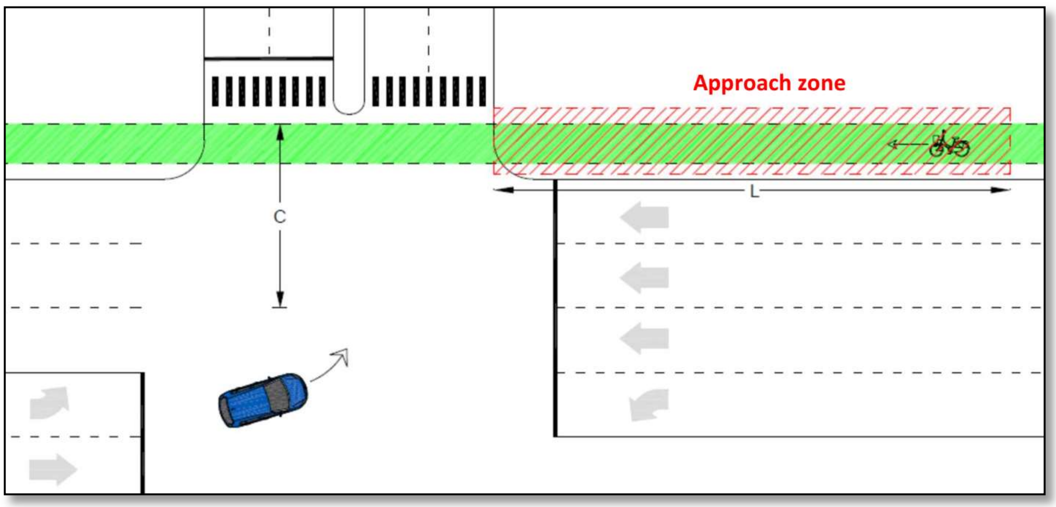


Exhibit 6-1: A left-turning passenger car versus an oncoming bicycle.

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.

Exhibit 6-2: Obstructed view between waiting vehicle and the approach zone on a sidepath in Boston. The car circled is the second vehicle in the left-turn queue (Photo Credit: Peter Furth).

4. 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.

5. High volume of left turns

High left turn volume increases pressure drivers feel to turn (rather than wait). It also increases the fraction of vehicles that turn left as a follower in a platoon. Research done for this project found that left turning drivers in the second or later position in platoon were 56 percent less likely to yield to a crossing bicycle or pedestrian than drivers who were not immediately following another vehicle. For separated bike lanes, the Massachusetts DOT *Separated Bike Lane Design Guide* recommends, for example, that the limiting volume for left turns from a two-way street across two lanes and one-way bike path is 50 vehicles per hour. Assuming a 90 second cycle length, that is approximately one left turning vehicle per cycle on average, thus avoiding platooned turns in most cycles.

6. High speed roads

On high-speed roads, vehicle-vehicle crashes involving left turns are often deadly.

6.1.2 **APPLICATION 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 multilane intersections and wherever left turns cross a two-way bike path. Permitted left turns are allowed on streets with one lane per direction; however, in practice, protected left turns are more common except from minor street approaches that are too narrow to have left turn lanes.

In the US, guidelines regarding the use of permitted left turns are comparatively less strict. For example, guidelines found in the *Signal Timing Manual* (which are themselves based on other national publications and are 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 related crashes, more than roughly 5 per year per left turn movement. Apart from the crash experience criterion, those are conditions that relatively few intersections meet. It also stands out that those 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, in Cambridge, MA, at all intersections with multilane roads, 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 website). The City of 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 website). New York City has also recently converted several intersections to protected only phasing.

6.1.2.2 BENEFITS AND IMPACTS

Protected only left turn improve safety for pedestrians, bicycles, and turning vehicles. A before-after study found that when 9 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 from conversions to protected-permitted left turns, which were applied in Chicago and Toronto (Goughnour et al., 2018).

Research done as part of this guidebook found that on a multilane road, in situations in which 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 Boston intersections 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, of 164 bicycle crossings that took place during the permitted phase while a left turning vehicle was waiting to turn and there was no opposing traffic blocking their 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, making its turn and 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 vehicle.

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 persists 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. Comparing the base case with leading protected lefts (**Exhibit 6-3**), bicycle and pedestrian delay 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.

Exhibit 6-3: Delay impacts of left turn phasing alternatives, Columbus Avenue and Heath Street, Boston, MA, AM 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

6.1.3 CONSIDERATIONS

6.1.3.1 ACCESSIBILITY CONSIDERATIONS

Protected crossings benefits 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 the through movements so 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 Massachusetts DOT *Separated Bike Lane Design Guide* recommends protected-only turns when turning volumes exceed those shown in **Exhibit 6-4.** It recommends, for example, that the limiting volume for left turns across two lanes and one-way bike path is 50 vehicles per hour. Assuming a 90 second 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 is discussed above).

Exhibit 6-4: Turning volume criteria for protected only left and right turns (Source: MassDOT, 2015).

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

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.
- 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**).
- Flashing Yellow Arrow (FYA) operation can be used to run protected-only at certain times of day or when pedestrians are detected (see **Section 6.8**).

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, which may, in turn, 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.

6.1.5 **REFERENCES**

Amiridis, K., Stamatiadis, N., & Kirk, A. (2017). Safety-Based Left-Turn Phasing Decisions for Signalized Intersections. Transportation Research Record, 2619(1), 13-19.

City of Boulder, CO website. https://bouldercolorado.gov/transportation/traffic-signals [Accessed April 28, 2020)

City of Cambridge (2014). Bicycle Crash Fact Sheet. https://www.cambridgema.gov/-/media/Files/CDD/Transportation/Bike/bicyclesafetyfacts_final_20140609.pdf

City of Cambridge, MA website. https://www.cambridgema.gov/traffic/engineeringplanning/trafficsignals [Accessed April 28, 2020].

Goughnour et al. (2018). Safety Evaluation of Protected Left-Turn Phasing and Leading Pedestrian Intervals on Pedestrian Safety. Report FHWA-HRT-18-044, U.S. DOT.

Hauer, E. Left Turn Protection, Safety, Delay and Guidelines: a Literature Review. University of Toronto, January 2003.

MassDOT (2015). *Separated Bike Lane Planning and Design Guide*.

New York City DOT (2016). Don't cut corners: Left turn pedestrian & bicyclist crash study. August, 2016.

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 are separated in time from both right turns and left turns by providing turning movements distinct phases (**Exhibit 6-5**). The objective is to improve safety by separating pedestrians and bicycles from conflicts with turning vehicles.

Protected 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. It also applies to protecting crossings from left turns from a one-way street.

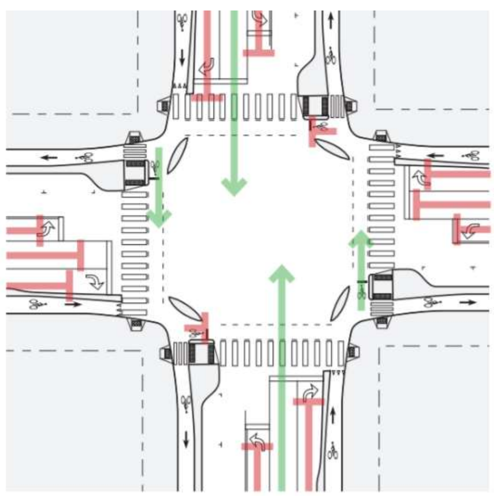


Exhibit 6-5: Concurrent-protected crossings.

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**, where, for example, southbound right is parallel to eastbound left, so the two movements can run together during phase 01 (similarly, northbound right and westbound 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.

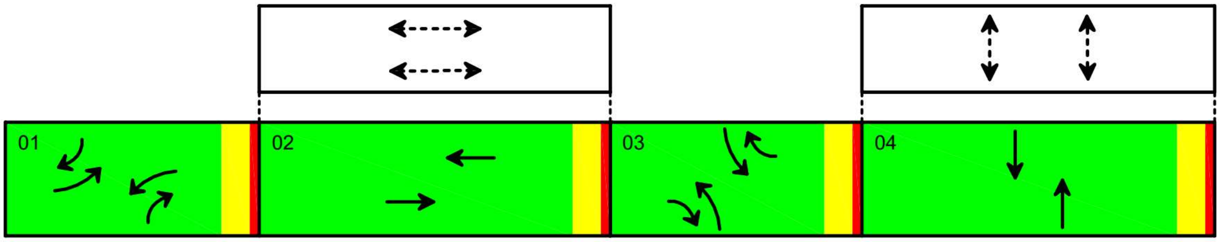


Exhibit 6-6: Right turns served with simple left turn overlaps in a single-ring phasing plan.

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 runs 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 while phase 02 serves left turning vehicles.

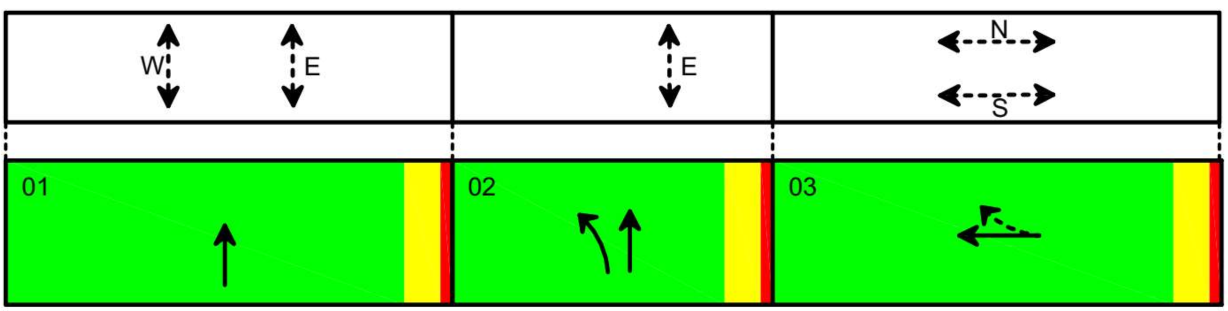


Exhibit 6-7: Split through phase as applied along one-way avenues in New York City.

6.2.1.4 OPERATING CONTEXT

This treatment is useful whenever certain conditions make it more desirable to separate (in time) crossings from right turns as well as left turns. Those 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 where 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 or near a major transit station.

This treatment also requires an exclusive right turn lane. At intersections without exclusive right turn lanes, it can 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 is widened to three lanes as it approaches an intersection is common; one lane each for left turns, one for 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 US, 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, New York, and Boston and Cambridge (MA) have used this treatment over the last 15 years to create safer bicycle and pedestrian crossings.

With regard to protecting bicycles from right turn conflicts, the experiences and policies of Amsterdam, New York City, and Montreal are instructive for understanding the trade-off between protection and delay. In Amsterdam, concurrent-protected bicycle and pedestrian crossings became the norm in the 1970's. 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 non-compliance led to a change in policy in the early 1980's. Since then, while concurrent-protected phasing is still used on approaches with high right-turn volumes or high right turn speeds and anywhere right turns can be served with a simple left turn overlap, right turn conflicts are permitted at most intersections (Linders, 2013).

New York City's policy regarding protected crossings evolved similar 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 non-compliance 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, described **Section 0**, in which the bicycle crossing is protected only during an initial interval (e.g., 10 or 15 s), after which conflicting left turns (from a one-way street) are allowed and governed by a *flashing yellow arrow* (see **Section 0**) to alert drivers of a potential conflict. New York City's current policy prefers concurrent-protected crossings only where there are high volume or high speed turn conflicts (provided a turn lane is available or can be created); otherwise, if a turn lane can be provided, they prefer delayed turn or, where no turn lane can be created, Leading Pedestrian Interval (**Section 0**) (Danny Nguyen, personal communication, October 10, 2019).

Montreal approached the protection-delay tradeoff from the other direction. Montreal has long used the delayed turn treatment **(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, concurrent with through traffic after that, left turns across the bicycle path were permitted during the rest of the through phase However, over the years, bicycle volumes increased, and motorists could not find enough safe gaps to turn left, particularly since the bike path is two-way; that, in turn, 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 9.1.1**).

6.2.2.2 BENEFITS AND IMPACTS

While both *exclusive pedestrian and bicycle phases* (**Section 6.3**) and concurrent-protected crossings 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 operated 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).

Compared to crossings with permitted right turn conflicts, concurrent-protected crossings eliminate turn conflicts, making crossings safer. 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 implement with no footprint impact. In Cambridge, for example, at the junction of Broadway and Galileo Galilei Way, converted in 2017 to concurrent-protected phasing, two of the approaches already had right turn lanes; on the other two approaches, the rightmost through lane was converted to an exclusive right turn lane. The through phases still had sufficient capacity in spite of having one fewer lane fewer because right turning traffic and pedestrian interference were removed. Cycle length was left unchanged, and level of service for vehicles was unchanged. For pedestrians, however, it has been called a “night and day” improvement because they can now cross without danger from right turning cars (Patrick Baxter and Cara Seiderman, personal communication, 2018).

There is almost no delay impact to pedestrians or bicycles where right turns can be served using simple overlap with a left turn phase; otherwise, concurrent-protected crossings can increase pedestrian and bicycle delay 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 Lovejoy Street in Portland, Oregon, found that providing a protected crossing increased average cyclist delay by 4 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 can be confusing to pedestrians, as well. Provide an accessible pedestrian signal (APS) to provide guidance 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 the City of Boston recommend protected pedestrian crossings where concurrent right turns would exceed 250 vehicles per hour (approximately 7 vehicles per cycle since most intersections have 100 s cycle length). 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 Conflicts (**Section 6.1**) and *No Turn on Red* (**Section 6.8**) are a necessary part of this treatment.

Exclusive Pedestrian and Bicycle Phases (**Section 6.3**) is an alternative treatment providing fully protected pedestrian crossings.

Delayed Turn (**Section 0**) is an alternative treatment providing partially protected crossings.

Channelized Right Turns (**Section 0**) also provide concurrent-protected crossings, but allow their 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 with Galileo Galilei Way, 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 **(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 **Exhibit 6-8**, for any given crossing (e.g., the north-side crossing, running during phase 02) there is a clear sequence: the conflicting left turn leads (phase 01), the crossing is in the middle (phase 02), 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.

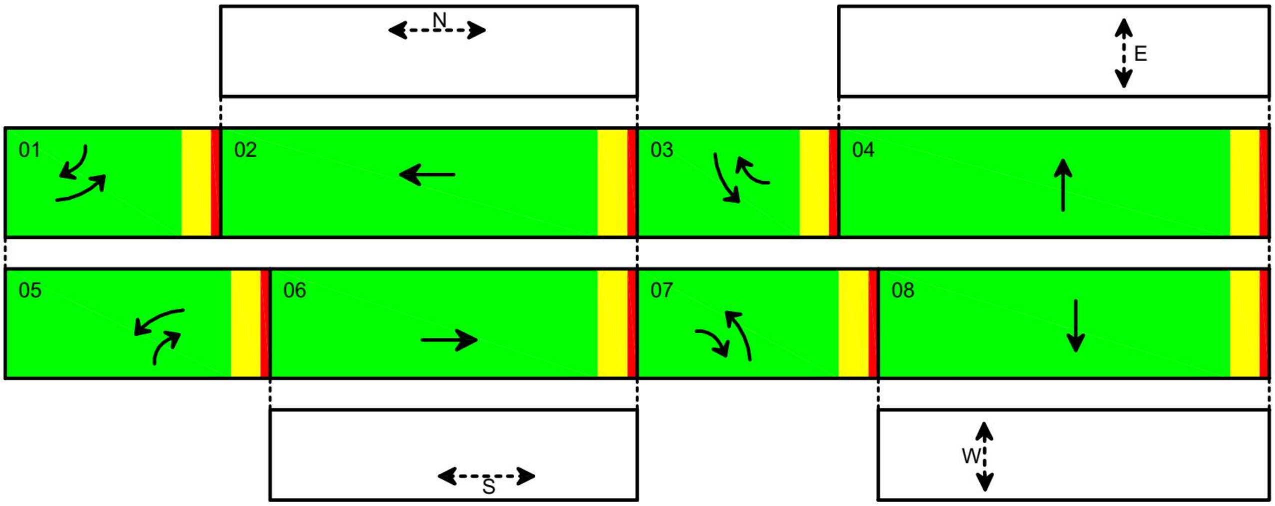


Exhibit 6-8: Dual ring phasing using simple left turn overlaps to serve right turns.

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 (that is, phase 09), westbound right turns can run; during the latter part (phase 02), the northside 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 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).

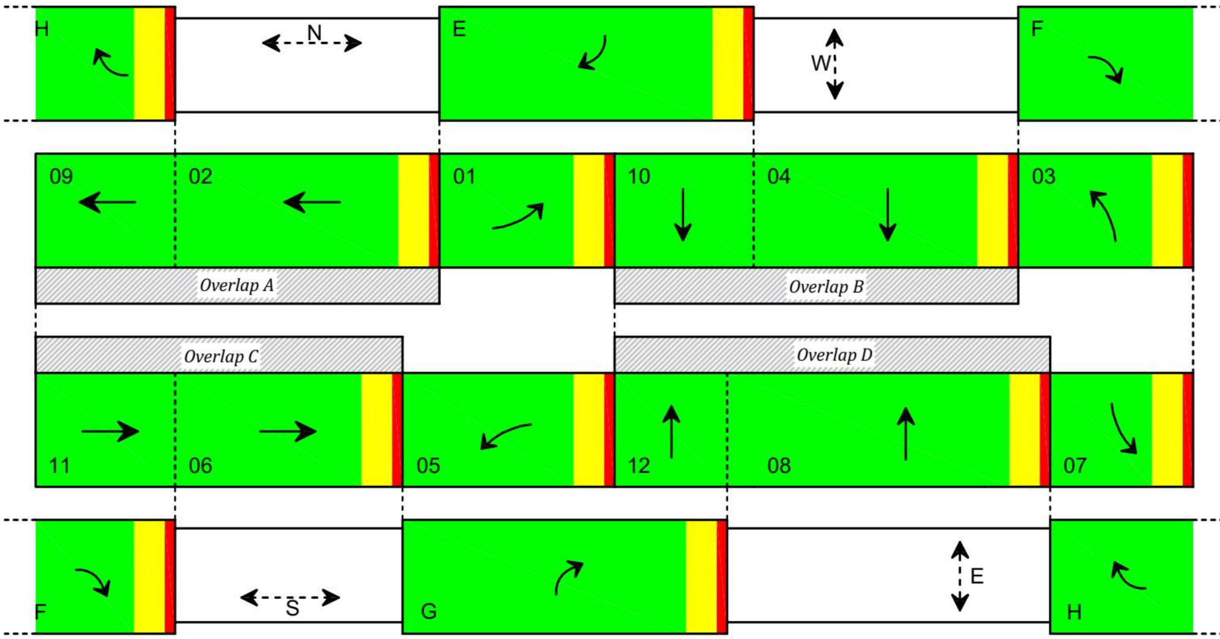


Exhibit 6-9: Using complex overlaps to create a full set of concurrent-protected crossings.

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 that time not needed by right turning vehicles reverts to the crossing phase. This, in turn, 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 the right turn phase can appear several times within a cycle, a technique called *reservice* (**Section 7.2**).

6.2.4.3 SIGNING AND STRIPING

Not applicable for this treatment.

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.

6.2.5 REFERENCES

City of Boston. (2013). Boston Complete Streets Design Guidelines.

CROW (2016). Design Manual for Bicycle Traffic. Ede, The Netherlands: CROW.

Furth, P. G., Koonce, P. J., Miao, Y., Peng, F., & Littman, M. (2014). Mitigating Right-Turn Conflict with Protected Yet Concurrent Phasing for Cycle Track and Pedestrian Crossings. *Transportation Research Record*, *2438*(1), 81-88.

Harkey, D. L., Carter, D. L., Barlow, J. M., & Louise, B. B. (2007). NCHRP web-only document 117A: Accessible pedestrian signals: A guide to best practices. *Transportation Research Board of the National Academies, Washington, DC*.

Lin, P. S., Wang, Z., Guo, R., & Kourtellis, A. (2016, May). A pilot study on interactions between drivers and pedestrian features at signalized intersections—using the SHRP2 naturalistic driving study data. In *Proc. 11th Asia Pac. Transp. Develop. Conf. 29th ICTPA Annu. Conf.* (pp. 70-77).

Linders, Sjoerd (2013). *STOP! 100 jaar verkeer regelen in Amsterdam, 1912 – 2012.* City of Amsterdam.

Magder, Jason (2019, November 8). Out of sync: 'Safer' downtown traffic lights exasperate Montreal cyclists. *Montreal Gazette* https://montrealgazette.com/news/local-news/out-of-sync-safer-downtown-traffic-lights-exasperate-cyclists

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. This treatment is also sometimes used to increase capacity for right turns when high pedestrian flows block concurrent right turns, to increase pedestrian capacity where 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 6-10a and Exhibit 6-10b).** 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.

Where exclusive pedestrian phases are provided, pedestrians can also be allowed to *cross concurrently* (that is, concurrent with the parallel vehicular movement), as illustrated in **Exhibit 6-10c.** This option results in high pedestrian crossing capacity and less waiting time for pedestrians, though of course 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), while in the Netherlands, all bike directions are allowed, which creates cross-direction conflicts that bicyclists appear to resolve, informally, without any safety issue. Exclusive phases shared by pedestrians and bicycles are still less common, although informally, bicycles often run during exclusive pedestrian phases.

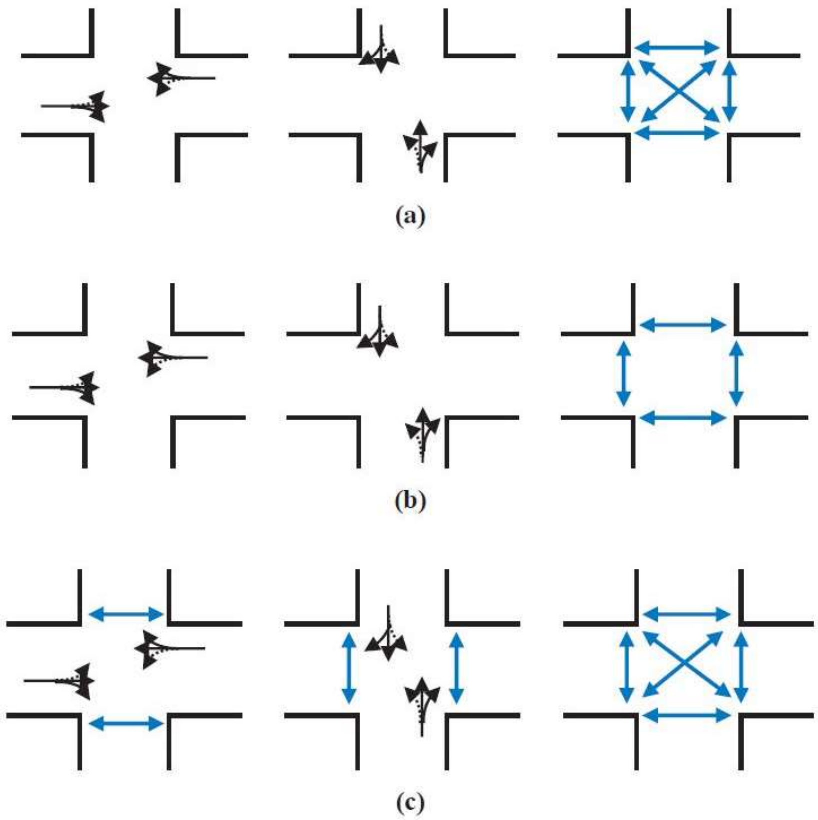


Exhibit 6-10: Typical phase sequences with an exclusive pedestrian phase. (a) With diagonal crossings, known as pedestrian scramble or Barnes Dance. (b) Without formal diagonal crossings. (c) With pedestrians also allowed to cross concurrently (Ismail, 2010).

6.3.1.4 OPERATING CONTEXT

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

- Where either high-speed right turns, a high volume or 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 very high pedestrian volume intersections, where pedestrians need the "green" for a large part of the cycle, by combining an exclusive pedestrian phase with concurrent crossings (see **Exhibit 6-10c**)
- Where there is high demand for diagonal pedestrian crossings
- 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 has many intersections with exclusive pedestrian phases that originally featured diagonal crossings. However, several years ago, when the city retimed its signals for a crossing speed of 3.5 ft/s instead of 4 ft/s, 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 6-10c**), resulting in high capacity and low delay for pedestrians. In downtown Washington, D.C., the same treatment can be seen at the 7th Street and H Street, NW intersection.

In Massachusetts, exclusive pedestrian phases have long been the default treatment for intersections on state highways and are also common at locally municipally intersections. However, because they typically involve long pedestrian waiting times and poor pedestrian compliance, pedestrian advocates generally prefer concurrent crossings, except where right turn volumes are high, or turns are made with 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 to cross diagonally to and from major transit stations, and where there is a high volume of turning vehicles. They also have 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 to serving a diagonal crossing, such as where a bicycle path switches from one side to another, with other bicycle movements not allowed during that phase. Most often, pedestrian movements are also not allowed. Portland (OR) has two such applications, including one at N. Interstate and Oregon Street. In Seattle, at 9th Avenue N and Westlake Avenue N (see **Exhibit 6-11)**, the diagonal bike crossing phase doubles as an exclusive pedestrian phase; however, other bike movements are held.

