Mitigating Right-Turn Conflict with Protected Yet Concurrent Phasing for Cycle Track and Pedestrian Crossings

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Where there are high turn volumes or speeds, pedestrian and bicycle crossings may need to be protected from right turns as well as left turns. Cycle tracks may need protected crossings even where right-turn volumes are modest. This research explores a phasing scheme in which right turns have their own phase and bike and pedestrian crossings run in their own distinct phase concurrent with the parallel vehicular through phase. This protected yet concurrent phasing scheme is more efficient than an all-pedestrian phase. A general framework for sequencing phases accounting for the right turn and crossing conflict is shown with four rings instead of the usual two. Seven examples of protected yet concurrent phasing from the United States and the Netherlands illustrate the scheme and characterize its likely impacts in terms of delay and street footprint. Overall delay and footprint impacts are found to be modest; factors that affect the impact of protected phasing include complexity of the phasing plan, coordination, and the possibility of using reservice. Because protected yet concurrent phasing makes efficient use of time, this phasing is also economical with space. Although the phasing requires right-turn lanes, its use can reduce the necessary number of through lanes, especially in comparison with all-pedestrian phasing.

Where a cycle track or bike lane runs to the right of motor traffic, there is a conflict between through-going bikes and right-turning traffic. The same conflict routinely exists between pedestrians and right turns. At a traffic signal, this conflict can either be permitted (turning vehicles see a green ball during the crossing phase and are expected to yield to bikes and pedestrians) or protected. Protected phasing can be provided either through an all-pedestrian phase (assuming bikes may use it) or by giving right turns their own signal phase, running at a different time than the crossing. In this latter scheme, the crossing phase usually runs concurrently with a parallel, nonconflicting through traffic phase; therefore it may be called protected yet concurrent phasing.

Permitted conflicts with right turns are generally considered acceptable for pedestrian crossings as long as the geometry forces right turns to be made at low speed and the right-turn volume is acceptably small. There is no national standard for "acceptably small." In Massachusetts, a state guideline is that for right-turn volumes up to 250 vehicles per hour, or about seven vehicles per cycle, conflicts between crosswalks and right turns may be permitted; beyond that, protected crossings are recommended in the form of an all-pedestrian phase.

There are no U.S. guidelines regarding right-turn conflicts with cycle track crossings. Dutch guidelines are that conflicts with up to 150 right-turning vehicles per hour are acceptable for one-way cycle tracks and that two-way cycle tracks should avoid all permitted conflicts (*1*). In Dutch practice, however, two-way cycle tracks often have permitted right-turn conflicts where turn volumes are low, along with warning signs for motorists. Permitted conflicts with left turns are always recommended against.

An alternative to protected-yet-permitted phasing is the all-pedestrian phase. All-pedestrian phases have three important drawbacks. One is that they severely reduce an intersection's capacity. Second, they lead to long cycles, resulting in long waits for motorists and pedestrians alike. Third, partly because of the long wait, pedestrians often refuse to wait for their phase and walk concurrently with parallel traffic, creating unexpected conflicts with turning vehicles.

Other treatments are also used to mitigate the bicycle and right-turn conflict. Advanced stop lines protect cyclists in the queue from conflict with right turns on a fresh green but provide no protection for cyclists arriving on a stale green. Pocket bike lanes (a bike lane between the right-turn lane and a through lane) move the conflict upstream of the intersection, where it can sometimes be resolved safely; however, many pocket bike lane configurations are stressful, particularly where high turning volumes necessitate a long right-turn lane or where intersection geometry allows right turns to be made at high speed (*2*). Raised bike and pedestrian crossings, a treatment used on several streets in Boulder, Colorado, improves the safety of permitted conflicts by reducing the speed of right-turning vehicles and reinforcing the priority of through bikes.

This paper explores the protected yet concurrent crossing treatment, with application to both bike and pedestrian crossings. The main research questions follow:

1. How does the application of this crossing treatment vary depending on what other phases are present and on arterial coordination?
2. One argument sometimes given against cycle tracks is that the protected phasing they require creates extra delay for cyclists and motorists (*3*). How much additional delay does protected yet concurrent phasing impose on pedestrians, bikes, and motor vehicles?

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Transportation Research Record: Journal of the Transportation Research Board, No. 2438, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 81–88.
DOI: 10.3141/2438-09