Exhibit 6-11: Diagonal bicycle crossings at 9th Avenue N and Westlake Avenue N in Seattle, Washington. Photo Credit: Kittelson and Associates, Inc.

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 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, and 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, 11/20/2019).

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, California that had been converted from concurrent crossings to an exclusive pedestrian phase, pedestrian-vehicle conflicts in which one party has to stop or change course unusually to prevent collision fell from 11.8 to 6.4 conflicts per 1000 pedestrians (Bechtel et al., 2004). A similar study of two converted intersections in Calgary 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 seconds, for example, that may require increasing the cycle length by 40 seconds 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, with concurrent crossings, saturation flow rate declines precipitously. In such a case, isolating pedestrians within a single phase can make the vehicular phases much more efficient, reducing 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 non-compliance, 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 non-compliance, with many people crossing concurrently with the parallel vehicular phase. Another New York study found that applying exclusive pedestrian phases with diagonal crossings at five intersections with high pedestrian volumes increased waiting time 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 an accessible pedestrian signal is 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)* notes this as an issue in consideration of 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 8-hour) 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 three years)
- There is moderate pedestrian volume with 25% of pedestrians who 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

No turn on red restrictions (see **Section 6.8**) should be applied either through 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.

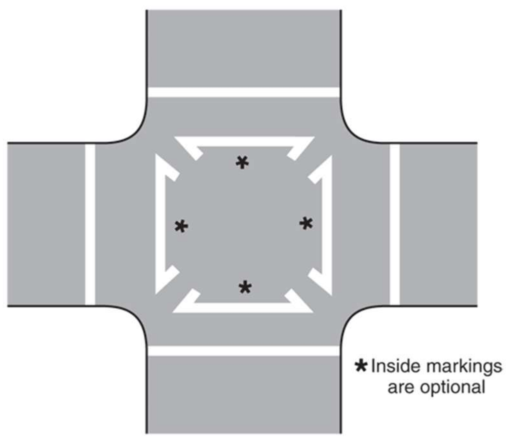


Exhibit 6-12: Example of Crosswalk Markings for an Exclusive Pedestrian Phase that Permits Diagonal Crossing (MUTCD Figure 3B-20).

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 regulated by traffic signals, as when bicycles are in a shared-use path or in protected bike lanes that are offset far enough from the curb that pedestrians have a waiting platform between the curb and the protected bike lane.

6.3.5 REFERENCES

Bechtel, A. K., Macleod, K. E., & Ragland, D. R. (2004). Pedestrian scramble signal in Chinatown neighborhood of Oakland, California: an evaluation. *Transportation research record*, *1878*(1), 19-26.

Bonneson, J., Sunkari, S. R., Pratt, M., & Songchitruksa, P. (2011). *Traffic signal operations handbook* (No. FHWA/TX-11/0-6402-P1). Texas. Dept. of Transportation. Research and Technology Implementation Office.

Chen, L., Chen, C., & Ewing, R. (2014). The relative effectiveness of signal related pedestrian countermeasures at urban intersections—Lessons from a New York City case study. *Transport policy*, *32*, 69-78.

City of Groningen. (2019, November 19). Green light for all cyclists. How does it work? https://groningenfietsstad.nl/en/green-light-for-all-cyclists-how-does-it-work/

Hediyeh, H., Sayed, T., & Zaki, M. H. (2015). The use of gait parameters to evaluate pedestrian behavior at scramble phase signalized intersections. *Journal of advanced transportation*, *49*(4), 523-534.

Ismail, K., Sayed, T., & Saunier, N. (2010). Automated analysis of pedestrian–vehicle conflicts: Context for before-and-after studies. *Transportation research record*, *2198*(1), 52-64.

Kattan, L., Acharjee, S., & Tay, R. (2009). pedestrian scramble operations: pilot study in calgary, Alberta, Canada. *Transportation research record*, *2140*(1), 79-84.

Korve, M. J., & Niemeier, D. A. (2002). Benefit-cost analysis of added bicycle phase at existing signalized intersection. *Journal of transportation engineering*, *128*(1), 40-48.

Kothuri, S. M., Kading, A., Smaglik, E. J., & Sobie, C. (2017). Improving Walkability Through Control Strategies at Signalized Intersections.

National Association of City Transportation Officials. (2019). Don’t give up at the intersection: Designing all ages and abilities bicycle crossings.

New York City Department of Transportation. (2017). Walk this way – Exclusive pedestrian signal phase treatments study. https://www1.nyc.gov/html/dot/downloads/pdf/barnes-dance-study-sept2017.pdf.

Wolfe, M., Fischer, J., Deslauriers, C., Ngai, S., & Bullard, M. (2006). Bike Scramble Signal at N Interstate & Oregon. *IBPI Research Digest*.

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, with a *delta island* forming between them. The delta island, also called *pork chop island*, serves as a pedestrian refuge and may also serve as a bicycle refuge (**Exhibit 6-13**).

Exhibit 6-13: Channelized right turn in Boulder (CO) (U.S. 36 at Baseline Rd) with delta island that serves as a refuge for a shared use path.. (Source: Google)

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 intersection.

At the same time, channelized right turns also pose challenges to pedestrians and cyclists that can make it advantageous to eliminate them. Where channelized right turns are unsignalized, replacing them with a conventional intersection layout with square corners forces right turns to be made at lower speed. Where those crossings are signalized, they create multistage crossings that, if not timed carefully, can entail extremely long pedestrian and cyclist delay (see **Section 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 implicit, since the crosswalk has priority). Where under STOP or YIELD control, the corner geometry should promote low turning speeds and yielding compliance using measures such as a 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 bicycles, 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 pre-signal that allows them to cross the slip lane. **Exhibit 6-14** shows a protected pocket lane and bicycle pre-signal at a Copenhagen intersection.

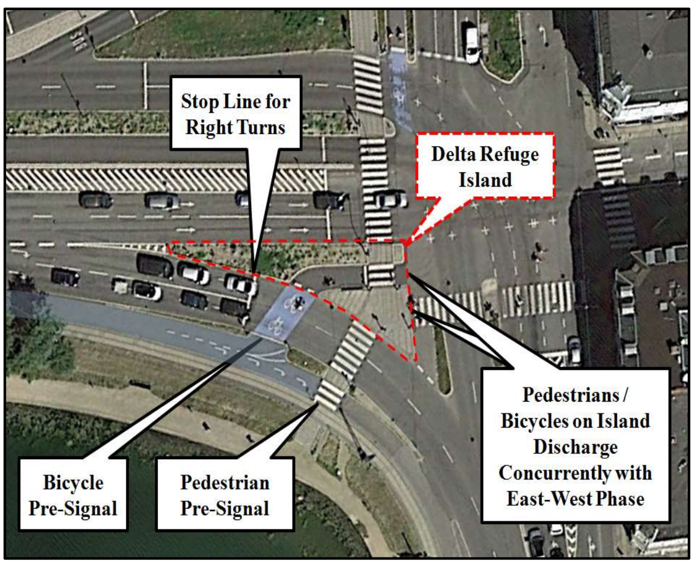


Exhibit 6-14: Delta island in Copenhagen (Hans Christian Andersen Blvd and Jarmers Pl.) with bicycle pre-signal and protected pocket bike lane. Source: Bachiochi and Furth, 2016.

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 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 assure crossing safety and compliance, such as raised crossings and prominent signs, have not been successful.

6.4.2 APPLICATIONS AND EXPECTED OUTCOMES

6.4.2.1 NATIONAL AND INTERNATIONAL USE

In the US, channelized right turns are common, particularly on wide, higher speed roads. Most were not made for pedestrians or bicyclists' benefit, but rather to reduce motorist delay by increasing turning speed. Most channelized right turns are unsignalized, but signalization is not unusual. Boulder (CO) has been a leader in improving the design of channelized turns that involve a shared use path crossing. Some U.S. cities including Chicago 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 are either a safety problem if left unsignalized, or create unacceptable delay for pedestrians and bicycles if signalized (Sjoerd Linders, personal communication, 8/1/2018). On the other hand, Copenhagen has a prominent application at an intersection 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-speed. They 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. That 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 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.

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.

Where 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 to all run concurrently. The shorter main crossing can also help enable a shorter cycle length (**Section 7.1**). A microsimulation 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 delay. However, if they are signalized, crossings for pedestrians and bicycles become multi-stage, which can lead to far greater pedestrian and bicycle delay 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 but, 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 signalized in a way that offers good progression. Where 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

Accessible pedestrian signals must be carefully installed and adjusted when used at channelized right turns (see *Manual on Traffic Control Devices (MUTCD)* Section 4E.13). Design of the channelizing island should consider how pedestrians who are visually impaired will approach to ensure that the accessible pedestrian signals 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 Report 834 provides assessment materials to determine if channelized right turn lane crossings are accessible to users with disabilities along with suggested treatments, depending on the results of the assessments (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 guidance on crossing distance is to provide crossing from curb/edge of shoulder to far side of traveled way. This can be interpreted to be from channelizing island to channelizing island, as this is the distance needed for a user to cross to safe spot.

6.4.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

If channelized right turns are signalized, they create *multistage crossings* (**Chapter 10**), which require attention to evaluating pedestrian and bicycle delay (**Chapter 3**) and signal timing treatments such as *reservice* (**Section 7.2**) to create good progression for pedestrians and bicycles.

Independently mounted pushbuttons are also needed where right turns are signalized (**Section 0**).

Flashing Yellow Arrow (FYA) can also be used with the channelized right turns to warn of conflicts with crossing pedestrians and bicycles (**Section 6.9**).

6.4.3.4 OTHER CONSIDERATIONS

In most cases, the pedestrian benefit to channelizing islands (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 a large design vehicle. 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 preferred 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 crossings, and sometimes bicycle crossings as well, multi-stage, which can result in long delays unless signals are timed for good progression for crossing pedestrians and cyclists. That is a challenge because four different streams of pedestrian movements cross any given channelized right turn lane (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 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, Tremont Street turning onto Melnea Cass Blvd. The right turn will end whenever the pedestrian pushbutton is actuated and 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 **(Exhibit 6-14)** with a channelized right turn in its northeast corner. The right turn phase is actuated, so that it gets only the time that it needs to clear the queue; the rest of the cycle, the crossing 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 either interval D or E.

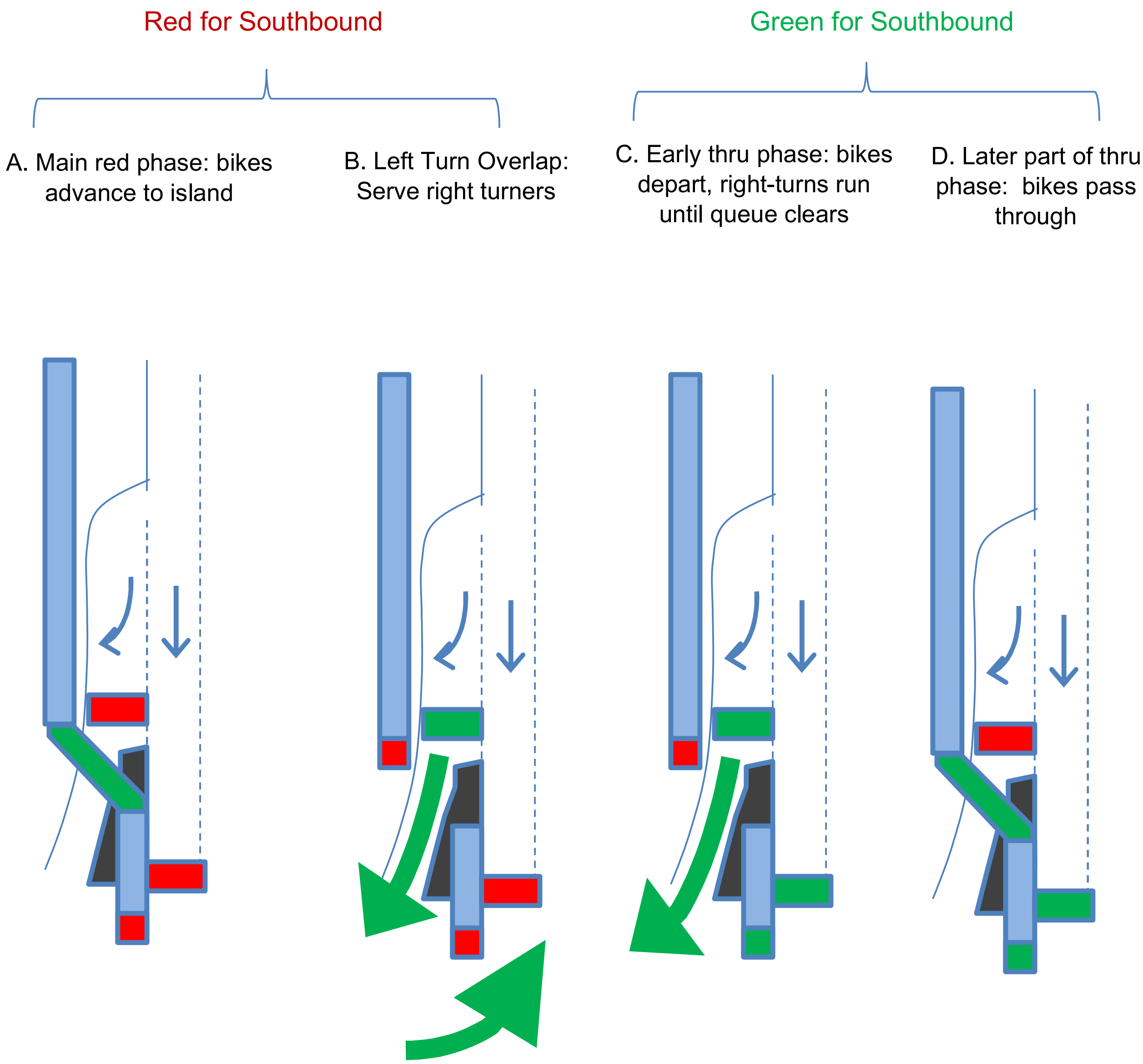


Exhibit 6-16: Phasing / progression plan for Copenhagen intersection for channelized right turns.

6.4.4.3 SIGNAGE AND STRIPING

Some channelizing islands are simply painted, without a physical median. These allow for larger truck movements, but do not provide protection for pedestrians. Painted islands are not detected or recognized by pedestrians who are visually impaired, so they may 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 it during high-demand cycles. Where periodic demand surges occur (e.g., at schools or sports venue), demand per cycle during such a surge should be accounted and designed for in the timing strategy. According to the *AASHTO Green Book,* a delta island should be no less than 50 square ft in urban areas (75 square ft in rural areas); larger than 100 square ft is preferable. The *Green Book* recommends sides should at least 12 ft (15 feet preferred) long after rounding of corners; however, this dimension can be overly restrictive since it implies an island area of at least 80 ft. Cut-through style 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 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.

Where 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 who have low vision cross at the correct location (Schroeder et al., 2017).

6.4.5 REFERENCES

Bachiochi, J., and Furth, P.G. (2016). Commonwealth Avenue Bridge: Protecting Pedestrians and Bicycles with Presignals and Delta Islands. http://www.northeastern.edu/peter.furth/comm-ave-bu-bridge-a-compact-intersection-based-on-a-copenhagen-design/.

Potts, I. B., Harwood, D. W., Bauer, K. M., Gilmore, D. K., Hutton, J. M., Torbic, D. J., ... & JM, B. (2011). NCHRP Web-Only Document 208: Design Guidance for Channelized Right-Turn Lanes. *Transportation Research Board of the National Academies, Washington, DC*.

Schroeder, B., et al. (2017). NCHRP Report 834: Application of Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities, A Guidebook. *Transportation Research Board, Washington DC*.

6.5 LEADING PEDESTRIAN INTERVALS

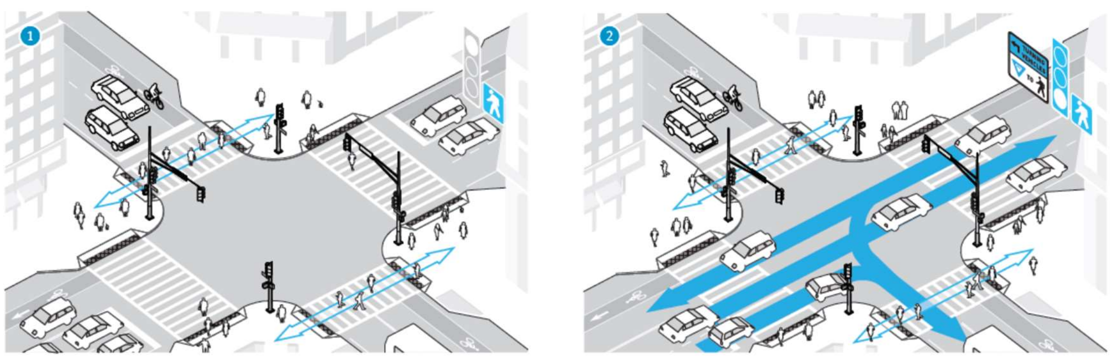
6.5.1 **BASIC DESCRIPTION**

6.5.1.1 ALTERNATIVE NAMES

Pedestrian Head Start, Partially Protected Crossing

6.5.1.2 DESCRIPTION AND OBJECTIVE

A leading pedestrian interval (LPI) is when 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*. **Exhibit 6-17** and **Exhibit 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).



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

Exhibit 6-17: Pedestrian and vehicular movements involved in an LPI (City of Boston, 2013).

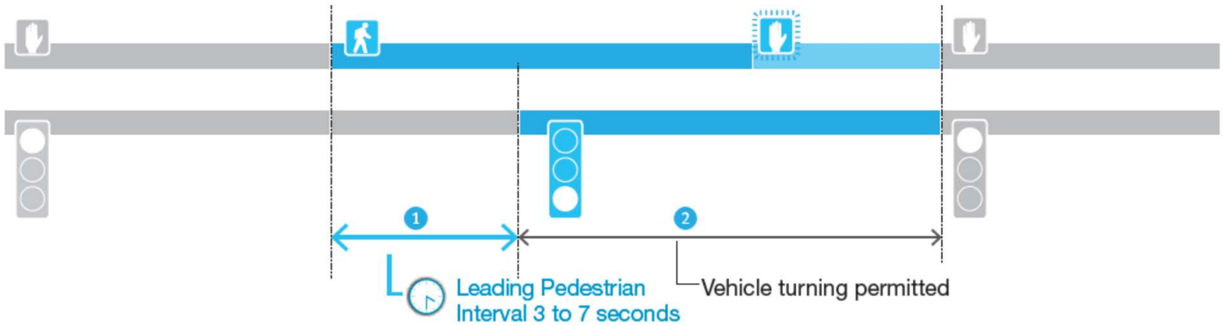


Exhibit 6-18: Pedestrian phase and its parallel vehicular phase during and after LPI (City of Boston, 2013).

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 (LBIs), serving bicycles as well as pedestrians, if local laws or enforcement policies support that function.

6.5.1.4 OPERATING CONTEXT

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

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 (**Section 0**), 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**)
2. The intersection layout fails to give pedestrians an adequate head start in space. Where the vehicular stop line is set back approximately 50 ft from the curb where pedestrians wait, often called a "protected intersection" layout **(NACTO, 2019)**, as shown in **Exhibit 6-19**, pedestrians get a head start in space. Detail on how to evaluate the head start in space afforded by a large vehicular setback is given at the end of this list.

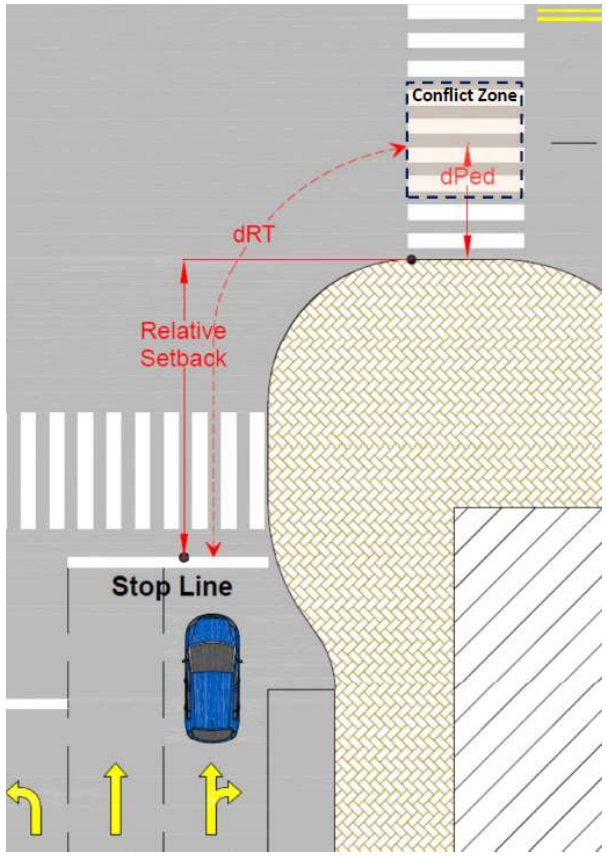


Exhibit 6-19: "Protected intersection" layout in which pedestrians have a large head start in space. (dPed is the distance a pedestrian covers to reach the middle of the conflict zone; dRT is the distance a right turning vehicle covers to reach the middle of the near edge of the conflict zone)

3. Conflicting right turn volume is low or moderate. Where right turn volume is high, there will be a lot of conflict between pedestrians and turning vehicles even with an LPI. Therefore, it may be more appropriate to provide a treatment that provides a fully protected crossing such as *Protected-Concurrent Phasing* (**Section 6.2**), *Exclusive Pedestrian Phases* (**Section 6.3**), or *Channelized Right Turns and Delta Islands* (**Section 0**). Where turn volume is low to moderate, LPI can be appropriate, but *Delayed Turn* (**Section 0**) may be preferred, even where there is no right turn lane, because it limits the impact on motor vehicle delay, thereby allowing to provide longer protected intervals for pedestrians.
4. Any level of pedestrian volume is appropriate for LPI. Where pedestrian volumes are low, pedestrian phases can be actuated, with the LPI occurring only when a pedestrian phase runs, avoiding unnecessarily delays on vehicle traffic.
5. At T-junctions and junctions with one-way streets, where there is no opposing through traffic to shield pedestrians from left turns during the early part of the pedestrian phase, an LPI can also be considered as a means of partial protection from left turns; however, that may require a longer LPI.

In Dutch cities, LPIs tend to be very short (1 s or less), and most intersections have none, because the typical Dutch intersection layout with a large stop line setback gives pedestrians a large head start in space (Sjoerd

Linders, personal communication, 8/2/2018). To determine the needed length of an LPI, engineers identify the conflict zone (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

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

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. Then the needed length of LPI is 4.0 – 3.0 = 1.0 s.

6.5.2 APPLICATION 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 LPI at more than 2,200 intersections (an interactive map for current locations with LPI can be found at http://www.vzv.nyc), 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 (New York City Department of Transportation, 2016). Cambridge, MA uses LPI at most of their intersections. Many other cities in the U.S. and Canada make extensive use of LPI. In U.S. practice, LPI is not limited to high-pedestrian volume locations; for example, in Charlotte, LPI is a standard treatment for arterials in suburban parts of the city (for more detail, see **Section 0** *Delayed Turn*).

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 such as , 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 intersection with corner bulbouts, protected bike lanes, and other features that work to 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 accomplish the objective of an LPI with very short LPIs.

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, during an LPI only). New York's law, enacted in 2019, followed a successful 6-month pilot program in which 50 intersections were signed to allow bicycles to follow the pedestrian signal.

In cities like Chicago and Cambridge (and, before 2019, New York), 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 7 s long LPIs (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 using bike signals would require either an exception from FHWA or a change in FHWA guidance regarding bicycle signals and permitted turn conflicts.

6.5.2.2 BENEFITS AND IMPACTS

Benefits and impacts discussed in this section include:

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

A comparison of 26 intersections in New York State found that LPI reduced pedestrian crashes with turning vehicles by 28%, or by 64% after adjusting for crash severity (King, 2000). The *Highway Safety Manual* assigns a Crash Modification Factor (CMF) of 0.413 for applying LPI based on a study of ten intersections in State College, PA where a 59% reduction in pedestrian-vehicle crashes was found (Fayish, and 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 (Houten et al. 2000), reduce the number of vehicles turning in front of pedestrians in a crosswalk (San Francisco Municpal Transportation Agency, 2008), and reduce the number of observed pedestrian-motor vehicle conflicts (Houten et al., 2000).

Where 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 (Danny Nguyen, personal communication, 8/16/2019). 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, alternatively, 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 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 seconds 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 seconds. The capacity and cycle length impact of LPIs is greatest where, as in this Boston example, cross streets have high traffic volumes and therefore cannot easily give up green time for an LPI.

Where a minor street's volume is low, using ***Pedestrian Overlaps with LPIs*** (**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 provide accessible pedestrian signals to notify visually-impaired pedestrians of the LPI because without an accessible pedestrian signal, visually-impaired pedestrians who rely on the sound of starting traffic to know when the green begins may miss 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 seniors or school children who tend to walk more slowly (Sanjeinejad and 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 where there are "high pedestrian volumes and high conflicting turning vehicle volumes," conditions repeated by several other publications (City of Boston, 2013; Houten et al., 2000; King, 2000; Staplin et al., 2001). However, as cities like Charlotte have found, pedestrian volume is irrelevant since the cost of the treatment is nominal, and because where pedestrian phases 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/hour for New York City (Danny Nguyen, personal communication, 8/16/2019) and 250 vehicles/hour for Boston (City of Boston, 2013). In Montreal, that threshold is 200 vehicles/hour where the crossing length is 20 meters (67 feet) or more. For shorter crossings, the threshold increases, reaching 500 vehicle/hour where the crossing length is 8 meters (27 feet) or less (City of Montreal, 2017).

The MUTCD 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, where 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 that pedestrians have in space. From Dutch experience, there does not appear to be any unintended negative consequence of using short LPIs.

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

6.5.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

Delayed Turn (**Section 0**), like LPI, is a partial protection treatment. 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 has less traffic operations impact (Furth and Saeidi Razavi, 2019). As a result, Delayed Turn typically allows providing a longer protected interval for pedestrians.

No Turn on Red (**Section 6.9**) should be applied to both streets whose right turns cross a treated crosswalk. That is, for an LPI parallel to the north-south street, No Turn on Red 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 will otherwise go. Hubbard et al. showed that without NTOR, LPI may lose its intended benefits (Hubbard et al., 2008). Where right turn on red is important for capacity or delay, **Section 09** discusses how to apply NTOR only during certain parts of a signal cycle.

The desire for ***Short Cycle Lengths*** **(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*** **(Section 6.8)** and by altering corner geometry to give pedestrians a greater head start in space, 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, and 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, and 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; Alexandria Department of Transportation and Environmental Services, 2015; Saneinejad, 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 can affect how long an LPI (a 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 needed LPI.

6.5.5 REFERENCES

Alexandria Department of Transportation and Environmental Services (2015). Alexandria Complete Streets Design Guidelines.

City of Boston. (2013). Boston Complete Streets Design Guidelines.

City of Montreal (2017). Feux pour piétons à décompte numerique.

Department of Civil and Coastal Engineering University of Florida (2008). Miami-Dade Pedestrian Safety Project: Phase II Final Implementation Report and executive Summary.

Fayish, A. C., & Gross, F. (2010). Safety effectiveness of leading pedestrian intervals evaluated by a before–after study with comparison groups. *Transportation research record*, *2198*(1), 15-22.

Furth, P. G., & Saeidi Razavi, R. (2019). Leading through intervals versus leading pedestrian intervals: more protection with less capacity impact. *Transportation research record*, *2673*(9), 152-164.

Hubbard, S. M., Awwad, R. J., & Bullock, D. M. (2007). Assessing the impact of turning vehicles on pedestrian level of service at signalized intersections: a new perspective. *Transportation research record*, *2027*(1), 27-36.

Hubbard, S. M., Bullock, D. M., & Thai, J. H. (2008). Trial Implementation of a Leading Pedestrian Interval: Lessons Learned. *ITE journal*, *78*(10), 37-41.

King, M. R. (2000, December). Calming New York City Intersections. In *Urban Street Symposium Conference Proceedings*.

New York City Department of Transportation (2016). Don't Cut Corners - Left Turn Pedestrian & Bicyclist Crash Study.

New York City Department of Transportation (n.d.). Bicyclists use of Leading Pedestrian Intervals: Pilot Program Results.

Pedsafe. (2018, June 29). Pedestrian Safety Guide and Countermeasure Selection System. http://www.pedbikesafe.org/PEDSAFE/

Saneinejad, S., & Lo, J. (2015). Leading Pedestrian Interval: Assessment and Implementation Guidelines. *Transportation Research Record*, *2519*(1), 85-94.

San Francisco Municipal Transportation Agency Pedestrian Program and University of California Traffic Safety Center (2008). San Francisco PedSafe Phase II - Final Implementation Report and Executive Summary.

Staplin, L., Lococo, K., Byington, S., Harkey, D., & TransAnalytics, L. L. C. (2001). *Guidelines and recommendations to accommodate older drivers and pedestrians* (No. FHWA-RD-01-051; 1495/FR; NCP 3A6a-0042). Turner-Fairbank Highway Research Center.

Van Houten, R., Retting, R. A., Farmer, C. M., & Van Houten, J. (2000). Field evaluation of a leading pedestrian interval signal phase at three urban intersections. *Transportation Research Record*, *1734*(1), 86-92.

6.6 DELAYED TURN / LEADING THROUGH INTERVALS (LTI)

6.6.1 BASIC DESCRIPTION

6.6.1.1 ALTERNATIVE NAMES

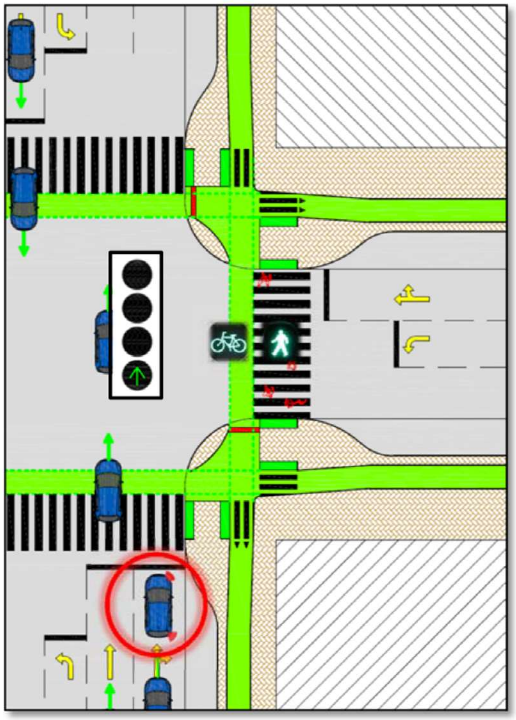
Leading through arrow, leading bicycle interval

6.6.1.2 DESCRIPTION AND OBJECTIVE

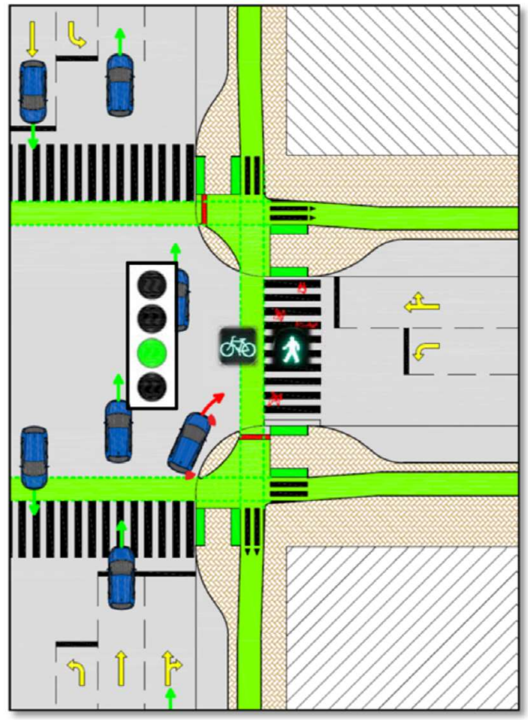
At the start of a vehicular through phase, pedestrians, bicycles, and through vehicles are allowed to go while turning movements (right turns, left turns, or both) are held for an interval called a *leading through interval (LTI)* or *leading bicycle interval (LBI)*. This interval typically lasts 7 to 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 leading pedestrian interval (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 while the through movement is permitted. This allows providing a longer protection interval, since only the turning vehicles are held. **Exhibit 6-20** and **Exhibit 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, D.C. are exceptions that allow bicycles to legally use LPIs).
- To reduce delay to bicycles, pedestrians, and turning traffic while proving partial protection at intersections where it is safe to have permitted turn conflicts after a conflict-free initial interval.



(a) During leading through interval



(b) After leading through interval

Exhibit 6-20: Pedestrian, bicycle, and vehicular movements during and after a leading through interval.

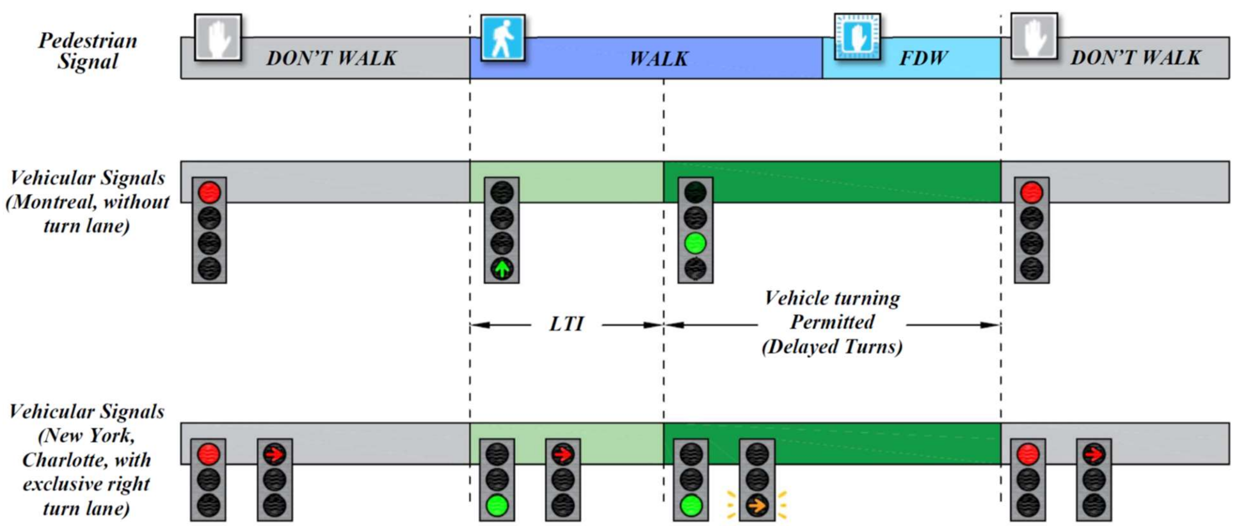


Exhibit 6-21: Alignment of pedestrian and concurrent vehicular phases with Delayed Turn/LTI.

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, while in New York 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 a flashing yellow arrow (see **Section 6.9**) during the permitted turn period. In Montreal, only a through green arrow is displayed during the leading interval, and a circular green is displayed during the permitted turn interval (**Exhibit 6-22**). Whether a through green arrow alone is enough to prohibit turning movements will depend on state/provincial law.

Exhibit 6-22: Through green arrow followed by a circular green in Montreal (Photo Credit: Peter Furth).

6.6.1.4 OPERATING CONTEXT

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

- Where there is a desire to provide a partially protected crossing for bicycles as well as pedestrians without causing high delays for vehicles and pedestrians/bicycles.
- 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 (*Concurrent-Protected Crossings*, **Section 6.2**; *Exclusive Pedestrian and Bicycle Phases*, **Section 6.3**; and *Channelized Right Turns*, **Section 0**).

Where there is an exclusive turn lane, delayed turn is a superior alternative to LPI. Where there is no exclusive turning lane, delayed turn can be considered as an alternative to LPI when 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 APPLICATION 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 and at other intersections with moderate or high pedestrian traffic (Montreal Department of Transportation, 2017; J. Hamaoui, Personal Communication, 6/5/2018). 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’s used have only pedestrian crossings; however, it is also used where there are bicycle crossings.

In New York, delayed turn has been used since approximately 2015—usually with a 10 s leading through interval—and always in conjunction with *flashing yellow arrow* during the permitted turn interval. New York City has at least 37 intersections where this treatment has been installed *(New York City 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 where turn volume is not high. Where turn volume exceeds 200 vehicles/h, they prefer to use *concurrent-protected crossings* (**Section 6.2**). It is also used at intersections with moderately heavy pedestrian volumes where a turn lane can be provided (Danny Nguyen, personal communication, 8/16/2019).

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/h; after a few years’ experience, that threshold was raised to 200 vehicles/h (Danny Nguyen, personal communication, 8/16/2019).

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 (Nathan Conrad, Personal communication, 12/26/2018, 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 (NCSITE, 2016). Unlike New York and Montreal, Charlotte has applied delayed turn only 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 leading protected interval encompasses the entire pedestrian phase and becomes a *concurrent-protected crossing* (**Section 6.2**). Where no right turn lane is available, they use LPI (**Section 6.5**), typically lasting 3 to 5 s and 10 s for some crossings at schools.

Exhibit 6-23: A leading through interval in Charlotte. During the permitted turn interval, the red arrow is replaced by a flashing yellow arrow. The "NO TURN ON RED" sign is blank except during the leading through interval.

Kothuri et al. (2018) report that in a survey of professionals regarding bicycle signal control strategies, 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
- Capacity and delay impacts to vehicular traffic

For pedestrians, the delayed turn improves safety and comfort by providing them 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 enable far-side crossers to reach the conflict zone before turning vehicles, as well.

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, 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 flashing yellow arrow during the permitted turn interval. **Exhibit 6-24** shows results of a before-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, as when a vehicle interrupts its turn for crossing pedestrians (Kothuri et al., 2018).

Exhibit 6-24: Bicycle-Vehicle Conflicts with Leading Pedestrian Interval versus Delayed Turn, 6th Avenue at 23rd Street, New York. (Data source:.Kothuri et al, 2018; our analysis of that data).

	Leading Pedestrian Interval	Delayed Turn with added left turn lane and flashing yellow arrow
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

Delayed turn should not affect delay for any movements other than the turns that are held during the leading interval, if turns are from an exclusive lane. 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 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 Right Turn on Red 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 and Saeidi, 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 lanes 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 – a 15 s LTI has the same capacity impact as a 3 second LPI. 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, accessible pedestrian signals (APS) can be helpful to notify visually impaired pedestrians of when the WALK interval begins. Without an APS, visually impaired pedestrians may be confused by the delayed start of the nearest lane by the traffic, 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/h (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 Blvd de Maisonneuve, described earlier). The pedestrian volume threshold, below which delayed turn is preferred and above which fully protected crossings are preferred, is 700/h in Manhattan and 300/h 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, but unless bicycle/pedestrian volume is moderately high, they will not remove parking to create a turn lane (Danny 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 *Manual on Uniform Traffic Control Devices (MUTCD)* but is consistent with *MUTCD* 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 (**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 flashing yellow arrow (**Section 6.9**) and displayed during the permitted turn interval.

No Turn on Red (NTOR) (**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 a flashing yellow arrow for the permitted turn phase.

6.6.4.2 PHASING AND TIMING

New York's policy is that delayed turn should be 10 s long, but they can be as short as 7 s if needed for traffic capacity. Charlotte also uses 10 s. Montreal's delayed turn/LTIs range from 7 to 13 s and often match the Walk interval. They have 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 (Jean Hamaoui, personal communication, 2018).

When pedestrian or bicycles 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

No Turn on Red (NTOR) signs may be needed to prevent turns during the leading through interval. 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, Massachusetts) or where compliance is poor. Where right turn on red (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.

6.6.5 REFERENCES

Furth, P. G., & Saeidi Razavi, R. (2019). Leading through intervals versus leading pedestrian intervals: more protection with less capacity impact. *Transportation research record*, *2673*(9), 152-164.

Kothuri, S., Kading, A., Schrope, A., White, K., Smaglik, E., Aguilar, C., & Gil, W. (2018). Addressing Bicycle-Vehicle Conflicts with Alternate Signal Control Strategies.

Montreal Department of Transportation (2017). Feux pour Piétons à Décompte Numérique. Guide DT2001.

New York City Department of Transportation (2016). Don't Cut Corners - Left Turn Pedestrian & Bicyclist Crash Study.

North Carolina Section of the Institute of Transportation Engineers (2016). 2016 Outstanding Project of Year: Charlotte Leading Pedestrian Interval Plus (LPI+). http://ncsite.org/2016/09/16poy-lpiplus

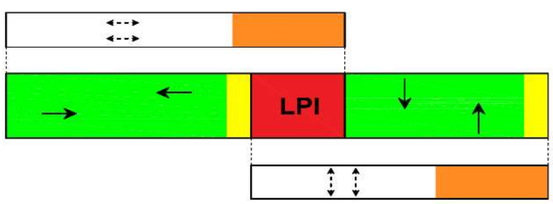
6.7 Pedestrian Overlaps with Leading Pedestrian Intervals and Vehicular Holds

6.7.1 BASIC DESCRIPTION

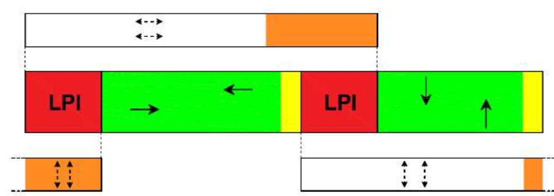
6.7.1.1 ALTERNATIVE NAMES

6.7.1.2 DESCRIPTION AND OBJECTIVE

During a ***leading pedestrian interval (LPI)*** or other 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 has 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.



(a) Overlapping one LPI



(b) Overlapping two LPIs

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

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 or southbound left – are held, allowing the two crosswalks shown to run without conflict.

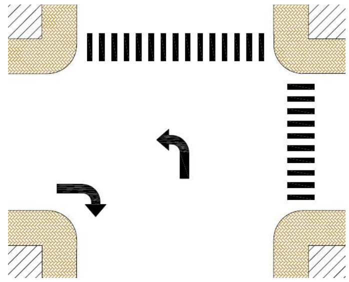


Exhibit 6-26: Pedestrian movements that can overlap a left turn phase (example of a Partial Vehicular Hold).

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 yellow, counting the following LPI as part of the pedestrian phase end buffer, which then enables them to have a longer WALK interval compared to ending FDW at the start of yellow. This reduces pedestrian delay and creating additional crossing opportunities for slower pedestrians. While it 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 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 later in this section.
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 later in this section.
4. *Where demand for a left turn is high compared to the demand for the opposite direction 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* (**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 of course, 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 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 N-S street) and Kammerlingh Onneslaan. When the only demand for the E-W street is for eastbound left, that vehicular movement is served alone, and the non-conflicting bicycle crossings eastbound and northbound, 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:

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

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 also make it also possible to add an LPI to the major street, with its attendant safety benefits, without taking time from the major street green phase. Example 1, below, illustrates this idea.

Example 1 (major-minor intersection, with low traffic on the minor). Consider an intersection with an 80 s cycle whose phase diagram is as shown in **Exhibit 6-27a**. 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 four seconds.

- Inserting a 4-second LPI on the minor street by starting its green later (**Exhibit 6-27b**) will have very little impact on traffic. However, because the major street cannot afford to give up four seconds of green, there is no LPI on the major street.
- Because the minor street has available capacity, it can afford an additional four seconds of vehicular green time where its vehicular green can also end four seconds early. During this interval while all traffic is held for four seconds, the minor street’s pedestrian phase can still run while an LPI begins on the major street (**Exhibit 6-27c**). 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 four seconds 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 (**Exhibit 6-27d**). Note that this final step will not be possible if the intersection includes left turn phases.

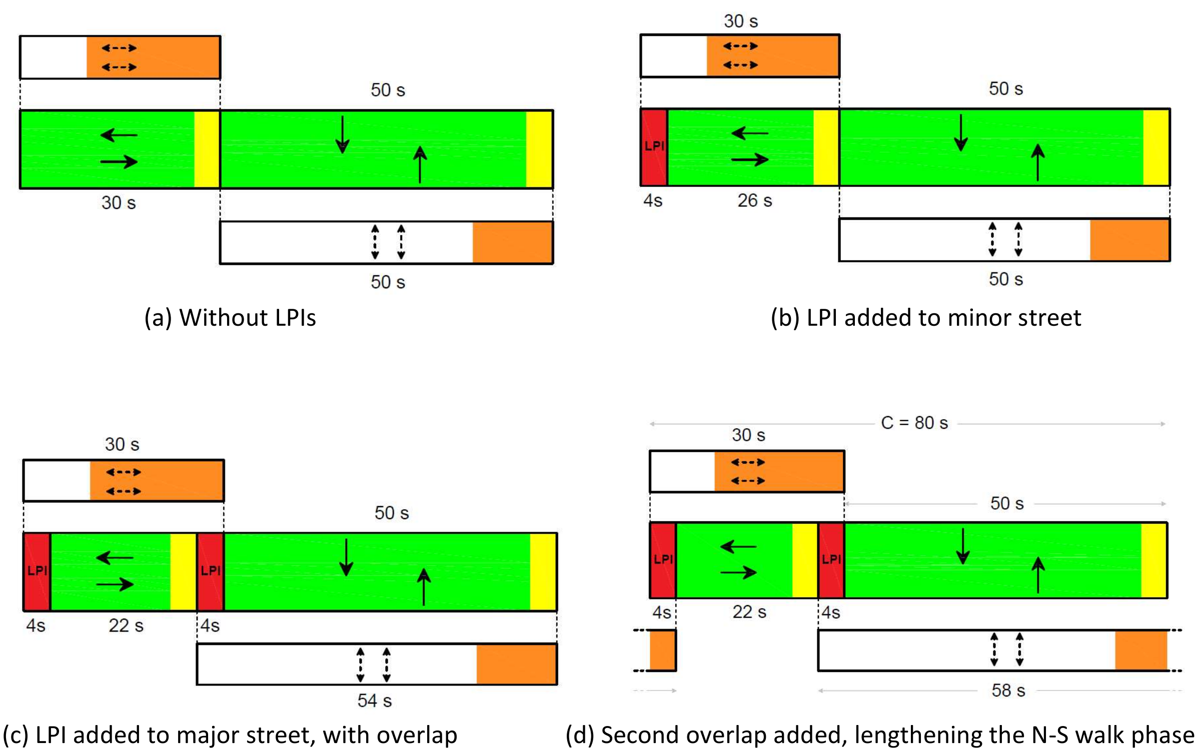


Exhibit 6-27: Introducing LPIs and pedestrian overlaps in a way that leaves the lengths of major street (north-south) vehicular phase and minor street pedestrian phase unaffected.

Shortening signal cycles. In periods in which vehicular volumes on both intersecting streets are low enough that pedestrian timing needs dominate, letting pedestrian phases overlap 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 percent reduction in cycle length, with average pedestrian delay falling from 24 seconds to 18 seconds and no perceptible change in vehicular delay (Furth et al., 2012).

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**.

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, Reducing delay and making intersections more accessible for slower pedestrians.

6.7.3 CONSIDERATIONS

6.7.3.1 ACCESSIBILITY CONSIDERATIONS

As described in **Section 6.5** on LPIs, accessible pedestrian signals are recommended wherever LPIs are used because otherwise visually impaired pedestrians who take their cue from the sound of starting traffic will not know when the pedestrian phase begins. With 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 *Leading Pedestrian Interval (LPI)* (**Section 6.5**), *Short Cycle Length* (**Section 7.1**), *Pedestrian Clearance Settings for Serving Slower Pedestrians* **(Section 7.4)**, and *Multistage Crossings* (**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 6-25b**. It might have the following phase and overlap assignments:

- Phase 1: E-W LPI
- Phase 2: E-W vehicular movement
- Phase 3: N-S LPI
- Phase 4: N-S vehicular movement
- Overlap A, consisting of phases 1, 2, and 3: E-W pedestrian movements.
- Overlap B, consisting of phases 3, 4, and 1: N-S pedestrian movements.

To effectively use the second LPI in each of the overlaps, the through phase (phases 02 and 04) must be either pretimed or coordinated in such a way that its ending time is known in advance.

Overlaps likes 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 SIGNING AND STRIPING

Not applicable for this treatment.

6.7.4.4 GEOMETRIC ELEMENTS

Not applicable for this treatment.

6.7.5 **REFERENCES**

Furth, P. G., Muller, T. H., Salomons, M., Bertulis, T. A., & Koonce, P. J. (2012). Barrier-free ring structures and pedestrian overlaps in signalized intersection control. *Transportation research record*, *2311*(1), 132-141.

Furth, Peter G., Yue Danny Wang, and Michael A. Santos. "Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Turns: Delay Estimation and Signal Timing Techniques for Limiting Pedestrian and Bicycle Delay." *Journal of Transportation Technologies* 9.04 (2019): 489.

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

No Turn on Red (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 between 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 including 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 only 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 moderate or high pedestrian/bicycle volume or with a significant volume of vulnerable crossers (e.g., children, seniors).
- Where the crosswalk location is such that drivers turning right block the crosswalk while waiting for a gap.
- Crossings used by bicycles approaching from the right side (e.g., a two-way path)

NTOR is also necessary in conjunction with Leading Pedestrian Interval (**Section 6.5**), Delayed Turn (**Section 0**), Exclusive Pedestrian/Bicycle Phases (**Section 6.3**), and Concurrent-Protected Crossings (**Section 6.2**). These treatments all aim to hold right turning vehicles during certain phases, and 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 the island of Montreal are the only places in the US 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 Ithaca (NY), Charlotte, and Portland (OR), 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. Where they apply the Delayed Turn technique (see **Section 0**), 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, they display a red right turn arrow and a dynamic NTOR sign. For the remainder of the through phase, the dynamic sign reads “Yield to Pedestrians” and the red turn arrow is replaced with a flashing yellow arrow (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 crash modification factor (CMF) ranging from 1.43 to 2.08 (1982). A CMF of 1.69 is given in the *Highway Safety Manual, First Edition* 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. (2008), No Turn on Red signs are estimated to reduce crashes by about 3%, with a CMF of 0.97.

A review of Fatality Analysis Reporting System (FARS) 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, more than half of those crashes involved a bicycle or pedestrian (NHTSA, 1994). California conducted a comparable study of their crash data and found similar results, suggesting that their current policy of selectively restricting RTOR was better than a blanket ban at all intersections (Fleck & Yee, 2002).

A 2002 study in Arlington, Virginia, 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 am–7 pm, 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 from only 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 number of pedestrians yielding to RTOR vehicles. A recent study conducted by Lin et al. (2016) found that driver compliance was the highest (70%) with signs readings “No Turn on Red” 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 (Zeeger and Cynecki, 1986). However, a study of different treatments at a Miami intersection found dynamic NTOR signs were considerably more effective than static signs (Pecheux, Bauer, and McLeod, 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.

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.

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

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, and therefore increases the need for accessible pedestrian signals (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 turn right on red (Barlow et al., 2003).

6.8.3.2 GUIDANCE

The *Manual on Uniform Traffic Control Devices (MUTCD)* indicates six conditions for when a 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 leading pedestrian interval
- An unacceptable number of pedestrian conflicts with RTOR maneuvers, especially involving children, older pedestrians, or persons with disabilities
- More than three RTOR crashes reported in a 12-month period for the particular approach

The *MUTCD* also provides guidance for the design of various types of NTOR regulatory signs. Detailed discussion is provided below under Implementation Support.

6.8.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

NTOR should be used in combination with the following treatments, which could be dynamic restrictions or restrictive of RTOR only during phases in which the treatment is active:

- Concurrent-protected crossings (**Section 6.2**)
- Leading Pedestrian Interval (**Section 6.5**)
- Delayed Turn/Leading Through Interval (**Section 0**)
- Exclusive Pedestrian/Bicycle Phases (**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 Leading Pedestrian Interval 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 (RO-11) have been shown to be more effective than standard black-and-white signs.

While the MUTCD indicates that right turn on red 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 sign 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 sign mounting near the signal head including 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

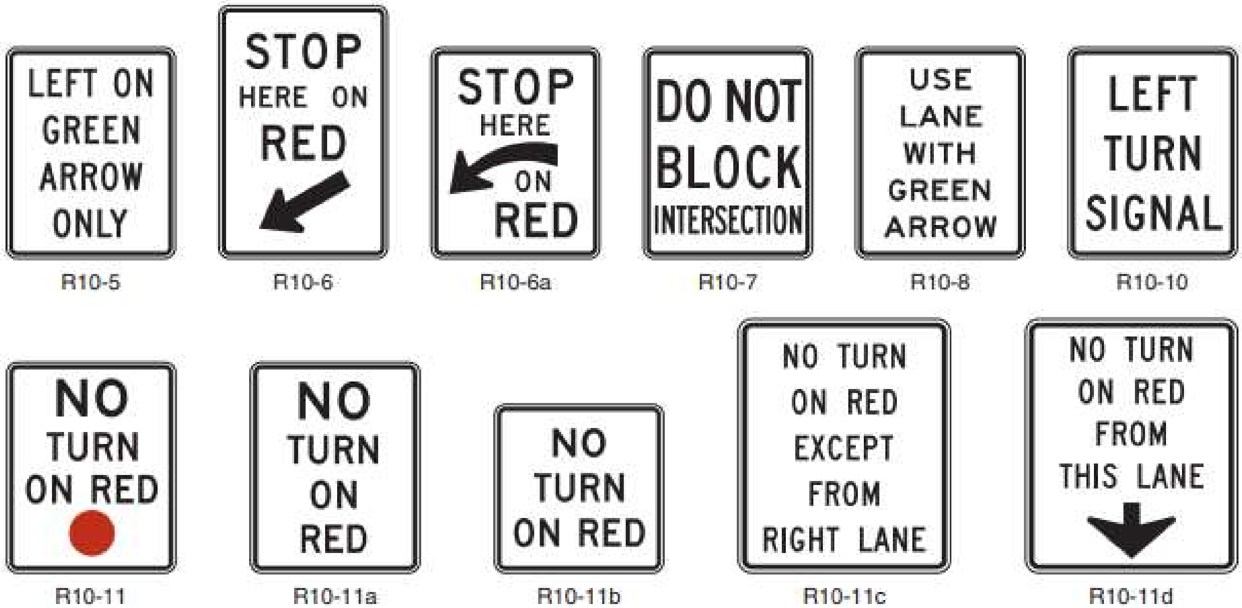


Exhibit 6-28: MUTCD No Turn on Red Signs (R10-11 Series).

6.8.4.4 GEOMETRICS

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

NTOR is an effective countermeasure when the skew angle of the intersecting roadways makes it difficult for drivers to see traffic approaching from their left or when 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.

6.8.5 **REFERENCES**

AAA Mid-Atlantic. (2019, February 5). Seeing Red: District Moves to Ban Right Turns on Red at Nearly 100 Intersections in the Nation's Capital. https://dccommutetimes.com/news_releases/article/seeing-red-district-moves-to-ban-right-turns-on-red-at-nearly-100-intersect

Barlow, J. M., Bentzen, B. L., & Tabor, L. S. (2003). *Accessible pedestrian signals: Synthesis and guide to best practice* (No. 278). Transportation Research Board.

City of Alexandria, Virginia (2019, June 11). New No Turn on Red Restrictions to be Installed as Part of Vision Zero Initiative. https://www.alexandriava.gov/tes/info/default.aspx?id=107669

City of Seattle. (2017, May). Vision Zero 2017 Progress Report. https://www.seattle.gov/Documents/Departments/beSuperSafe/VZ_2017_Progress_Report.pdf

Fleck, J. L., & Yee, B. M. (2002). Safety evaluation of right turn on red. *ITE journal*, *72*(6), 46-48.

Harkey, D. L., Tsai, S., Thomas, L., & Hunter, W. W. (2006). *Pedestrian and bicycle crash analysis tool (PBCAT): version 2.0 application manual* (No. FHWA-HRT-06-089). United States. Federal Highway Administration. Office of Safety Research and Development.

Lin, P. S., Wang, Z., Guo, R., & Kourtellis, A. (2016, May). A pilot study on interactions between drivers and pedestrian features at signalized intersections—using the SHRP2 naturalistic driving study data. In *Proc. 11th Asia Pac. Transp. Develop. Conf. 29th ICTPA Annu. Conf.* (pp. 70-77).

NHTSA. (1994). Impact of Right Turn on Red (DOT HS 808 200). *Washington, DC.*

Pecheux, K., Bauer, J., & McLeod, P. (2009). Pedestrian Safety and ITS-Based Countermeasures Program for Reducing Pedestrian Fatalities, Injury Conflicts, and Other Surrogate Measures Draft Zone/Area-Wide Evaluation Technical Memorandum.

Preusser, D. F., Leaf, W. A., DeBartolo, K. B., Blomberg, R. D., & Levy, M. M. (1982). The effect of right-turn-on-red on pedestrian and bicyclist accidents. *Journal of safety research*, *13*(2), 45-55.

Retting, R. A., Nitzburg, M. S., Farmer, C. M., & Knoblauch, R. L. (2002). Field evaluation of two methods for restricting right turn on red to promote pedestrian safety. *ITE journal*, *72*(1), 32-36.

Thomas, L., Thirsk, N. J., & Zegeer, C. V. (2016). *NCHRP Synthesis 498: Application of Pedestrian Crossing Treatments for Streets and Highways*. Transportation Research Board

Zegeer, Charles V., and Michael J. Cynecki. "Evaluation of countermeasures related to RTOR accidents that involve pedestrians." *Transportation Research Record* 1059 (1986): 24-34.

6.9 Flashing Pedestrian and Bicycle Crossing Warnings

6.9.1 BASIC DESCRIPTION

6.9.1.1 ALTERNATIVE NAMES

Flashing yellow arrow, 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.

6.9.1.3 VARIATIONS

Flashing yellow arrow (FYA) is the only commonly used flashing warning in the US. 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, and Portland (OR), and Bostonuse 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.

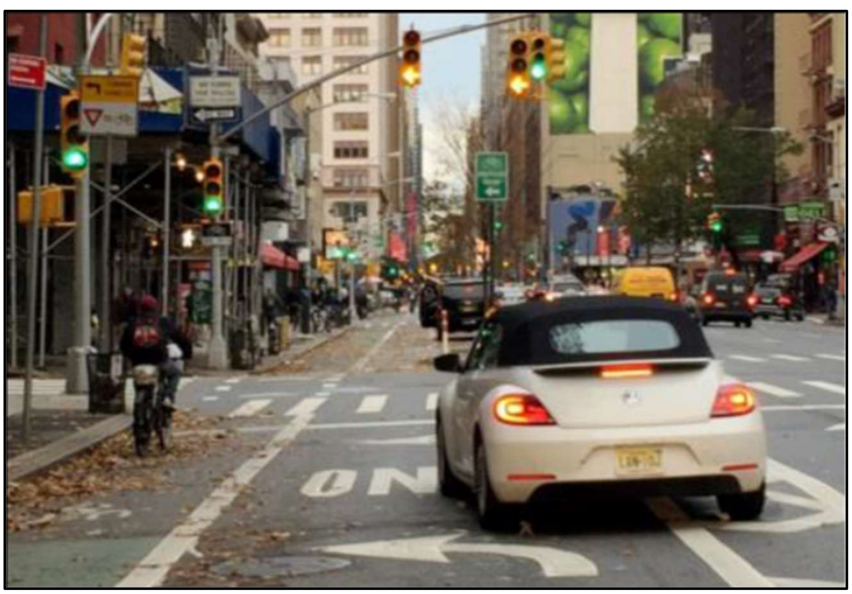


Exhibit 6-29: Flashing yellow arrow in New York warning of a permitted conflict with adjacent bicycle and pedestrian crossings. (New York City Department of Transportation, 2016).

A custom flashing sign (**Exhibit 6-30**) called a *flashing right hook warning* is used at one intersection approach in Portland (OR) 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 a an approaching bicycle.

Exhibit 6-30: Flashing "Turning Vehicle Yield to Bikes" Sign, Portland, Oregon (Andersen, 2015).

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 both the static sign and the flashing sign with the image of a crosswalk with a large, red exclamation sign. This link shows the flashing sign in operation.

a. Static warning sign

b. Flashing warning sign

c. Closeup of flashing sign

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

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 link shows the flashing sign in operation. This kind of signal is not currently allowed in the US because of confusion from displaying a flashing yellow ball (even if it's outside a signal head) at the same time as a solid green.

Exhibit 6-32: Flashing Yellow Warning Light, Amsterdam, Netherlands.

University researchers have proposed different forms of flashing pedestrian/bicycle crossing warnings and tested them in a laboratory setting. The one 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, while the flashing warning would run throughout the pedestrian phase, including the FDW interval), the concept may have promise.

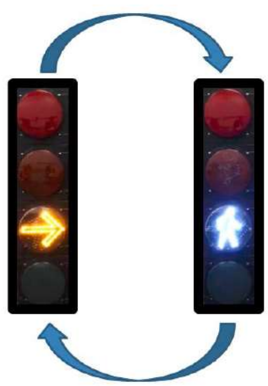


Exhibit 6-33: Flashing Pedestrian Indicator proposed by Florida State University researchers (Boot et al., 2015).

At the University of Wisconsin, research by Noyce et al. found that the flashing sign shown in **Exhibit 6-34** was the most promising design among alternatives tested to alert drivers 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.

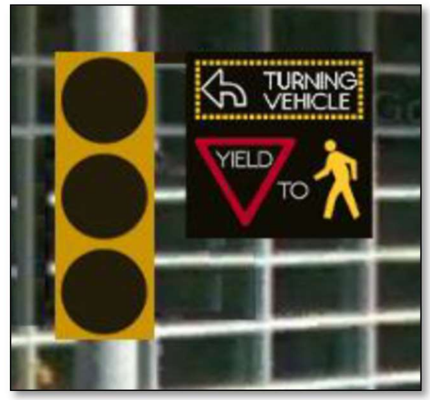


Exhibit 6-34: Flashing pedestrian crossing warning design by Noyce et al. (2018)

6.9.1.4 OPERATING CONTEXT

Flashing crossing warnings are used where permitted right turns or left turns conflict with crossing bicycles or pedestrians. It 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 US 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, used at more than 100 intersection approaches. It 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 (OR) (**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 (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 their proposed warning device found that with the device, drivers showed greater caution and searched more thoroughly for pedestrians. Using a questionnaire, they also found it increased participants' recognition of their obligation to yield when turning from 68% (without the flashing sign) to 87% (with it) 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 their 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 resulting 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 encounters a FYA, versus 0.74 when the signal display is circular green.

FYA is used extensively across the country in connecting 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 a benefit in respect to crashes with opposing motor vehicles, Van Houten et al. (2012) found that the safety benefit to pedestrians was 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 0**). However, it is not possible to assess how much of that reduction stems from using a FYA as opposed to other features of the treatment – a leading, protected interval and the addition of a turn lane.

6.9.3 CONSIDERATIONS

6.9.3.1 ACCESSIBILITY CONSIDERATIONS

6.9.3.2 RELATIONSHIPS TO RELEVANT TREATMENTS

FYA is combined with *delayed turn* (**Section 6.6**) in New York and Charlotte and is sometimes combined with leading pedestrian interval (**Section 6.5**) as well.

6.9.4 IMPLEMENTATION SUPPORT

6.9.4.1 EQUIPMENT NEEDS AND FEATURES

Flashing yellow arrows are a standard signal display which 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 during the relevant phase only.

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 after 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.

6.9.5 REFERENCES

Andersen, M. (2015, April 2). "Right-hook risk drops with flashing Yield to Bikes sign on NE Couch". https://bikeportland.org/2015/04/02/right-hook-risk-drops-flashing-yield-bikes-sign-ne-couch-136458

Boot, W., Charness, N., Roque, N., Barajas, K., Dirghalli, J., & Mitchum, A. (2015). The flashing right turn signal with pedestrian indication: human factors studies to understand the potential of a new signal to increase awareness of and attention to crossing pedestrians (No. BDV30-977-13). Florida. Dept. of Transportation.

Hurwitz, D., Monsere, C., Kothuri, S., Jashami, H., Buker, K., & Kading, A. (2018). Improved Safety and Efficiency of Protected/Permitted Right Turns in Oregon (FHWA-OR-RD-18-14). Portland, OR. Oregon Department of Transportation.

Jashami, H., Hurwitz, D. S., Monsere, C., & Kothuri, S. (2019). Evaluation of driver comprehension and visual attention of the flashing yellow arrow display for permissive right turns. *Transportation research record*, *2673*(8), 397-407.

New York City Department of Transportation (2016). Don't Cut Corners - Left Turn Pedestrian & Bicyclist Crash Study.

Noyce, D. A., Chitturi, M. V., Alsghan, I., Santiago, K. R., & Bill, A. R. (2018). Evaluating Countermeasures to Improve Pedestrian and Bicycle Safety. *Safer-Sim.*

Van Houten, R., LaPlante, J. and Gustafson, T. (2012). Evaluating Pedestrian Safety Improvements (Report RC-1585). Michigan Department of Transportation, pp.98-101.

Chapter 7 Treatments that Reduce Pedestrian and Bicycle Delay

This section describes six treatments aimed at reducing delay for pedestrians and bicycles and at 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 vs. 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**), aim 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 matter littles if vehicles arrive during a green period as part of a "green wave." To a large extent, traffic signal timing in the US 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 (transit riders, cross street traffic, 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 therefore 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 aim to increase the time 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 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 deal with balancing traffic control's flexibility, or demand-responsiveness, with impact on users. *Pedestrian Recall vs. 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 has 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 offer good service to both pedestrians and vehicles, 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 control switches phases. A cycle length for 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 seconds; at more complex intersections with protected turning phases, longer pedestrian crossings, and greater levels of traffic, the minimum cycle length could be 90 seconds 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, subject to 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, and *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 operate with half of the corridor's prevailing cycle length. That 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 intersection is long** enough for queuing with little risk of spillback (around 600 ft, depending on traffic volume and cycle length), c**oordination zones can be broken to create short coordination zones, with each given the cycle length its most demanding intersection needs**.
- Where 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 (intersections with fewer phases and less cross traffic) can be considered for double cycling.
- **One-way grids are especially amenable to short cycles, since one-way streets do not require turn** phases. For example, downtown Portland, Oregon uses cycles of 56 seconds during off-peak and 60 seconds during peak periods, and would use still shorter periods if not for the long clearance time needed by street-running light rail (Peter 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. New York City DOT employs 90-second cycles across Manhattan to limit pedestrian delay, with few exceptions (Danny Nguyen, personal communication, August 16, 2019). Cambridge (MA) uses 90-second cycles during peak hours and 75-second cycles during off-peak hours (Patrick Baxter, personal communication, 2019).

Amsterdam's policy is that cycles should be as short as possible, never exceeding 100 seconds. One of their 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 (Sjoerd Linders, personal communication, 2018). At compact intersections, even with pedestrian calls, cycle lengths can be as low as 40 seconds, and they can be even shorter when there are no pedestrian calls.

U.S. practice tends 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 wait time (due to the low cycle lengths), which helps compress the platoon and deter speeding (Jürg Christen and Roger 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 supports. This creates an opportunity to lower cycle lengths by dividing longer periods when one part of the period has considerably less traffic than another.

Fully actuated control is widely used in the US, 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, using upstream detectors for gap-out, and using 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, say, 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 can’t stay in the green wave because of stops) have longer delay. Using shorter cycle lengths, breaking up long coordination zones, and using fully actuated control will therefore 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, Oregon reduced average pedestrian delay from 45 seconds to 30 seconds compared to coordinated control with fixed cycle lengths, and at the same time reduced average vehicle delay from 26.5 seconds to 23 seconds. 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 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, while 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 further 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, with each zone having its own cycle length, and one intersection was in a zone by itself and ran free (Furth et al., 2018). Results, summarized in **Exhibit 7-1,** showed that both small zone coordination and running free led to cycle lengths 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 five seconds 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.

Exhibit 7-1: Changes in Delay and Speeding Opportunities Compared to Coordinated-Actuated Control (Furth et al., 2018).

	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%

7.1.3 CONSIDERATIONS

7.1.3.1 ACCESSIBILITY CONSIDERATIONS

Not applicable for this treatment.

7.1.3.2 GUIDANCE

The *Signal Timing Manual* 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. NACTO’s *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* (**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.

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* (**Section 6.3**) and *leading pedestrian intervals* (LPIs) (**Section 6.5**), which can require a longer cycle length. 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* (**Section 6.2**) requires a far shorter cycle length than exclusive pedestrian phases while still providing fully protected pedestrian crossings, and *delayed turn* (**Section 6.6**) can provide the same or greater partial protection as an LPI with less cycle length impact. With LPIs, changing some aspects of an intersection's corner geometry can shorten the needed LPI (see **Section 6.5**), and using overlapping pedestrian phases (**Section 0**) 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 short-term analysis framework that assumes fixed travel patterns, ignoring human response. Over time, traffic control that reduces travel time to 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 a formula found in the *Highway Capacity Manual*:

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

where X_{target} is the target degree of saturation (typically in the range 0.85 to 0.95); C_{min} is the minimum cycle length necessary to avoid exceeding that target; both sums are over the critical movements only; L_{ci} is the lost time associated with critical phase *i*; and v_{ci} and s_{ci} are the volume and saturation flow rate, respectively, 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 four second increase in critical lost time (as might be caused by an LPI applied to a critical movements) would increase the necessary cycle length by 16 seconds.

Some controllers have special features that can reduce phase lengths and sometimes 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

Reducing crossing lengths will allow for shorter cycle lengths when the pedestrian phase is critical.

7.1.5 **REFERENCES**

Cesme, B., & Furth, P. G. (2014). Self-organizing traffic signals using secondary extension and dynamic coordination. *Transportation Research Part C: Emerging Technologies*, *48*, 1-15.

Chowdhury, S. E. S., Stevanovic, A., & Mitrovic, N. (2019). Estimating pedestrian impact on coordination of urban corridors. *Transportation research record*, *2673*(7), 265-280.

Denney Jr, R. W., Curtis, E., & Head, L. (2009). Long green times and cycles at congested traffic signals. *Transportation research record*, *2128*(1), 1-10.

Furth, P. G., Cesme, B., & Muller, T. H. (2009). Lost time and cycle length for actuated traffic signal. *Transportation research record*, *2128*(1), 152-160.

Furth, P. G., Halawani, A. T., Li, J., Hu, W., & Cesme, B. (2018). Using traffic signal control to limit speeding opportunities on bidirectional urban arterials. *Transportation research record*, *2672*(18), 107-116.

Gordon, R. L. (2010). *NCHRP Synthesis 409: Traffic signal retiming practices in the United States*. Transportation Research Board.

Ishaque, M. M., & Noland, R. B. (2007). Trade-offs between vehicular and pedestrian traffic using micro-simulation methods. *Transport Policy*, *14*(2), 124-138.

Kothuri, S. M., Koonce, P., Monsere, C. M., & Reynolds, T. (2015). Exploring Thresholds for Timing Strategies on a Pedestrian Active Corridor.

Kothuri, S. M., Kading, A., Smaglik, E. J., & Sobie, C. (2017). Improving Walkability Through Control Strategies at Signalized Intersections.

National Association of City Transportation Officials. (2019). Don't give up at the intersection: Designing all ages and abilities bicycle crossings.

Sobie, C., Smaglik, E., Sharma, A., Kading, A., Kothuri, S., & Koonce, P. (2016). Managing user delay with a focus on pedestrian operations. *Transportation Research Record*, *2558*(1), 20-29.

7.2 RESERVICE

7.2.1 BASIC DESCRIPTION

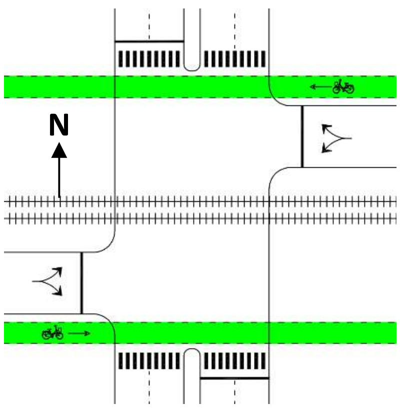
7.2.1.1 ALTERNATIVE NAMES

Not available.

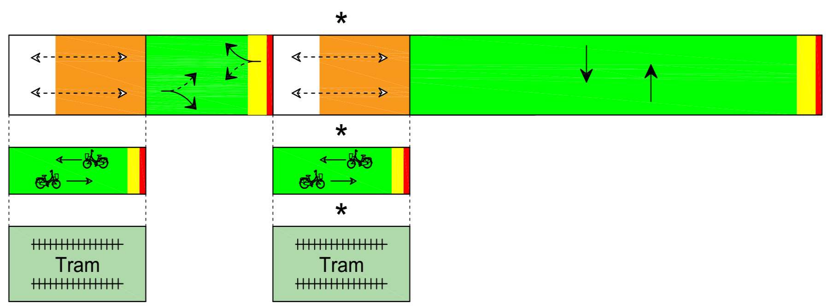
7.2.1.2 DESCRIPTION AND OBJECTIVE

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.

a. Intersection layout



b. Phasing Plan



* Phase served only if there is enough time in the cycle before the scheduled start of the N-S phase, or due to transit signal priority

Exhibit 7-2: Bicycle and pedestrian reservice at the intersection of Sarphatistraat and Weesperstraat, Amsterdam (Furth, 2019). Detail for the north-south phase has been suppressed.

7.2.1.3 VARIATIONS

Within a coordinated system, if every phase is served twice per cycle, 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 their own intersection, running free. That 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 to 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.
- At *channelized right turns* with signal-protected crossings. This context typically involves *multistage crossings* (see **Section 0** and **Chapter 10**).

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

7.2.2 **APPLICATION 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 and for left turns whose turn bay is too short to store the full left turn demand of a cycle, and is sometimes used 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, where 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 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, and 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 (**Section 6.1**) or to prohibiting right turn on red (**Section 6.8**). When a protected bicycle lane was installed on W 3rd Street in Long Beach, California, 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 (though, at the same time, delay for pedestrians and bicycles would increase only little).

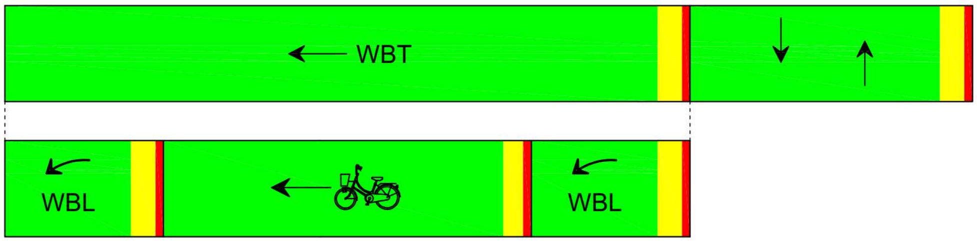


Exhibit 7-3: Phasing plan in which a protected left turn across a protected bike lane has both a leading and lagging phase. Based on operations along W 3rd Street, Long Beach, CA (Furth et al., 2014).

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

7.2.3.2 GUIDANCE

Not applicable for this treatment.

7.2.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

Where crossings of *channelized right turns* (**Section 0**) 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

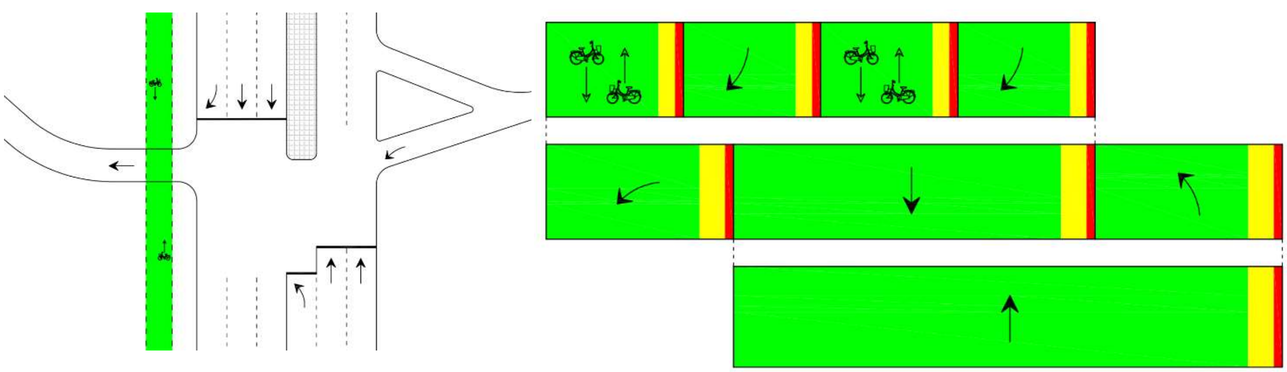
Not applicable for this treatment.

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 terminated.

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



(a) (b)

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

7.2.4.3 SIGNAGE AND STRIPING

Not applicable for this treatment.

7.2.4.4 GEOMETRIC ELEMENTS

Not applicable for this treatment.

7.2.5 REFERENCES

Furth, Peter G. (2019). Reservice (two bike-ped phases per cycle) at an Amsterdam intersection (video). YouTube, https://youtu.be/J-q4HAzIJAg.

Furth, P. G., Koonce, P. J., Miao, Y., Peng, F., & Littman, M. (2014). Mitigating Right-Turn Conflict with Protected Yet Concurrent Phasing for Cycle Track and Pedestrian Crossings. *Transportation Research Record*, *2438*(1), 81-88.

Furth, P. G., Wang, Y. D., & Santos, M. A. (2019). Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Turns: Delay Estimation and Signal Timing Techniques for Limiting Pedestrian and Bicycle Delay. *Journal of Transportation Technologies*, *9*(04), 489.

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 the Walk interval, thereby reduce pedestrian delay, increase 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. As signal controllers in the U.S. are configured, this setting can be applied only to coordinated phases, whose start time 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 Flashing Don’t Walk (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.

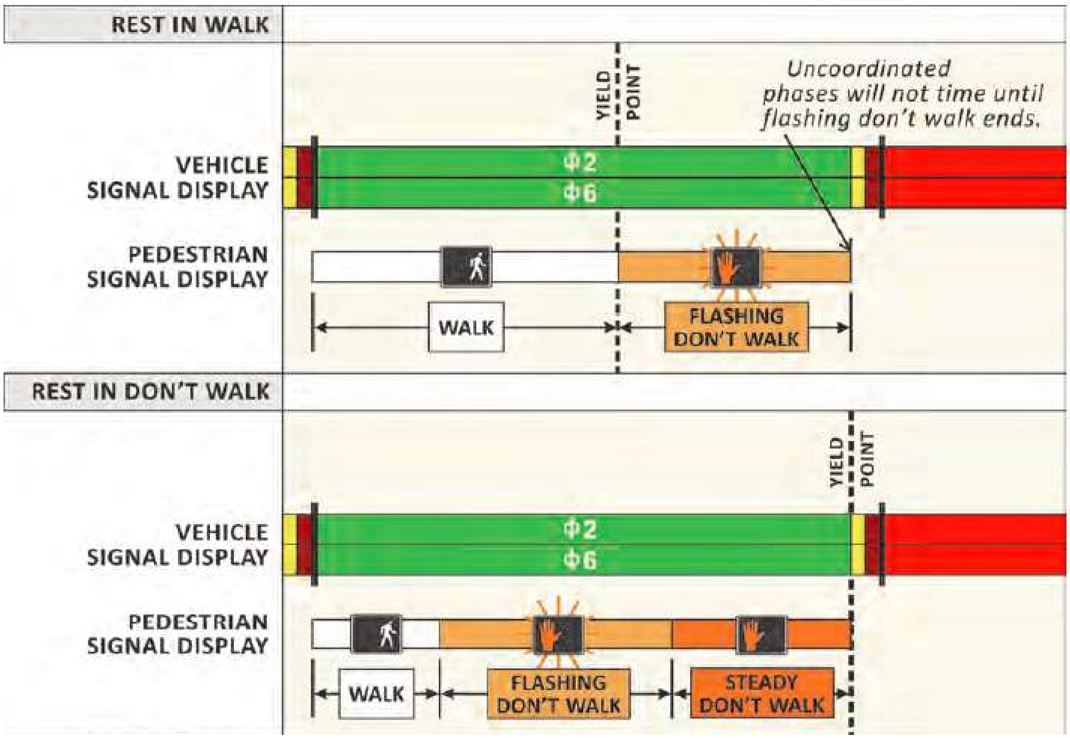


Exhibit 7-5: Rest in Walk and Rest in Don't Walk Modes (Signal Timing Manual).

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

If the concurrent vehicular phase is *pretimed*, the formula is

$$W = \max\left(\left(Split_{ve} \; - FDW - t_{buffer}\right),\ W_{min}\right) \qquad \text{(Equation 7-2)}$$

where *W* is the length of the Walk interval based on the Rest in Walk principle, $Split_{veh}$ is the split duration (i.e., green, yellow, and red clearance) for the concurrent vehicle phase, *FDW* is the length of the Flashing Don't Walk interval, t_{buffer} is the length of the pedestrian phase end buffer time, and W_{min} is the minimum interval allowed by policy (typically 7 seconds).

If the concurrent vehicular phase is *actuated*, the formula is

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

where $MinSplit_{veh}$ is the minimum split duration (minimum green, yellow, and red clearance) for the vehicular phase. For additional discussion on determining the lengths of Flashing Don't Walk and the pedestrian phase end buffer, see **Section 7.4**.

Example 1: Suppose a pretimed vehicular phase has a split of 35 s, consisting 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 Rest in Walk logic, the length of the Walk interval should be 35 – 9 – 5 = 21 s.

Example 2: Same 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. Then, 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 are usually set at their minimum value (usually 7 s). However, if vehicular demand is such that the phase routinely runs past its minimum green, 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 only 30 percent of the cycles (and those will be cycles that are well below capacity, creating low risk of creating any significant impact on traffic operations).

Example 3: Same 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; that is, 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 is adjusted to 16 s (7 s longer than before.)

Example 4: Same 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 percent of cycles. That makes the 30th percentile green time equal 30 s. Increase the minimum green to 30 s (making the phase, in effect, 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 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 APPLICATION 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 equations 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 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 that software's recommendation without checking when 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 requires custom programming, and has not yet been applied in the U.S. A form of this logic is used in Amsterdam under the name Variable Max Green (Sjoerd Linders, personal communication, 8/1/2018).

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.

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 pedestrian from nine percent to 70 percent for one comparison pair, and from 31 percent to 79 percent 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 intersection, one coordinated-actuated and one fully actuated, *Adaptive Walk Intervals* reduced average pedestrian delay by as much as 15 seconds with an impact to vehicular traffic of less than one second (Furth and Halawani, 2016). Another advantage of adaptive control is that adjusts to changes in vehicular demand without requiring manual traffic counts.

7.3.3 **CONSIDERATIONS**

7.3.3.1 ACCESSIBILITY CONSIDERATIONS

The MUTCD recommends that where Rest in Walk is applied, the automatic length of the audible Walk interval for accessible pedestrian signals 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

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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, 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 would 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 **Equation 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 is provided above.

7.3.4.3 SIGNAGE AND STRIPING

Not applicable for this treatment.

7.3.4.4 GEOMETRIC ELEMENTS

Not applicable for this treatment.

7.3.5 REFERENCES

Furth, P. G., & Halawani, A. T. (2016). Adaptive walk intervals. *Transportation research record*, *2586*(1), 83-89.

Kothuri, S. M. (2014). Exploring Pedestrian Responsive Traffic Signal Timing Strategies in Urban Areas.

Kothuri, S. M., Kading, A., Smaglik, E. J., & Sobie, C. (2017). Improving Walkability Through Control Strategies at Signalized Intersections.

Mirabella, J. A. (2013). Understanding Pedestrian and Bicyclist Compliance and Safety Impacts of Different Walk Modes at Signalized Intersections for a Livable Community.

Virginia Department of Transportation. (2020, February 14). *Smart Traffic Signal System*. https://www.ite.org/pub/?id=e1bc66ee-2354-d714-513b-cc4f59e84e0d

7.4 Pedestrian Clearance Settings for Serving Slower Pedestrians

7.4.1 BASIC DESCRIPTION

7.4.1.1 ALTERNATIVE NAMES

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*, a new concept representing that 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.
- Whether concurrent vehicular yellow and red clearance intervals count toward needed pedestrian clearance time

Effective Phase End Buffer. The MUTCD 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 0 – 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, abbreviated as effBuffer, is defined as that portion of the pedestrian phase end buffer that pedestrians can reasonably rely on to finish their crossing in comfort, and can therefore count against needed clearance time. This Guidebook proposes that effBuffer be limited to 3 or 4 s – 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 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, and 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.

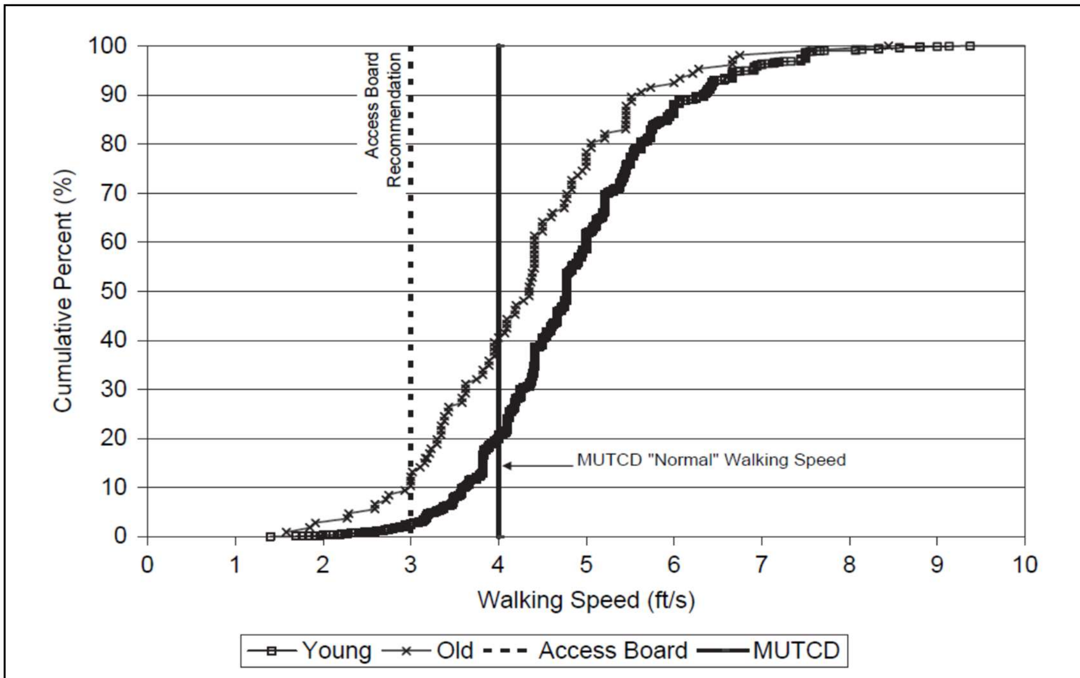


FIGURE 1 Older than 60 (old) and 60 and younger (young) walking speed distribution.

Exhibit 7-6: Walking speed distribution for young (under 60 years) and old crossing pedestrians.
Source: Fitzpatrick et al. (2006). Note: since publication of this figure, the MUTCD 'normal' walking speed has changed to 3.5 ft/s.

Primary pedestrian clearance time needed is:

$$\boldsymbol{t_{cl,needed}} = \frac{\boldsymbol{D}}{\boldsymbol{s_p}} \qquad \text{(Equation 7-4)}$$

where

$t_{cl,needed}$ = primary pedestrian clearance time needed (s)

D = crosswalk length, curb to curb (ft)

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 designedd*, given by

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

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)

$t_{p,eff}$ = effective pedestrian phase length (s)

and where effective pedestrian phase length is given by

$$t_{p,eff} = W + FDW + effBuffer \qquad \text{(Equation 7-6)}$$

where *W*, *FDW*, and *effBuffer* are the lengths of the Walk interval, FDW interval, and effective phase end buffer, respectively, in seconds. 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}, making 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's 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, and 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 seniors, 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 speed at crossings near schools and senior 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 design 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 Walk, 26 s FDW, and 4s of effective phase end buffer. If the pushbutton is 5 ft from the curb, applying equation 7-5, 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. Because many pedestrians in the area are seniors, 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 Walk, 16 s 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. Applying equation 7-5, 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. 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 pedestrian phase end buffer. Yellow times typically range from 3 to 5 s, and red clearance time from 0 to 4 s, which can result in pedestrian phase end buffers of up to 9 s. Because no more than 4 s 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 time to count toward needed pedestrian clearance time, which forces FDW to be longer. This restriction is similar to lowering the pedestrian clearance speed in that it gives pedestrians more time to cross, but unlike lowering clearance speed, it also adds time to the end of the phase that cannot be counted on to serve pedestrians.

VARIATIONS

There are no variations to this treatment.

OPERATING CONTEXT

Can be applicable at every signalized crossing.

7.4.2 **APPLICATION 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 seniors. In the last few years, New York City DOT has classified nearly the entire city as a "senior zone" and, as signals are retimed, is converting crossings to a primary clearance speed of 3.0 ft/s. At the same time, they have 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. Where cities have chosen to use 3.0 ft/s as primary clearance speed, they 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; many do not. There are also several agencies that, by policy, do not let FDW overlap with the yellow interval. One reason for this latter restriction is a common limitation of countdown devices that they 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**). This limitation combined 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 a leading pedestrian interval (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). Their two green intervals together are comparable to our Walk interval, and their pedestrian clearance interval is comparable to our combined FDW interval and phase end buffer.

In the Netherlands, primary pedestrian clearance speed (for those 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 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 at the same time 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 time 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, which 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 two seconds.
B. Letting the yellow begin while FDW is still timing lowers the phase length to 31 s. The unproductive 2 final seconds 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 still meets the performance target. The final two seconds of the phase are, again, of no benefit to pedestrians.
D. Relaxing both restrictions allows the phase length to be 27 s, which is what one would have normally 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.

Exhibit 7-7: Alternative Pedestrian Timings for a Crossing 70 ft long, 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

Alternative C, the second most efficient, is one that agencies may not have considered because before now, 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 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.

Exhibit 7-8: Alternative Pedestrian Timings for a Crossing 70 ft long, Phase Length is Fixed.

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

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 seniors 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* (**Section 7.1**) and can help *maximize Walk interval length* (**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 countdowns 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**). Because countdown timers need to end simultaneously with FDW, that 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, as might be accomplished using corner bulbouts, require less clearance time, which can make signals more efficient and improve accessibility.

7.4.5 REFERENCES

Coffin, A., & Morrall, J. (1995). Walking Speeds of Elderly Pedestrians at Crosswalks. Transportation Research Record, 1487, 63.

Fitzpatrick, K., Brewer, M. A., & Turner, S. (2006). Another look at pedestrian walking speed. Transportation research record, 1982(1), 21-29.

Knoblauch, R. L., M. T. Pietrucha, and M. Nitzburg. Field Studies of Pedestrian Walking Speed and Start-Up Time. In Transportation Research Record 1538, TRB, National Research Council, Washington, D.C., 1996, pp. 27–38.

LaPlante, J. N., & Kaeser, T. P. (2004). The continuing evolution of pedestrian walking speed assumptions. Institute of Transportation Engineers. ITE Journal, 74(9), 32.

7.5 PEDESTRIAN RECALL VS. 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 configured on pedestrian recall or pushbutton-actuated. With pedestrian actuation, the pedestrian phase is omitted from a cycle unless a pedestrian manually places a call, while 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, while 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, but 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

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**, *Accessible Signals without Pushbutton Actuation*.)

Where signals are coordinated-actuated, **Exhibit 7-9** is a 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 pedestrian demand is large enough that there is a call for service in most cycles (horizontal axis showing 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 (vertical axis). This second condition, which is regardless of pedestrian demand, almost always applies to the coordinated phase, which is why coordinated phases should usually have pedestrian recall. That condition also applies to non-coordinated phases with high vehicle demand.

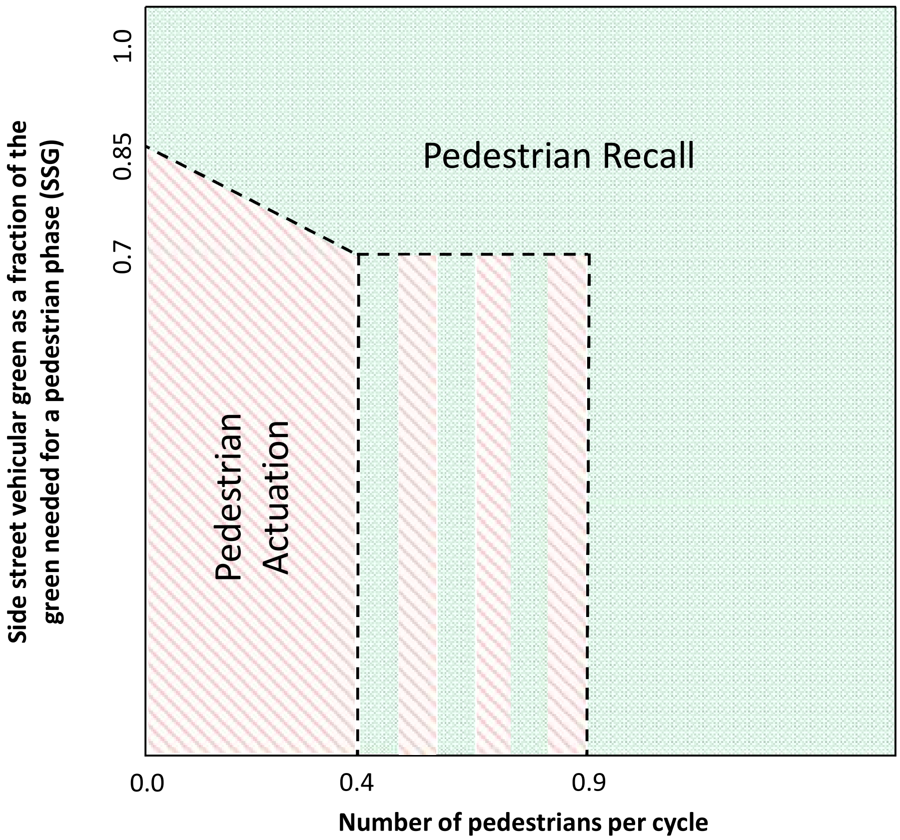


Exhibit 7-9. Criteria for pedestrian recall versus pedestrian actuation with coordinated-actuated control.

Finally, where signals are fully actuated, pedestrian actuation is the better choice in most cases, because it leads to shorter signal cycles, which reduce 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 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). Usually, when a side street is set to pedestrian recall, a signal's operation 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, which is the case with coordinated-actuated control, pedestrian recall reduces pedestrian delay, as shown in **Section 3.3**, which cites an example in which average pedestrian delay is 10 s greater with actuation than with recall. Lower delay, in turn, improves pedestrian safety because it tends to improve pedestrian compliance (Otis and 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. Then, 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 one 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 factor is traffic volume on the concurrent vehicle phase. If that volume is low, then, without a pedestrian call, the phase would have a very short green time. 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 is found that delay to vehicles from a pedestrian recall setting is greatest when pedestrian volume is low; but once pedestrian volume was great enough 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 percent 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, pushbuttons are not needed to call for service, but can still play a valuable role in making a traffic signal accessible. For more detail, see **Section 8.4**, *Accessible Signals without Pushbutton Actuation*.

7.5.3.2 GUIDANCE

The National Association of City Transportation Officials (NACTO) *Urban Street Design Guide* recommends using pretimed signals in urban areas, which results in pedestrian phases being on recall. The *Traffic Signal Timing Manual* 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, the City of Boston recommends pedestrian recall where pedestrians are present for at least than 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* (**Section 7.1**).

7.5.3.4 OTHER CONSIDERATIONS

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* (**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 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. That 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.

7.5.5 **REFERENCES**

City of Boston. (2013). Boston Complete Streets Design Guidelines.

Kothuri, S. M. (2014). Exploring Pedestrian Responsive Traffic Signal Timing Strategies in Urban Areas.

Otis, S. C., & Machemehl, R. B. (1999). *An analysis of pedestrian signalization in suburban areas* (No. SWUTC/99/472840-00065-1). Center for Transportation Research, Bureau of Engineering Research, the University of Texas at Austin.

Van Houten, R., Ellis, R., & Kim, J. L. (2007). Effects of various minimum green times on percentage of pedestrians waiting for midblock “walk” signal. *Transportation research record*, *2002*(1), 78-83.

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 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 (**Exhibit 7-10**). 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; then there is a clearance period involving flashing red (to autos) and, to pedestrians, first FDW and then solid Don't Walk for a few seconds (the "pedestrian phase end buffer"), after which the sign becomes dark again. **Exhibit 7-11** shows the a PHB's display sequence.

Exhibit 7-10: Pedestrian Hybrid Beacon in Portland, Oregon proving a protected crossing (Photo Credit: NACTO).

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 (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., 4 lanes or more), particularly those lacking a median refuge island,
- Crossings of high speed (e.g., 35 mph or more) and high-volume two-lane roadways,
- 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, and
- Crossing location deemed as high-risk area (e.g., schools, shopping-centers, etc.),
- Crossings with a large number of vulnerable users (e.g., children, elderly or disabled).

PHBs can be coordinated with adjacent signalized intersections or 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 to maintain coordination for vehicles. This typically results in longer pedestrian delay.

7.6.2 APPLICATION 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 – prohibited 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 PHB’s *beacons* and not *traffic signals*.

Some PHBs involve 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 percent and 86 percent, respectively. During the same before-and-after analysis, a control group of 36 signalized intersections saw a 16 percent reduction in both total crashes and pedestrian related crashes, and a control group of 102 unsignalized intersections saw a 9 percent reduction in total crash rate and 143 percent increase in pedestrian crash rate, indicating the effectiveness of PHBs in improving pedestrian safety, especially compared to unsignalized crossings (Fitzpatrick and Park, 2010). A study of PHBs with advanced yield or stop marking 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 (Zeeger et al., 2017).

Studies have generally found that motorist yielding rate at PHBs 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 percent to 95 percent at PHBs compared to 99% at signalized, midblock crossing (Godavarthy, 2010). A study of 20 PHBs in Arizona and Texas, most of them at intersections, found a yielding rate of 96 percent (Fitzpatrick and Pratt, 2016).

The same research of PHBs in Arizona and Texas by Fitzpatrick and Pratt indicated some drivers may not understand all the signal phases. In particular, 5 percent 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 seven percent of pedestrians crossed the roadway during the dark indication (Fitzpatrick and Pratt, 2016).

With respect to the impact on drivers, the analysis of two PHB sites was found to have significantly less unnecessary delay as compared to a signalized mid-block 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 (person who is visually impaired stepping out and needing to be stopped to prevent collision) of zero percent compared to interventions on 2.4 percent to 2.8 percent on two-lane roundabouts with similar crossings without PHB. The intervention rate was 0.8 percent to 1.4 percent 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, in turn, 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 unduly delay for vehicles. Where a PHB is operated 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 to 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, the pedestrian will not hear the expected sound of the parallel traffic. Therefore, it is important to include APS which 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 Report 834 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 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 (**Section 8.1**), *Call Indicators* (**Section 8.2**), and *Independently Mounted Pushbuttons* (**Section 8.3**) are helpful at PHBs, just as at signalized crossings.

7.6.3.4 OTHER CONSIDERATIONS

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 is 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, the "pedestrian clearance interval", the pedestrian display shows Flashing Don't Walk for most of the interval, and Don't Walk for the final 3 seconds as a pedestrian phase end buffer. When the beacon is inactive, the pedestrian indication rests in solid Don't Walk.

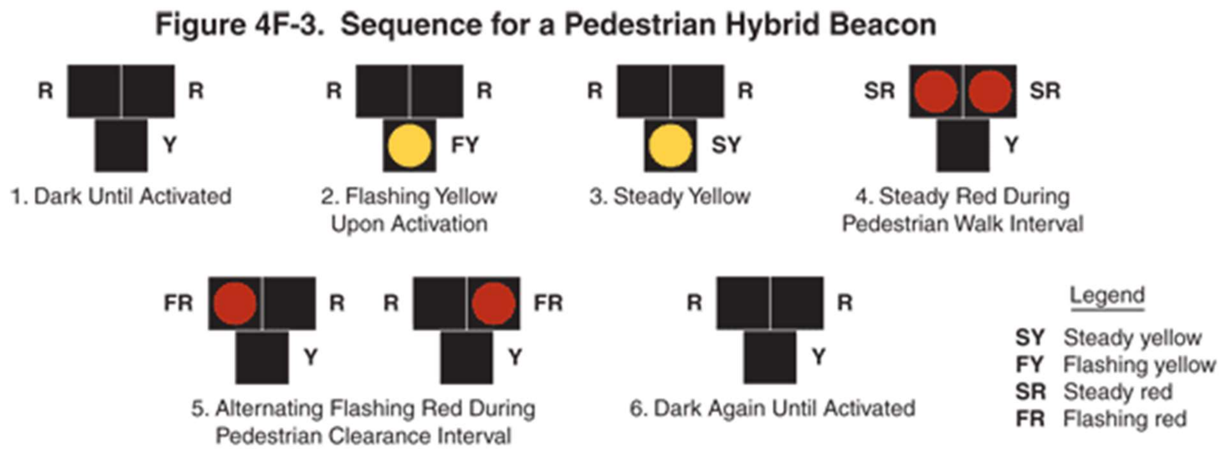


Exhibit 7-11: Phase Sequences for Pedestrian Hybrid Beacon (Source: MUTCD Figure 4F-3).

The duration of the solid yellow indication timing can be calculated using the typical procedure for a vehicular change interval. The pedestrian Walk, Flashing Don't Walk, and pedestrian phase end buffer should be timed as detailed in **Section 4.2** and **Section 7.4.**

7.6.4.3 SIGNAGE AND STRIPING

The MUTCD requires 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 increased the distance between the crosswalk and the yielding vehicles. This helps prevent vehicles in one lane from screening a pedestrian 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.

7.6.5 **REFERENCES**

DeLorenzo, S. S., Jiang, M., & Attalla, M. (2019). *Current Policies throughout the Nation for Pedestrian Hybrid Beacon (PHB) Installation*. Illinois Center for Transportation/Illinois Department of Transportation.

Fitzpatrick, K., & Park, E. S. (2010). *Safety effectiveness of the HAWK pedestrian crossing treatment* (No. FHWA-HRT-10-045). United States. Federal Highway Administration.

Fitzpatrick, K., & Pratt, M. P. (2016). Road user behaviors at pedestrian hybrid beacons. *Transportation research record*, *2586*(1), 9-16.

Godavarthy, R. P. (2010). *Effectiveness of a Pedestrian Hybrid Beacon at mid-block pedestrian crossings in decreasing unnecessary delay to drivers and a comparison to other systems* (Doctoral dissertation, Kansas State University).

Schroeder, B., et al. (2011). NCHRP Report 674: Crossing solutions at roundabouts and channelized turn lanes for pedestrians with vision disabilities. *Transportation Research Board of the National Academies, Washington, DC*.

Schroeder, B., et al. (2017). NCHRP Report 834: Application of Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities, A Guidebook. *Transportation Research Board, Washington DC*.

Zegeer, C., Lyon, C., Srinivasan, R., Persaud, B., Lan, B., Smith, S., ... & Van Houten, R. (2017). Development of crash modification factors for uncontrolled pedestrian crossing treatments. *Transportation research record*, *2636*(1), 1-8.

Chapter 8 Treatments Offering Added Information and Convenience

This section describes treatments aimed at providing pedestrians 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 Countdowns (**Section 8.1**) have become mainstream within the last decade, though they are still not employed everywhere. This section 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 certainty to crossing pedestrians.

Call Indicators (**Section 8.2**) are lights that come on when a call is registered. They can be used with pushbuttons, and, for bicycles, with passive detection using inductive loops. 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 0**) are pushbuttons mounted on their own pole, rather than mounted 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 for pedestrians' convenience and for making 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**) are pedestrian signals that provide audible and tactile signals without creating the expectation that pedestrians must push a button in order to be served, because the pedestrian phase is on recall. 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

8.1.1.2 DESCRIPTION AND OBJECTIVE

Pedestrian countdowns display the number of seconds remaining until the end of the FDW interval. The countdown typically starts at the beginning FDW, called the pedestrian clearance interval in the MUTCD. By providing this information, they aim 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 Flashing Don't Walk, 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 seconds. There is no prohibition on countdowns that run for 7 seconds or less. This rule, which took effect with the 2009 edition of the MUTCD, applies to any new signal or one that is substantially modified.

8.1.2 APPLICATION 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 D.C. 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 Manual MUTCD allowing countdown timing during the Walk interval (District of Columbia, 2018).

8.1.2.2 BENEFITS AND IMPACTS

Many studies have found that countdowns reduced 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 percent (Van Houten et al., 2014). A recent study of more than 300 intersections in Philadelphia and Charlotte found that after countdown signals were installed, total crashes fell by eight percent and pedestrian related crashes by nine percent. These improvements were statistically significant at the 95 percent and 90 percent confidence level, respectively (Srinivasan et al., 2019).

One metastudy found that countdowns led to pedestrian crash rate reductions ranging 70 percent (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 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 percent 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., 2017).

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 study sites showing an increase. A decline in compliance as measured by pedestrian departures after the Walk interval ends should not be surprising, because with a countdown, people see the remaining time and decide based on that, and their own walking speed, whether to cross. However, measured by pedestrians who have failed to clear the intersection before conflicting traffic is released, it is likely that they improve compliance. 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 starting 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, MUTCD does not allow an audible countdown although some manufacturers offer that option. 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 is because the continuous sound of the countdown speech may mask vehicular sounds that pedestrians who are visually impaired need to be able to hear. Another reason, as stated by a visually impaired pedestrian: “I’m already walking as fast as I can; knowing I only have 3 more seconds doesn’t help if I can’t see how much further I have to go!”

8.1.3.2 GUIDANCE

8.1.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

Countdown device limitation can affect *Pedestrian Clearance Settings for Serving Slower Pedestrians* (**Section 7.4**). Countdowns must be configured to reach their zero point at the moment the FDW interval ends. The software controlling 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.

8.1.4 IMPLEMENTATION SUPPORT

8.1.4.1 EQUIPMENT NEEDS AND FEATURES

Pedestrian countdown requires pedestrian signal heads with countdowns. The countdown should be displayed simultaneously with the Flashing Upraised Hand (symbolizing Don’t Walk) signal indication displayed for that crosswalk, as shown in **Exhibit 8-1**.

Exhibit 8-1: Typical Pedestrian Signal Indication with Walk Countdown (Source: MUTCD Figure 4E-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.

8.1.5 **REFERENCES**

8.1.6 **TREATMENT 8.1**

Arhin, S. A., Noel, E. C., & Lakew, M. (2011). Evaluation of two countdown pedestrian signal displays for pedestrian safety. *WIT Transactions on The Built Environment*, *117*, 349-359.

Camden, A., Buliung, R., Rothman, L., Macarthur, C., & Howard, A. (2012). The impact of pedestrian countdown signals on pedestrian–motor vehicle collisions: a quasi-experimental study. *Injury prevention*, *18*(4), 210-215.

District of Columbia Municipal Regulation 18 §2100.2 (2008).

Kwigizile, V., Boateng, R. A., Oh, J. S., & Lariviere, K. (2016). *Evaluating the Effectiveness of Pedestrian Countdown Signals on the Safety of Pedestrians in Michigan* (No. 16-4159).

Harkey, D. L., Carter, D. L., Barlow, J. M., & Louise, B. B. (2007). NCHRP web-only document 117A: Accessible pedestrian signals: A guide to best practices. *Transportation Research Board of the National Academies, Washington, DC*.

Huitema, B., Van Houten, R., & Manal, H. (2014). *An Analysis of the Effects of Installing Pedestrian Countdown Timers on the Incidence of Pedestrian Crashes in the City of Detroit, Michigan* (No. 14-0227).

Markowitz, F., Sciortino, S., Fleck, J. L., & Yee, B. M. (2006). Pedestrian countdown signals: experience with an extensive pilot installation. *Institute of Transportation Engineers. ITE Journal*, *76*(1), 43.

Rothman, L., Cloutier, M. S., Macpherson, A. K., Richmond, S. A., & Howard, A. W. (2019). Spatial distribution of pedestrian-motor vehicle collisions before and after pedestrian countdown signal installation in Toronto, Canada. *Injury prevention*, *25*(2), 110-115.

Srinivasan, R., Lan, B., Carter, D., Smith, S., Signor, K., & Persaud, B. (2019). *Safety Evaluation of Pedestrian Countdown Signals* (No. FHWA-HRT-19-045). United States. Federal Highway Administration. Office of Safety Research and Development.

Thomas, L., Thirsk, N. J., & Zegeer, C. V. (2016). *Application of Pedestrian Crossing Treatments for Streets and Highways* (No. Project 20-05 (Topic 46-10)).

U.S. Access Board (2001). Building a True Community: Final Report, Public Rights-of-Way Access Advisory Committee. *Washington, DC:*

Van Houten, R., & LaPlante, J. (2012). *Evaluating Pedestrian Safety Improvements* (No. RC-1585).

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 (**Exhibit 8-2**). Call indicators are universally used in connection with elevator pushbuttons, but in the US, 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 they 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 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 (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.

Exhibit 8-2: Typical American Accessible Pedestrian Signal with the Call Indicator Illuminated.

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 (**Exhibit 8-3**).[1] In the Netherlands, pedestrian pushbuttons have indicator lights either above or surrounding the pushbutton.

Exhibit 8-3: Standard Pushbutton in the United Kingdom.

In the U.S., call indicators are present wherever accessible pedestrian signals (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.

Call indicators for bicycles are unknown in the US outside of Portland (OR). In the Netherlands, they are used all intersections where a bicycle phase depends on detection. In the Netherlands, 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 thereby know that they don't need to push the button. The photo below 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 (**Exhibit 8-4**).

[1] https://depositphotos.com/63060109/stock-photo-wait-plate-is-operated-at.html

Exhibit 8-4: Bicycle pushbutton assembly, Illuminated Call Indicator, and In-pavement Loop Detectors in the Netherlands (Photo Credit: Peter Furth).

Portland (OR) has developed a different kind of call indicator for bicycles: a blue LED light 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.

Exhibit 8-5: Bicycle call indicator using blue LED light in Portland, Oregon.

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're 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 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-after study found that bicycle red light compliance improved significantly at every one of the nine locations studied (Alviani 2014).

8.2.3 **CONSIDERATIONS**

8.2.3.1 ACCESSIBILITY CONSIDERATIONS

For signals to be accessible, per the *MUTCD*, 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* states that a call indicator installed with a pedestrian pushbutton must not be illuminated until actuated, and once actuated, must remain illuminated (that is, 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* (**Section 8.4)** and in connection with *bicycle detection* (**Section 0**).

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 have call indicator lights and provide audible call confirmations ("Wait"), as well. 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.

For a call indicator to illuminate based on a system actuation where the pedestrian phase is on recall can, for some pushbutton controllers, require custom programming.

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 hours 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 the meaning of blue light (**Exhibit 8-6**).

Exhibit 8-6: Blue Light Bicycle all Indicator Sign to Inform Cyclists in Portland, Oregon (Photo Credit: J. Maus/BikePortland).

8.2.4.4 GEOMETRIC ELEMENTS

8.2.5 **REFERENCES**

Alviani, Carl. (2014, October 28). The Traffic Signal Knows You're There. *Re:Form*. https://medium.com/re-form/the-traffic-signal-knows-youre-there-d9e6d690dffe

Hagen, L. T. (2005). Selecting the Most Effective ITS Application for Pedestrian Safety in Florida. *Floridaa Department of Transportation.*

Harkey, D. L., Carter, D. L., Barlow, J. M., & Louise, B. B. (2007). NCHRP web-only document 117A: Accessible pedestrian signals: A guide to best practices. *Transportation Research Board of the National Academies, Washington, DC*.

Huang, H. F., & Zegeer, C. V. (2001). *An evaluation of illuminated pedestrian push buttons in Windsor, Ontario* (No. FHWA-RD-00-102). United States. Federal Highway Administration.

Van Houten, R., Ellis, R., Sanda, J., & Kim, J. L. (2006). Pedestrian push-button confirmation increases call button usage and compliance. *Transportation research record*, *1982*(1), 99-103.

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 equipment. The purpose is to locate pushbuttons for user convenience and to keep pushbuttons far enough apart that users at a corner can tell which button should be pressed to cross which leg, and so that visually impaired pedestrians can 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 reachable from their queuing position. And if a pushbutton is too close to the curb, a bicyclist may not be able to reach it without their front wheel encroaching on the street.

Exhibit 8-7: Independent poles with pedestrian displays and pushbuttons only (U.S. Access Board, 2011).
(source: http://accessforblind.org/aps/aps-installation-recommendations/) (U.S. Access Board, 2011)

8.3.1.3 VARIATIONS

Not applicable for this treatment.

8.3.1.4 OPERATING CONTEXT

Independently mounted push buttons can be considered at almost any crossing, particularly with accessible pedestrian signals and at crossings 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 photo in **Section 8.2**) 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 is 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 from 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 location for serving 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 feet from the edge of curb.

APS with pushbuttons located close to the curb ramp greatly reduce errors 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 three feet 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).

8.3.2.2.1 QUALITATIVE IMPACTS

8.3.3 CONSIDERATIONS

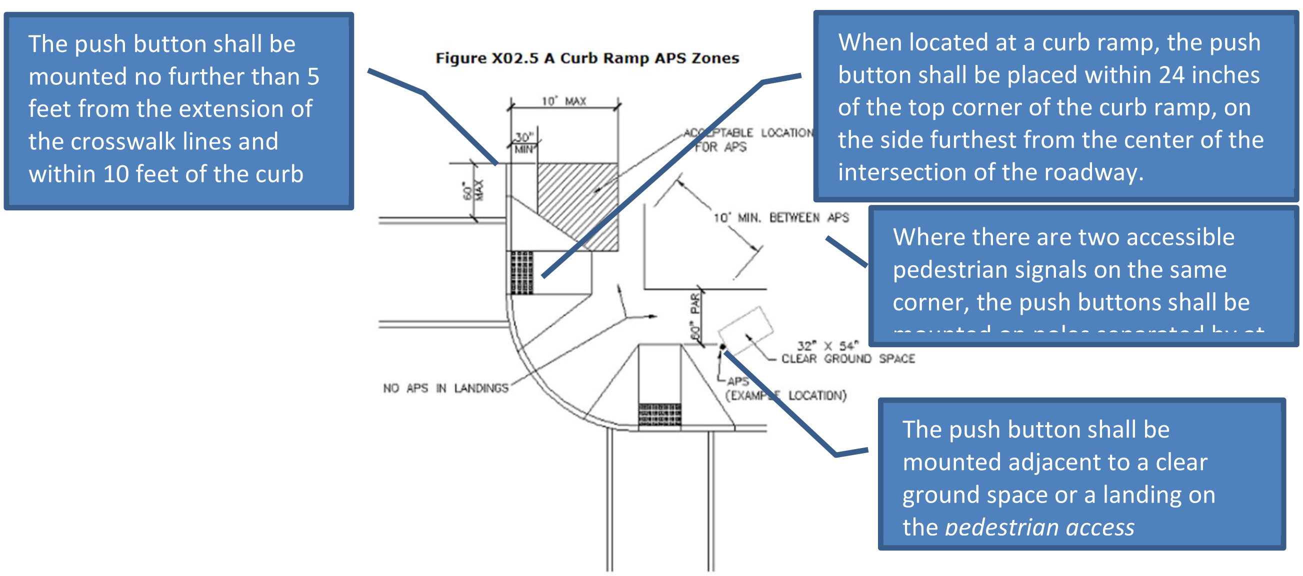
8.3.3.1 ACCESSIBILITY CONSIDERATIONS

Independently mounted pushbuttons can increase accessibility in several ways. The can reduce 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 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 (2011) 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 guidelines often 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 never 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 feet or more apart, they may be placed closer together or on the same pole. If APS are closer than 10 feet apart, the audible messages must include the street name and there must be an additional pushbutton information message providing the street name.



Curb ramps at an intersection with APS zones indicated in plan.

Exhibit 8-8: Curb ramps at an intersection with APS Zones (U.S. Access Board, 2011).

8.3.3.2 GUIDANCE

8.3.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

8.3.3.4 OTHER CONSIDERATIONS

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 DOT (2015) recommends a 4” outer diameter aluminum pipe about 5.5 feet tall for a pedestrian push button post.

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

Exhibit 8-9: Independent push button pole example (source:https://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/guidance-and-research/common-problems-arising-in-aps-installation/introduction U.S. Access Board, 2011)

8.3.4.2 PHASING AND TIMING

8.3.4.3 SIGNAGE AND STRIPING

Not applicable for this treatment.

8.3.4.4 GEOMETRIC ELEMENTS

The MUTCD has guidelines regarding pushbutton placement, including the recommendation that pushbuttons at a corner serving two crosswalks be placed at least 10 feet apart, and provides useful graphics about pushbutton installation with various curb ramp configurations. Another resource on APS pushbutton location and curb ramps is Special Report: Accessible Public Rights-of-Way Planning and Design for Alterations at https://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/guidance-and-research/accessible-public-rights-of-way-planning-and-design-for-alterations/chapter-6%E2%80%94curb-ramp-examples

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 not so far that bicyclists cannot reach it without going out of their way. They should be located where a bicyclist who can reach the button can wait without encroaching on the road and not on a steep ramp.

8.3.5 **REFERENCES**

Florida Department of Transportation (2015). Pedestrian Detector Assembly Installation Details.

Harkey, D. L., Carter, D. L., Barlow, J. M., & Louise, B. B. (2007). NCHRP web-only document 117B: Accessible pedestrian signals: Final Report. *Transportation Research Board of the National Academies, Washington, DC*.

Scott, A. C., Myers, L., Barlow, J. M., & Bentzen, B. L. (2005). Accessible Pedestrian Signals: The Effect of Push-Button Location and Audible “Walk” Indications on Pedestrian Behavior. *Transportation research record*, *1939*(1), 69-76.

U.S. Access Board (2011). Proposed accessibility guidelines for pedestrian facilities in the public right-of-way. *Washington, DC*.

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. Accessible pedestrian signals (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 wherever pedestrian recall or pretimed control is the preferred operating mode, and 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. New York City DOT is installing 150 APS intersections per year, nearly all of them at pretimed locations (Danny Nguyen, personal communication, 8/16/2019). 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 offers 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 reduces their delay (Harkey et al., 2007).

Holding in the pushbutton for more than one second (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

Accessible pedestrian signals 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 (**Exhibit 8-**). While most APS pushbuttons are designed to serve a dual function as both a standard pedestrian pushbutton and an APS, they can be used for their accessible features only, or similar units that lack the pedestrian actuation function can be provided.

Exhibit 8-10: Accessible pedestrian signal example (Photo Credit: SFMTA).

8.4.3.2 GUIDANCE

Many U.S. cities including New York, Portland (OR), San Francisco, and Seattle 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. Minnesota, Maryland, San Francisco, and many municipalities install APS at all reconstructed or newly signalized intersections.

The *Manual on Uniform Traffic Control Devices (MUTCD)* provides guidance on APS, including a requirement that APS clearly indicate which pedestrian crossing is served by each device. Guidance on pushbutton location is provide 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 0**).

All APS currently on the market in the U.S. provide a latching *call indicator* or pilot light (**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

8.4.4 **IMPLEMENTATION SUPPORT**

8.4.4.1 EQUIPMENT NEED AND FEATURES

Standard APS equipment may be used with the button not used as 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 phases' call status.

The 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* allows the 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 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.

8.4.5 **REFERENCES**

Harkey, D. L., Carter, D. L., Barlow, J. M., & Louise, B. B. (2007). NCHRP web-only document 117A: Accessible pedestrian signals: A guide to best practices. *Transportation Research Board of the National Academies, Washington, DC*.

Chapter 9 Treatments Addressing Special Bicycle Needs

This section 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 possible with bicycle detection	9.4	Bicycle Detection
Provide information to increase cyclist compliance	9.5	Bicycle Wait Countdown
Reduce bicycle delay	9.6	Easing Restrictions on Bicycle Right Turn on Red

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 0**) provides signal timing guidance for providing green waves for bicycles, that is, enabling 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 Restrictions on Bicycle Right Turn on Red (**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; bike red clearance; bicycle yellow; 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 yellow and red clearance intervals. 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*. 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 interval*.

9.1.1.3 VARIATIONS

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 crossing wide streets that have a short minimum green, because 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, for which the clearance time set based on considerations of vehicle safety may not be enough for bike clearance.

Bicycle yellow interval timing applies wherever there are bicycle 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 AND IMPACTS

9.1.2.1 NATIONAL AND INTERNATIONAL USE

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

In the U.S., bike minimum green is recommended in the California MUTCD (2014), and 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, using the stopline 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 NACTO bikeway design guide, it is not even mentioned in the AASHTO *Guide for the Development of Bicycle Facilities* or the *Signal Timing Manua*l because for long crossings, there is a common belief that it would demand very long red clearance times that are 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 demanding 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:

$$BXT_{standing} = \frac{D+L}{v} + StartupOffset \qquad \text{(Equation 9-1)}$$

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)

$StartupOffset$ = 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 eight California intersections and found that median and 15-percentile speeds were approximately 12 mph and 8.5 mph, respectively, and that median and 90-percentile startup offsets were approximately 3.5 s and 5.5 s, respectively. The California 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 used combined with a less extreme startup offset of 4.5 s, calculated crossing times differ by less than 0.5 for crossing distances within the range 75-160 ft. The AASHTO manual's crossing time equation has a different form, but reduces essentially to the California 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 and Shladover et al., 2011).

Bike Minimum Green

Two formulas that may be considered for bicycle minimum green:

$$BikeMinGreen = \ BXT_{standing} - Y - RClear \qquad \text{(Equation 9-2)}$$

$$BikeMinGreen = \ BXT_{standing} - Y - RClear - t_{conflict} \qquad \text{(Equation 9-3)}$$

where

BikeMinGreen = bike minimum green (s)

Y = yellow time (s)

RClear = red clearance time (s)

$t_{conflict}$ = time needed for a vehicle released in the next phase to enter the conflict zone (s)

Equation 9-2, used both by the AASHTO guide and the California MUTCD, aims to ensure that the design bicyclist has reached the end of the most distant travel lane before conflicting traffic is released. The *Signal Timing Manual*, which provides the same guidance regarding bike minimum green as the California MUTCD, has a table (Exhibit 6-7) showing the total minimum phase length needed (minimum green plus yellow plus red clearance) as a function of crossing length.

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 being 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 automobile needs. To illustrate, consider two crossings, one 80 ft long and one 120 ft long, both with 3 s yellow times, and with red clearance times of 2 s and 3 s, respectively. Using California MUTCD default values, bike minimum green would be 6.9 s and 8.6 s, respectively. Because most agencies use 6 s as the least minimum green for through phases (many agencies use 10 s), bike minimum green presents a very minor constraint on signal operations.

Bike Red Clearance

Three formulas may be considered for bike red clearance:

$$BikeRClear = \frac{D+L}{v} \qquad \text{(Equation 9-4)}$$

$$BikeRClear = \frac{D+L}{v} + \left(t_{reaction} + \frac{v}{2d} \right) - Y \qquad \text{(Equation 9-5)}$$

$$BikeRClear = \frac{D+L}{v} + \left(t_{reaction} + \frac{v}{2d} \right) - Y - t_{conflict} \qquad \text{(Equation 9-6)}$$

where

BikeRClear = bike red clearance time (s)

$t_{reaction}$ = reaction time for a cyclist reacting to a signal turning yellow (s)

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 the Ontario 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 crossing, 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 that are far enough upstream of the stopline) *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 (Ontario, 2018). The time from the start of yellow to the moment the last cyclist who could not stop enters the intersection is $\left(t_{reaction} + \frac{v}{2d} \right)$, which, using the suggested default values, 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 nevertheless 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, it further reduces needed clearance by 1.8 s.

A further 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 stopline. This can be appropriate where cyclists routinely stop at that curb line rather than at the stopline. (One advantage of the "protected intersection" layout is that it places the bicycle stopline in this advanced position, reducing needed bicycle clearance.)

Together, reductions in needed bicycle red clearance from 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 s to only 2.3 s; for a 120 ft crossing, from 10.1 s 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. With that policy, red clearance time needed by vehicles is 2.2 for an 80 ft crossing, and 3.1 s for a 120 ft crossing. Continuing the earlier examples, the extra red clearance time needed to time 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 can be provided only in cycles in which a bicycle is detected – in the case of minimum green, if a bike is detected during the red interval, and in the case of red clearance, if a bike is detected 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 in Section 9.4, there is at least one commercial system using video detection 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 stopline detector, but requires a special upstream detector, located so that a cyclist that 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, using performance parameters that pertain to bikes:

$$Y = t_{reaction} + \frac{v}{2d} \qquad \text{(Equation 9-7)}$$

Because 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, when 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 recently reduced the yellow time for its bicycle signals from 3 s 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, seniors, tourists, and people new to cycling. Benefits depend, of course, on the number of cyclists, and so crossings with high cyclist volume or that are used by 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 second or less). The impact of applying it 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 s to 10 s will have a negligible effect on average delay. Shladover et al. (2009), using microsimulation, 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 s 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 s or 6 s, and so 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's 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 the realm of safety. For small increases in clearance time, there may be a small improvement 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" (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 a critical intersection, 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, providing bike red clearance is a part of traffic signal policy, but extra red clearance time is limited to 1 s (Ontario, 2018; Toronto, 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 is particularly relevant for slower bicyclists, including children, seniors, 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

9.1.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

Bicycle detection (**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 will lower the treatment's efficiency.

Using efficient *pedestrian clearance settings* (**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, 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.

For applying detector-actuated bike minimum green, some controllers have a built-in feature to enter a 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 stopline 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 stopline detector is in a shared travel lane rather than a bike lane, or because right turning vehicles routinely overrun the detector – 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

9.1.4.3 SIGNAGE AND STRIPING

9.1.4.4 GEOMETRIC ELEMENTS

Geometric changes that shorten bike crossings reduce clearance time need. Examples include advanced stop lines for bikes, corner bulbouts, 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.

9.1.5 REFERENCES

California (state of) (2014). California Manual on Uniform Traffic Control Devices.

McGee Sr, H., Moriarty, K., & Gates, T. J. (2012). Guidelines for timing yellow and red intervals at signalized intersections. *Transportation research record*, *2298*(1), 1-8.

Ontario (province of) (2018). Bicycle Traffic Signals: Traffic Manual Book 12A.

Rubins, D. I., & Handy, S. (2005). Bicycle clearance times: a case study of the city of Davis. In Transportation research board annual meeting.

Schattler, K. L., Datta, T. K., & Hill, C. L. (2003). Change and clearance interval design on red-light running and late exits. *Transportation research record*, *1856*(1), 193-201.

Shladover, S. E., Kim, Z., Cao, M., Sharafsaleh, A., & Li, J. Q. (2009). Bicyclist intersection crossing times: Quantitative measurements for selecting signal timing. Transportation research record, 2128(1), 86-95.

Shladover, S., Sharafsaleh, A., Cheong, A., Spring, J., & Leung, K. (2010). Bicycle Detection and Operational Concept at Signalized Intersections Phase 2B: Testing a Bicyclist Detection System (No. UCB-ITS-PRR-2012-3).

Taylor, D. B. (1993). Analysis of traffic signal clearance interval requirements for bicycle-automobile mixed traffic. Transportation Research Record, 1405, 13-20.

Toronto Transportation Services (2015). Traffic Signal Operation Policies and Strategies.Curtis, E. J. (2015). Comprehensive on-street bicycle facilities: an approach for incorporating traffic signal operational strategies for bicycles (Doctoral dissertation, Georgia Institute of Technology).

Wachtel, A., Forester, J., & Pelz, D. (1995). Signal clearance timing for bicyclists. ITE journal, 65(3), 38-38.

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 are 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. On a one-way street, to determine offsets, a progression speed is first chosen, then offsets for each successive intersection (*j* = 2, 3, …) are then determined using the following formula:

$$offset_{1j} = \frac{d_{1j}}{v_{progression}} \qquad \text{(Equation 9 − 8)}$$

where

$offset_{1j}$ = offset of signal *j* relative to signal *1* (s)

d_{1j} = distance from signal *1* to signal *j* (ft)

$v_{progression}$ = 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 at the first intersection, offsets for successive intersections are 20, 40, 60, … seconds.

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 (bicycles can typically get through only a few intersections, then 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 and are therefore 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, which is 12 to 13.5 mph (roughly 17.5 to 20 ft/s) on level ground. That 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/or bicycles released from the critical intersection can pass through downstream intersections without stopping.

Corridor- or grid- level coordination times 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 where an important bicycle route passes through a critical intersection with a long cycle length and a short green phase for bicycles, and there are other nearby traffic signals on the same route.

Because bicycle platoons disperse due to bicyclists' varying speeds, there is little benefit to coordination where signal spacing is more than 1,200 ft apart.

9.2.2 APPLICATIONS AND EXPECTED OUTCOMES

9.2.2.1 NATIONAL AND INTERNATIONAL USE

Both Copenhagen and Amsterdam 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 where 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) (Copenhagenize, 2014).

On Amsterdam's Raadhuisstraat, 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). Again, 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, it also improves safety by effectively limiting motor vehicle speed to 18 km/h and removes the incentive for motor vehicles to pass bicycles.

Both Copenhagen and Utrecht (Netherlands) have installed pilot projects providing 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, in both Copenhagen and Amsterdam, they have found that where intersection spacing is not large, cyclists quickly learn what speed will enable them to stay within the green wave (Copenhagenize, 2014; Linders, 2013).

In the United States, New York, Chicago, and San Francisco have retimed streets for bicycle progression. New York's first application is the one-way couplet of Hoyt and Bond Streets in Brooklyn (see **Exhibit 9-1**), retimed in December 2018 with a progression speed of 15 mph (Colon, 2019; Danny 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.

Exhibit 9-1: Hoyt Street in Brooklyn, timed for a bicycle green wave at 15 mph (Photo Credit: Gersh Kuntzman, copied from StreetBlog NYC).

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 seconds. 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:

$$ideal\ two - way\ progression\ speed = \frac{signal\ spacing}{(cycle\ length)/2} \qquad \text{(Equation 9-9)}$$

For Valencia and Folsom Streets, 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 luck – if the cycle length instead had been 100 s, or signal spacing were 360 ft, the ideal progression speed would have been only 8 mph.

For vehicles as well as bicycles, the "ideal" progression speed is 13.5 mph (same formula), which means that if signals were timed for a speed better suited to vehicles – say, 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 bicycles 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).

Portland's (OR) downtown is a one-way grid with square blocks, 260 ft on a 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:

ideal progression speed (one-way grid) = block circumference / signal cycle length

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, since well before bicycling was popular. This regime serves bicycles well. For vehicles, too, this timing regime, known as "quarter cycle offsets," offers good service in which 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 N. Broadway, a one-way street, bicycles receive a short green period at 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 (Victoria) and downstream (Vancouver) intersections. When bicycles are released from Victoria, the bicycle phase at Williams is scheduled to begin a few seconds later; however, it is actuated, so that it is called only 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 showing 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 where 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, supporting the safety improvement. For example, at Portland's N. Broadway and Williams 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 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, which was critical to the safety improvement (Littman and 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 independently timed one-way streets (that is, not timed as part of a grid), ideal progression can be achieved for any desired progression speed. On such streets, while bringing progression speed closer to bicycle speed will decrease bicycle delay by enabling bicycle progression, it also increases 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 mile 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 is 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).

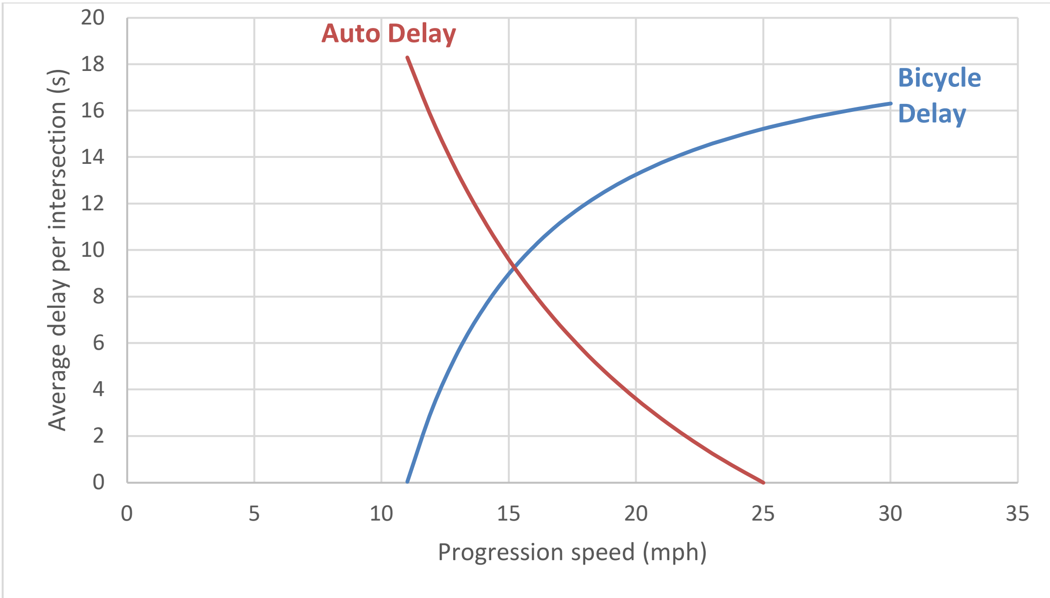


Exhibit 9-2: Through bicycle and auto delay per intersection versus progression speed for an uncongested one-way street with 25 mph target speed.

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

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) to 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

9.2.4.3 SIGNAGE AND STRIPING

Not applicable for this treatment.

9.2.4.4 GEOMETRIC ELEMENTS

Not applicable for this treatment.

9.2.5 REFERENCES

There are no sources in the current document. Littman, M. and Furth, P.G. (2013). Protecting the Bike – Dual Right Turn Lane Conflict in Portland (NE Broadway & Williams). Student project, Northeastern University. https://sites.google.com/site/studentprojectstraffic/home/protecting-the-bike-right-turn-conflict-in-portland-broadway-ne-williams?tmpl=%2Fsystem%2Fapp%2Ftemplates%2Fprint%2F&showPrintDialog=1

Stonehill, Laura (2016). Catch the green wave! Timing Signals for Bikes. Poster, ProWalk ProBike ProPlace Conference, Vancouver, BC.

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 westbound has the green.

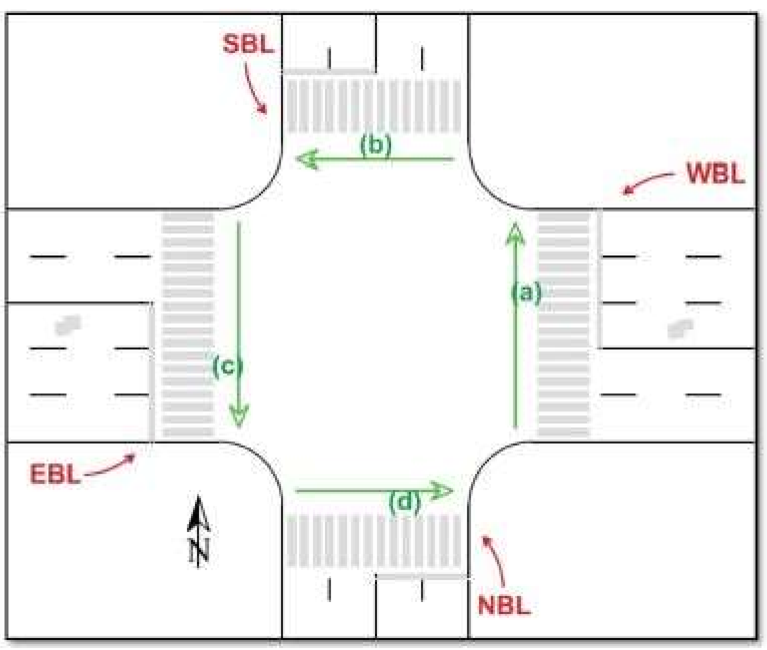


Exhibit 9-3: Unidirectional bicycle crossings for making a two stage left turn.

Two stage left turns are common in many European countries and are becoming popular in the United States. NACTO's Urban Bikeway Design Guide 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 9-9-4 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 the 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. That 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.

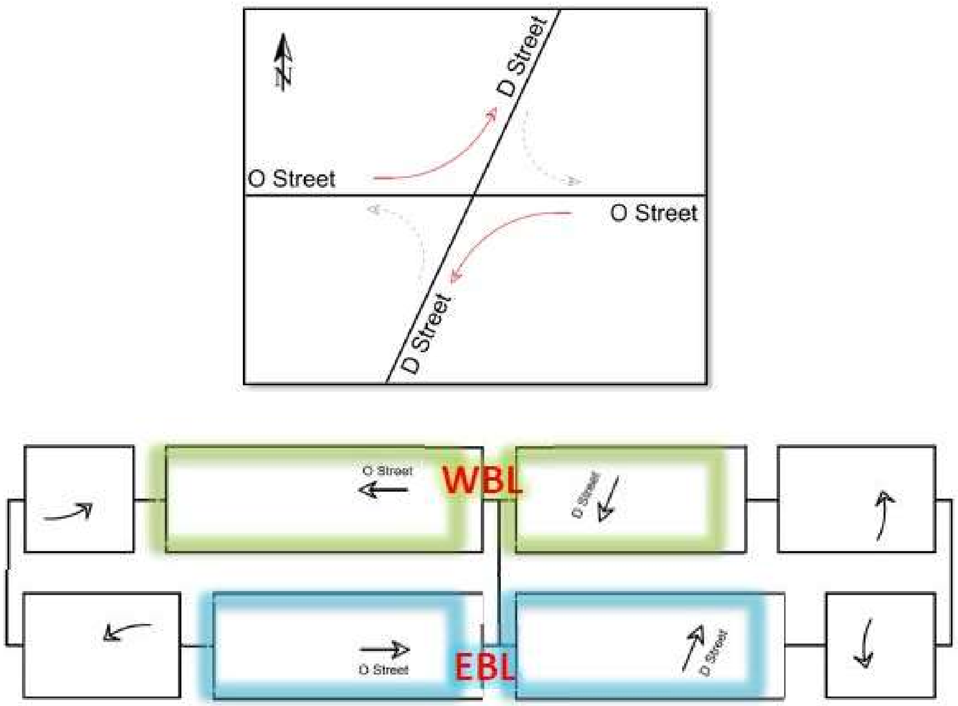
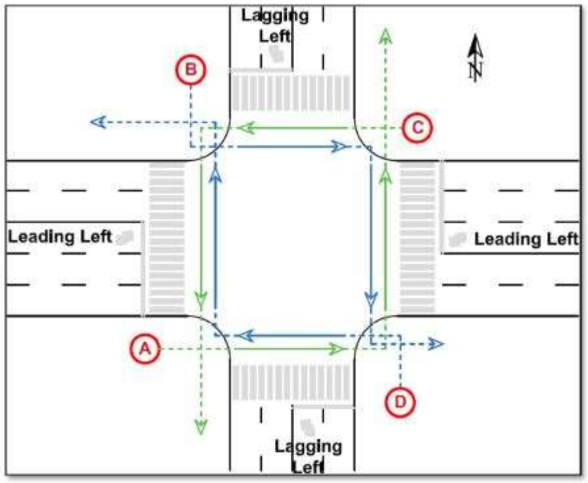


Exhibit 9-9-4: Lead-Lag Progression to Provide Progression for Bicycles Traveling from O Street to D Street.

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 the previous example, so that the through movements for one street (the east-west street) are immediately following by the other street's through movements. With bidirectional crossings, also shown in the exhibit, this phasing sequence creates good progression for all bicycle left turns, because 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 A and C can make their left turn by traveling counterclockwise (following the green arrows) and those approaching at B and D make can 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.



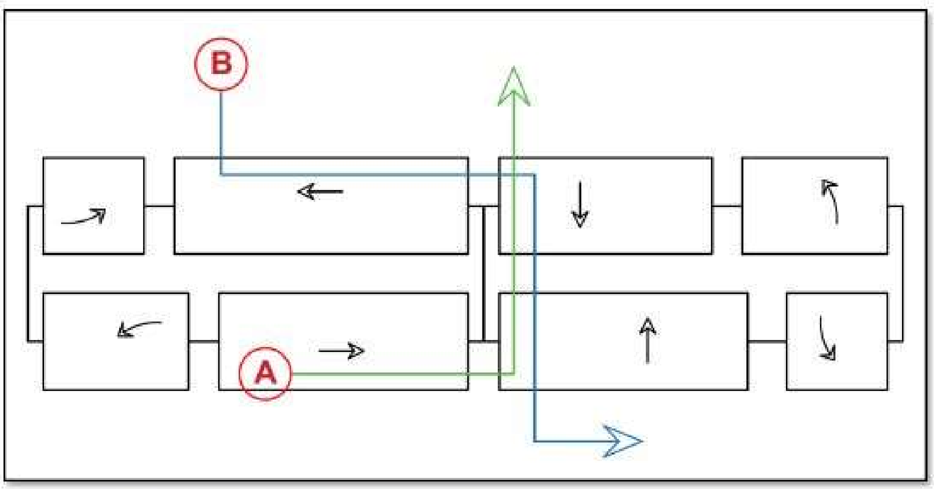


Exhibit 9-5: Bidirectional bicycle crossings, allowing additional crossing movements.

9.3.1.3 VARIATIONS

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 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, its 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 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, 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

9.3.3.2 GUIDANCE

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* (**Section 6.3**) where a bike path crosses from one side of the street to another or transitions between a bidirectional path and one-way bike lanes.

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

9.3.4.3 SIGNAGE AND STRIPING

Both NACTO and the MUTCD 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.

9.3.5 REFERENCES

CROW (2007). Design Manual for Bicycle Traffic. Ede, Netherlands.

Furth, P. G., Wang, Y. D., & Wang, Y. D. (2015). Delay Estimation and Signal Timing Design Techniques for Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Left Turns. In Transportation Research Board 94th Annual Meeting (No. 15-5365).

Furth, P.G., Wang, Y. and Santos, M.A. (2019) Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Turns: Delay Estimation and Signal Timing Techniques for Limiting Pedestrian and Bicycle Delay. Journal of Transportation Technologies, 9, 489-503.

9.4 BICYCLE DETECTION

9.4.1 BASIC DESCRIPTION

9.4.1.1 ALTERNATIVE NAMES

Bicycle Actuation

9.4.1.2 DESCRIPTION AND OBJECTIVE

With bicycle detection, the presence of bicyclists is made known to the signal controller, which can use that information to activate the signal for phase serving 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 (**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, including calling for a phase that bicycles share with autos, *mixed detection* – that is, picking up both bicycles and autos without distinguishing them – 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, to make right turns for example. For extending minimum green and red clearance time, 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 that is inconvenient for bicyclists except when used as a backup for another automatic detection method.

Bicycle detection can also be considered near the stop bar or upstream (in advance). Stop bar placement is appropriate for calling for service, extending minimum green, or extending red clearance. 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 detect bicycles are needed wherever the phase serving bikes is 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 connection with applying the treatments based on bicycle clearance (bike minimum green, bike red clearance, and green extension for bike clearance) 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/IMPACTS**

9.4.2.1 NATIONAL AND INTERNATIONAL USE

Using bicycle-sensitive call detectors for phases shared by bicycles and autos is common in the U.S. Where bikes share a lane with motor traffic, a special loop layout resembling a figure-8 used to increase sensitivity to the relatively small amount of metal in a bicycle. In keeping with an option described in the MUTCD, a small bicycle silhouette with a broken line can 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 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.

Exhibit 9-6: MUTCD Marking and Sign for Inductive Loop Bicycle Detectors.

Based on public outreach, Portland (OR) 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.

Exhibit 9-7: Bicycle loop detector marking developed in Portland (OR). Source: Maus (2016).

For detectors in bike lanes, the *Traffic Signal Timing Manual* recommends considering setting the detector back a short distance to minimize actuations from vehicles 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 sensed them, they don't 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 (OR) has been a leader in developing and applying inductive loop detectors for separated bike lanes. They also use pushbuttons (without loops) for bicycle detection. They have used educational campaigns to help cyclists better understand how to be detected.

In the Netherlands, an app named "Schwung" has been developed that enables signal controllers to detect approaching bikes using their smart phones several seconds before they arrive at an intersection. At the same time, controller logic has been modified to use this information to more quickly change the phase in favor of bikes and to extend a bike phase (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, with the standard layout of a bike-sensitive loop detector, the zone of heightened sensitivity is in the middle of lane, while cyclists tend to ride near the right edge of the lane. Boudart et al. (2016) found that with Portland's marking (shown earlier in **Exhibit 9-7**), 60% of survey respondents understood the meaning of the marking, a 30% improvement over locations without the explanation provided as part of the pavement marking.

A literature review done by the City of 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 technologies using active infrared, video image processing, and cell phone apps are developing rapidly, but at this time have not been well documented.

9.4.3 **CONSIDERATIONS**

9.4.3.1 ACCESSIBILITY CONSIDERATIONS

Pushbuttons intended for bicyclist use should be reachable without requiring that cyclists deviate from their path. Path deviations that require bicyclists to shift laterally are difficult for cyclists with limited strength or balance and for those carrying children. They should be set back enough from the curb so that the bicycle will not encroach on the conflicting roadway. For more detail, see **Section 8.3**, *Independently Mounted Pushbuttons*.

9.4.3.2 GUIDANCE

9.4.3.3 RELATIONSHIP TO RELEVANT TREATMENTS

Pedestrian recall versus actuation (**Section 7.5**) discusses considerations also relevant to bicycle phases being actuated.

With bicycle detection, it is desirable to provide *Call indicators* (see **Section 0**) to assure bicyclists that they have been detected, which may improve compliance.

Pushbuttons should be located for safety, convenience, and accessibility; see *Independently mounted pushbuttons* (**Section 8.3**).

Minimum green and change interval settings (**Section 9.1**), including bicycle red clearance, can be applied more efficiently using bicycle detection.

Flashing indicators for permitted conflicts (***SECTION 0***) could be dynamic, 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 of these methods advances, there will be opportunities to include them as bicycle detection at signalized intersections instead of 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

9.4.4.3 SIGNAGE AND STRIPING

9.4.4.4 GEOMETRIC ELEMENTS

9.4.5 **REFERENCES**

Bussey, S. W. (2013). The Effect of the Bicycle Detector Symbol and R10-22 Sign on Cyclist Queuing Position at Signalized Intersections.

City of Portland. (2010). Portland Bicycle Plan for 2030.

Grembek, O., Kurzhanskiy, A. A., Medury, A., Varaiya, P., & Yu, M. (2018). Introducing an Intelligent Intersection. *ITS Reports, 2018 (13)*.

Maus, Jonathan. (2016). 'Want more green? Help the transportation bureau make signals better for cycling'. *BikePortland.org*. https://bikeportland.org/2016/02/16/want-that-green-light-help-us-tell-pbot-what-works-best-171624

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*, in which an arc of lights becomes successively shorter (**Exhibit 9-8**)**,** or it can have a *digital display*, which shows the number of seconds remaining in the red period (**Exhibit 9-9** and **Exhibit 9-10**). The figurative display is more appropriate with fully actuated control in which the time remaining in the red interval is not known.

Exhibit 9-8: Wait signals in Amsterdam (left) and Portland (right), with time shown as a shrinking arc. "WACHT" is Dutch for "WAIT." Credit: Peter J. Koonce.

Exhibit 9-9: Numerical wait countdown in Amsterdam. Credit: Peter G. Furth.

Exhibit 9-10: Numerical wait countdown in Copenhagen. Credit: Mikhael Coleville Andersen.

9.5.1.4 OPERATING CONTEXT

Bicycle wait countdown signals may be an appropriate treatment at bicycle signals where 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 non-compliance 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 five seconds before bicycle signals are 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, Oregon (**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 cross street green and declines during the cross street's yellow and red clearance intervals.

9.5.2.2 BENEFITS AND IMPACTS

A 2003 international scan sponsored by the Federal Highway Administration (Fong et al., 2003) 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 the wait time was shorter, and 78% of users found the bicycle wait countdown information helpful.

However, Amsterdam officials report, based on an internal study, 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 (Sjoerd 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

9.5.3.4 OTHER CONSIDERATIONS

Where a wait countdown device is visible to waiting motorists, there is concern about whether motorists might use this information and its impact. In Amsterdam and Portland, using a shrinking arc display—or, in the case of a numeric display, halting it at the number five—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 (bicyclists) is clear.

A wait/countdown device can be smaller if it is mounted next to a bicycle signal that is near side, 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 US market. The one located in Portland was imported from Europe, and its wiring was adapted for American AC voltage and frequency.

9.5.4.2 PHASING AND TIMING

9.5.4.3 SIGNING AND STRIPING

Not applicable for this treatment.

9.5.4.4 GEOMETRIC ELEMENTS

Not applicable for this treatment.

9.5.5 **REFERENCES**

Fong, G., et al. (2003). *Signalized intersection safety in Europe* (No. FHWA-PL-03-020).

9.6 Easing Bicycle Right Turn on Red Restrictions

9.6.1 BASIC DESCRIPTION

9.6.1.1 ALTERNATIVE NAMES

Bicycle Turn on Red (BTOR).

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 only to 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 a NTOR restriction can be implemented by posting “Except Bikes”, as in **Exhibit 9-11**. For systematic application, state law can be changed to exempt bicycles from NTOR restrictions.

In New York City and on the island of Montreal, the only places in the U.S. and Canada where right turn on red is prohibited by default, spot application of an exemption could be applied using a sign such as those used in France to allow right turns on red and to allow cyclists at the top of “T” intersection to go through on red, with an obligation to yield to pedestrians.

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 in such a way that it applies only where bikes are allowed to turn right on red, or could be applied universally, thereby encompassing a universal NTOR exemption.

Exhibit 9-11: Bicycle exemption from No Turn on Red restriction, Cambridge, MA. Credit: Peter Furth.

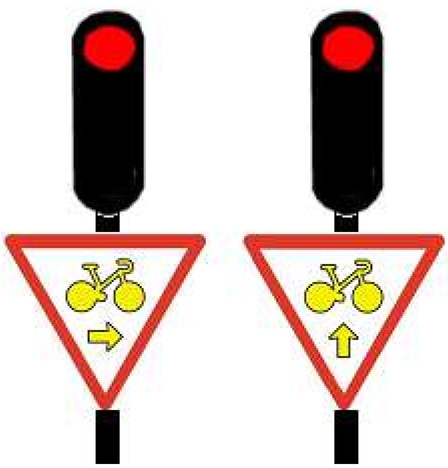


Exhibit 9-12: Signs permitting bikes to turn right on red and to go through on red (at the top of T intersection only) in France. Credit: Mieux se Déplacer à Bicyclette.

9.6.1.4 OPERATING CONTEXT

Exempting bikes from NTOR restrictions can be considered at any intersection with a NTOR restriction. It can be considered for specific locations, using signs, or universally by means of legislation.

Allowing bikes to turn right on red without stopping, but with an obligation to yield, is probably something that only be implemented statewide, through legislation. It could be limited to intersections where bicycles are already allowed, by existing laws, to turn right on red, or 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 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 general. In 2005, the law was amended reinstating 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 turning right on red.)

Posting bicycle exemptions to NTOR signage is rare. Cambridge (MA) 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 9-11**, at Broadway approaching Galileo Galiliei 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, who 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 (Patrick Baxter and Cara Seiderman, personal communication, September, 2018).

In the Netherlands, where RTOR for vehicles is almost unknown and enforcement against bicycles is stricter, bicycles may legally turn right at most signalized intersections. The most common mechanism, which applies where both intersection streets have cycle tracks (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, for the bicyclists who currently ignore those restrictions (which is often observed at intersections), easing those restrictions makes their behavior legal.

There is unlikely to be any negative safety impact from easing RTOR restrictions on bicyclists because they 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. Those reasons include turning onto high speed roads, which usually have a shoulder or bike lane into which a bicycle can turn safely; preventing turning vehicles from blocking a crosswalk while waiting to turn on red, which is not a problem for turning bicycles who usually wait beyond the crosswalk and whose ability to use bike lanes and shoulders means they rarely have to wait. This prevents collisions with crossing pedestrians, which, compared to motor vehicles, is far less likely with bicycles because of their smaller size and mass, their better lateral visibility (no A-pillar obstructing the view).

Easing RTOR restrictions on bicycles is similar to easing of restrictions at Stop signs. A study of the safety impact of the Idaho 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

9.6.3.4 OTHER CONSIDERATIONS

9.6.4 IMPLEMENTATION SUPPORT

9.6.4.1 EQUIPMENT NEEDS AND FEATURES

9.6.4.2 PHASING AND TIMING

9.6.4.3 SIGNING AND STRIPING

Not applicable for this treatment.

9.6.4.4 GEOMETRIC ELEMENTS

Not applicable for this treatment.

9.6.5 REFERENCES

Caldwell, J. et al. (2016). Policies for Pedaling: Managing the Tradeoff between Speed & Safety for Biking in Chicago. DePaul University, Chaddick Institute for Metropolitan Development.

Meggs, J. N. (2010). Bicycle Safety and Choice: Compounded Public Cobenefits of the Idaho Law Relaxing Stop Requirements for Cycling. https://bikeportland.org/wp-content/uploads/2019/06/idaho-law-jasonmeggs-2010version-2.pdf.

Wagenbuur, M. (2012). Cycling past red lights; it's often legal in the Netherlands. Blog post, bicycledutch.wordpress.com.

Chapter 10 Techniques for Multistage Crossings

This section describes treatments that might be applied in connection with multistage crossings that have not been described in previous sections:

Primary Function	Section	Treatment Name
Provide convenience and accessible crossings	10.1	Multistage Crossings – General
Reduce pedestrian delay using left turn overlaps	10.2	Left Turn Overlap for Half-Crossings
Provide safe crossings for bicycles at multistage crossings	10.3	Single-pass bicycle crossings with two-stage pedestrian crossings

Multistage Crossings – General (**Section 10.1**) addresses general themes related to pedestrian crossings, including pedestrian signalization options, accessibility considerations, and the critical importance of pedestrian progression on pedestrian delay at multistage crossings.

Left Turn Overlap for Half-Crossings (**Section 0**) is 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* (**Section 7.5**) and on *adapting minimum green 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

Elsewhere in this Guidebook, *Channelized Right Turns / Delta Islands* (**Section 0**) is a treatment that creates signalized multistage crossings if the crossing 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 Cycles* **(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),** especially in relation to partial crossings to and from delta islands.
- *Maximizing Walk Interval Length* **(Section 7.3).**
- *Pedestrian Recall versus Actuation* (**Section 7.5**), especially in relation to left turn overlaps.

In addition, *measuring pedestrian delay* (**Chapter 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. In addition, 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 (**Exhibit 10-1**).

Exhibit 10-1: Multistage Crossing Example at the Intersection of E Flamingo Road and Boulder Highway in Las Vegas, NV (Photo Credit: Google Maps).

By breaking a long crossing into parts, multistage crossings can improve pedestrian safety and comfort, and 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 one partial crossings to the next are given to pedestrians, such as by overlapping pedestrian phases with left turn phases that are not in conflict (see **Section 0**).

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.” 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 which determine the degree to which the crossing functions as a multistage versus single stage crossing:

a. *Treats it as a simple, single stage crossing, with no waiting intended in the island.* The passage through the island is treated as part of the crosswalk, and pedestrian clearance interval is based on crossing the full street. Formally, this is not a multistage crossing, and no signals or detection are 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 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 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, which 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, provide a long enough pedestrian phase 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 interval is based on the length of the half crossings and is therefore relatively short. To support a single stage crossing, the Walk interval is long and 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 wait there until the next cycle. Relative to option b, this option has less pedestrian delay, 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* (**Section 0**), crossings across the channelized turns are considered stages of a crossing if they are signalized.

It is possible to have a *two-stage crossing for pedestrians, yet a single stage crossing for bicycles*, as discussed in **Section 10.3**.

Where pedestrians have a strong desire line for a diagonal crossing but have to make it by following two "square" crossings, that can be considered as a two-stage pedestrian crossing. Techniques for multistage crossings can therefore be applied to serve such desire lines, just as they are for ***two-stage left turns for bicycles*** (**Section 9.3**), which can also be considered as 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
- Any crossing with an existing median that is 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 the partial crossings across the right turn lane unsignalized (**Section 0**)
- Where pedestrians or bicyclists have important diagonal desire line, which 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 **APPLICATION AND EXPECTED OUTCOMES**

10.1.2.1 NATIONAL AND INTERNATIONAL USE

Multistage crossings are a standard treatment both in the US and internationally. They are more common in countries such as the Netherlands where multilane roads usually have medians (because long, uninterrupted pedestrian crossings are discouraged).

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 LOS is F (*Highway Capacity Manual 2000*).

To avoid these long delays and associated safety problems, some US cities seek to avoid multistage crossings, or at least time signals to facilitate single stage crossings. For example, while before 2000 many New York City crossings of wide streets with medians were timed for two-stage crossings, they have all 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 timing signals for single stage crossings.
- Delay reductions as a result of improved pedestrian progression
- Delay reductions and safety improvements from 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 (Furth, 2015) is a free tool that can be used for this purpose.

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, with 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 60-s crossing phase and increasing the cycle length from 120 s to 150 s in peak periods. Average pedestrian delay was reduced from 144 s to 53 s. There were on average 10.0 pedestrian fatalities per year 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 single-stage crossing was implemented (New York City 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 LRT running in the middle). Pedestrian non-compliance 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. Non-compliance and friction with motorists at the start of the green largely disappeared. Impacts to motorists from the timing change were negligible.

Delay reductions from improving pedestrian progression using various techniques. 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 was recently reconfigured with a 3-stage crossing whose average pedestrian delay is 123 s. Neither the designer nor the approving agencies knew what the average pedestrian 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, with average pedestrian delay 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**).
- Using pedestrian overlaps with left turn phases (**Section 0**), a study found that average pedestrian delay at a two-stage crossing in Brookline, MA could be reduced 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 from 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 coordinate 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 30s 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 accessibility challenges with integrating accessibility features through 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 single crossings with the 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 this section.

10.1.4 **IMPLEMENTATION SUPPORT**

10.1.4.1 EQUIPMENT NEEDS AND FEATURES

Except for configuration (a) described at the start of this section, applying multistage crossings requires that crossing islands be equipped with pedestrian signals facing both direction with 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 so that pedestrians arriving at the island will 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

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, and preferably 8 ft, deep. 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 at entertainment venues, pedestrian volumes per hour are misleading; counts are needed by signal cycle, and elements should be sized for a high demand cycle.

10.1.5 **REFERENCES**

Furth, P. G., Wang, Y. D., & Santos, M. A. (2019). Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Turns: Delay Estimation and Signal Timing Techniques for Limiting Pedestrian and Bicycle Delay. Journal of Transportation Technologies, 9(04), 489.

New York City DOT (2007). Safe Streets NYC.
http://www.nyc.gov/html/dot/downloads/pdf/safetyrpt07_4.pdf

10.2 Left Turn Overlap for Pedestrian Half-Crossings

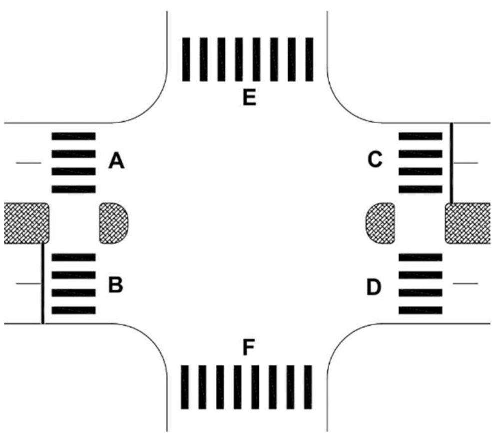
10.2.1 BASIC DESCRIPTION

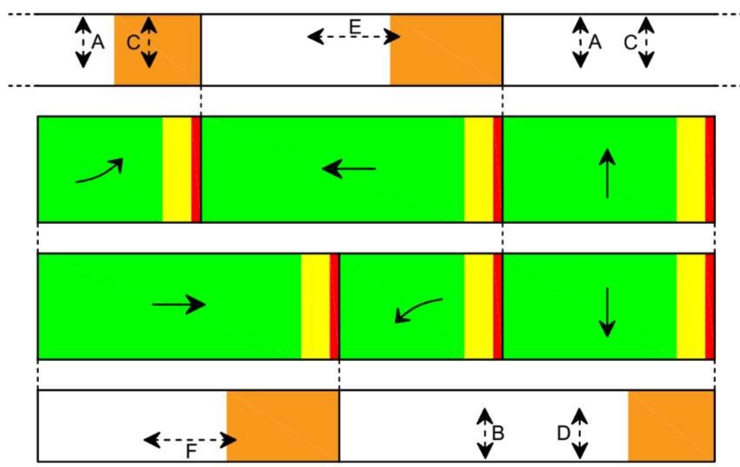
10.2.1.1 ALTERNATIVE NAMES

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**, during a phase serving eastbound and westbound left turns, crosswalks A and D could run concurrently. 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 left turn movement 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 longer 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 APPLICATION 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 in the US.

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. Often, these longer half-crossing phases 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 an intersection in the form 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; that reduces delay slightly for left turns and increases 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 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 second at the intersection studied.

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* (**Section 0**) 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

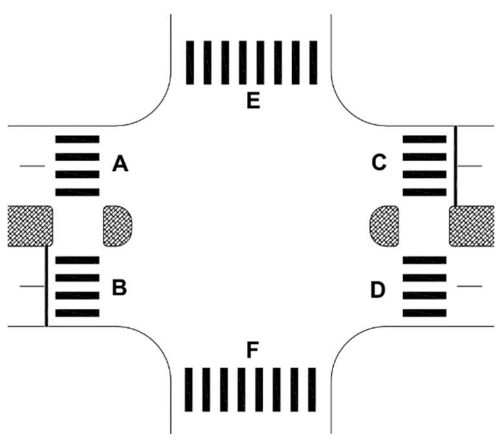
All modern controllers can support serving pedestrian phases during a left turn overlap.

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 expect the Walk interval to have a fixed length; however, with most controller software, the desired facility 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 10-3 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.



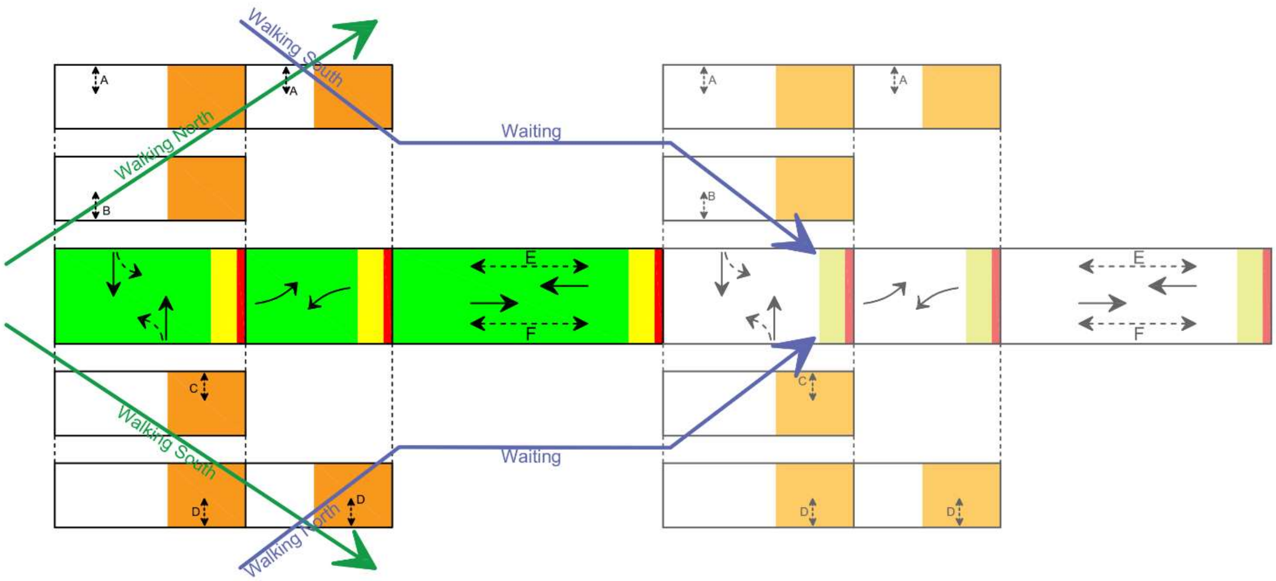


Exhibit 10-3: Phasing plan with leading lefts, which provides ideal progression for crossings B-A and C-D. From Furth et al., 2019.

With the 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 the crossing; similarly, southbound pedestrians, with crossings C and D. However, pedestrians making movement A-B and D-C cannot make a single pass crossing; their route involves waiting 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 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 instead left turn phases are lagging, as in **Exhibit 10-4**, 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. Average delay is a mirror image of the results given for leading lefts.

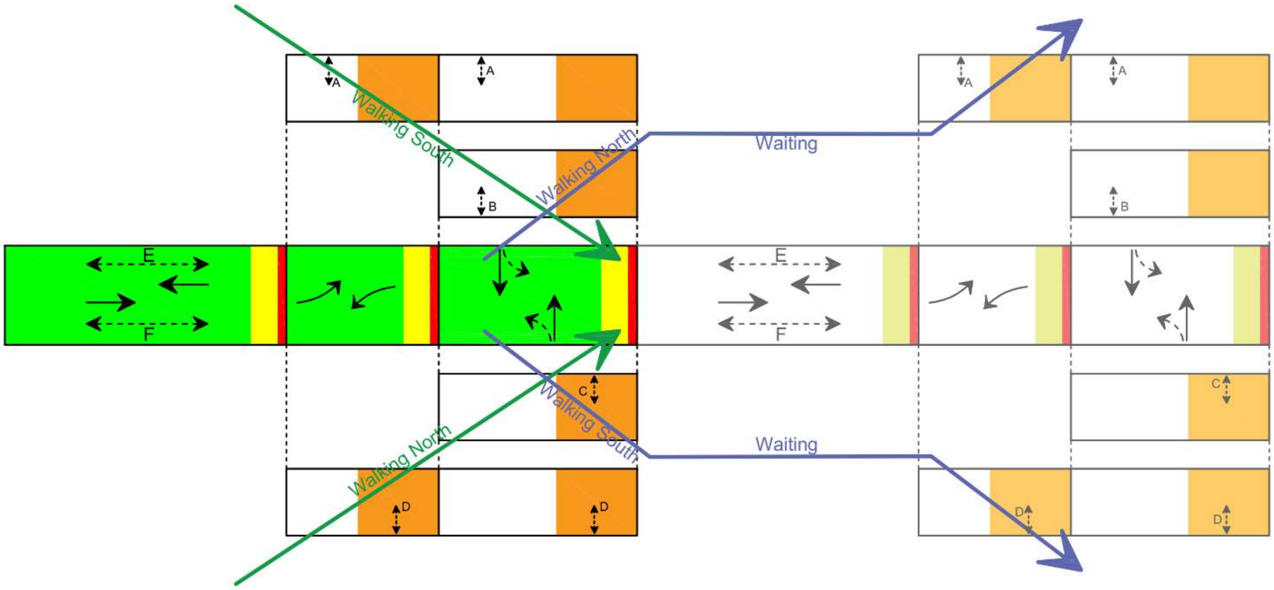


Exhibit 10-4: Phasing plan with lagging lefts, providing ideal progression for crossings A-B and D-C. From Furth et al., 2019.

And if one of the left turn phases leads while the other lags, as in **Exhibit 10-5**, both southbound crossings (A-B and C-D) get ideal progression, while northbound crossings do not have 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, 38 s for those walking northbound, which averages to 26 s.

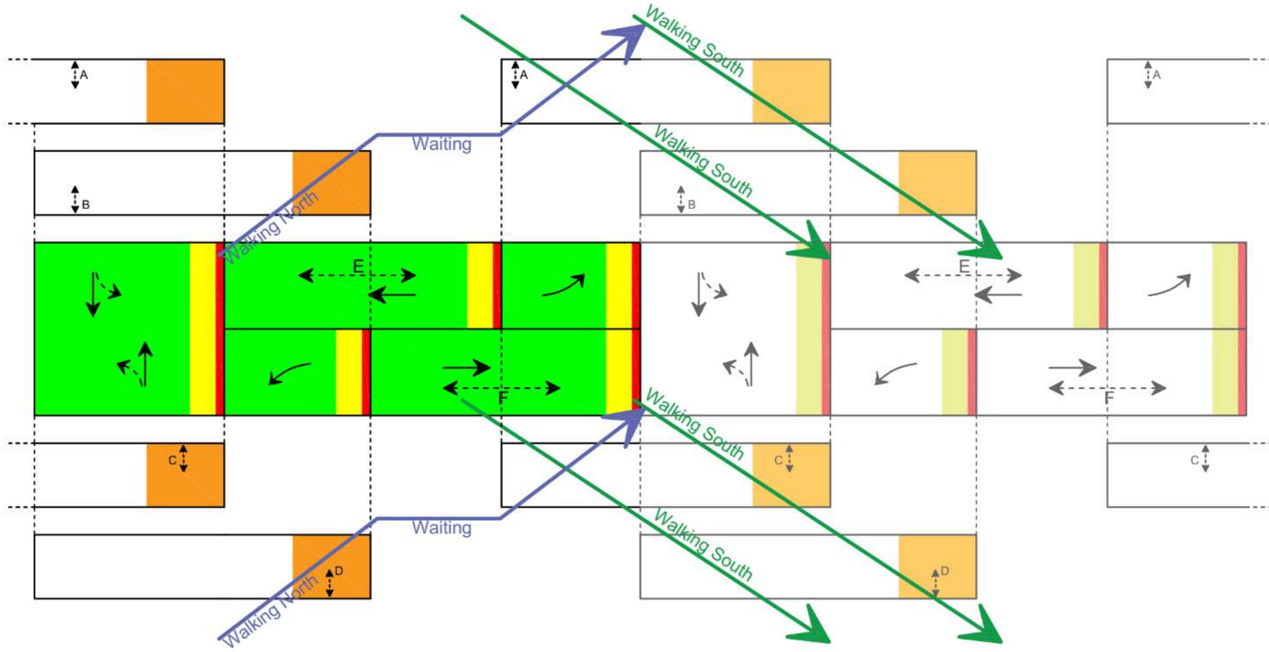


Exhibit 10-5: Phasing plan with one left leading and one lagging, providing ideal progression and a wide crossing window for crossings A-B and C-D. From Furth et al., 2019.

10.2.4.3 SIGNAGE AND STRIPING

Not applicable for this treatment.

10.2.4.4 GEOMETRIC ELEMENTS

Not applicable for this treatment.

10.2.5 **REFERENCES**

Furth, P. G., Wang, Y. D., & Santos, M. A. (2019). Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Turns: Delay Estimation and Signal Timing Techniques for Limiting Pedestrian and Bicycle Delay. *Journal of Transportation Technologies*, *9*(04), 489.

10.3 Single-Pass Bicycle Crossing 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 and 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 anywhere pedestrians have a two-stage crossing and/or the crossing island is not large enough to serve as a bicycle queuing area.

10.3.2 APPLICATION 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 Princes Beatrixlaan. Both examples use a *Left-Turn Overlap for Pedestrian Half-Crossings* (**Section 0**) in which pedestrians start crossing during a left turn phase, advancing to a median island and waiting 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 example (b), the median island is 13 ft, but the high bicycle and moped volume on this route makes it too small to be a bicycle queuing area.)

In the US, it is routine for bicycles, following vehicle signals, to cross in a single pass where pedestrians cross in two stages. In principle, it can be possible to follow the same strategy bicycles follow bicycle 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 3-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 was 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

10.3.3.2 GUIDANCE

While both the MUTCD and PROWAG 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 to provide bicyclists a short stopping zone and to provide a small offset between the bike and travel lanes. The AASHTO Guide for the Development of Bike Facilities (2012) recommends a minimum depth of 10 ft in order to support bicycles with trailers. Further guidance is needed that addresses both the depth and breadth of bicycle queueing area accounting for bicycle demand and the need to support cargo bicycles, bicycle with trailers, three-wheelers, and other large bicycles.

10.3.3.3 RELATIONSHIPS TO RELEVANT TREATMENTS

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 10-6 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).

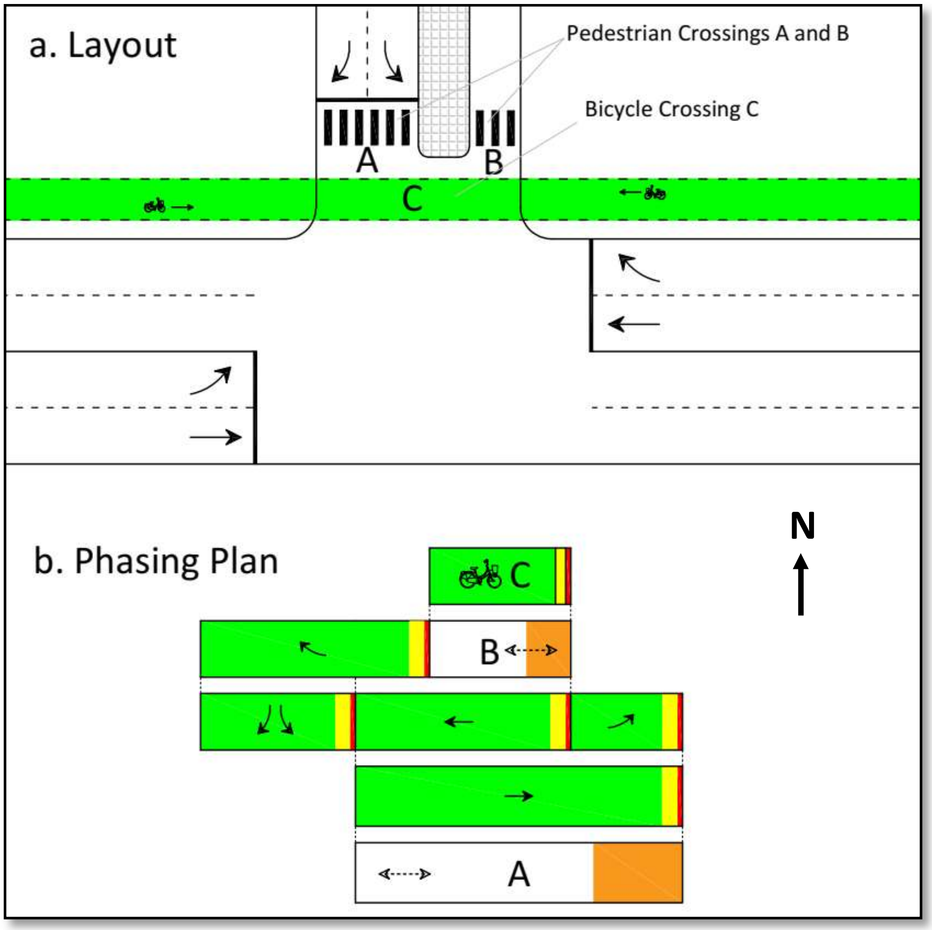


Exhibit 10-6: Intersection with a single-pass crossing for bicycles while pedestrians have a two-stage crossing. (a) Layout; (b) Phasing plan.

10.3.4.3 SIGNAGE AND STRIPING

Not applicable for this treatment.

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 at least 10 ft deep) and have a queuing area wide enough to hold the anticipated demand per cycle.

10.3.5 REFERENCES

Furth, P. G., Wang, Y. D., & Santos, M. A. (2019). Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Turns: Delay Estimation and Signal Timing Techniques for Limiting Pedestrian and Bicycle Delay. *Journal of Transportation Technologies*, *9*(04), 489.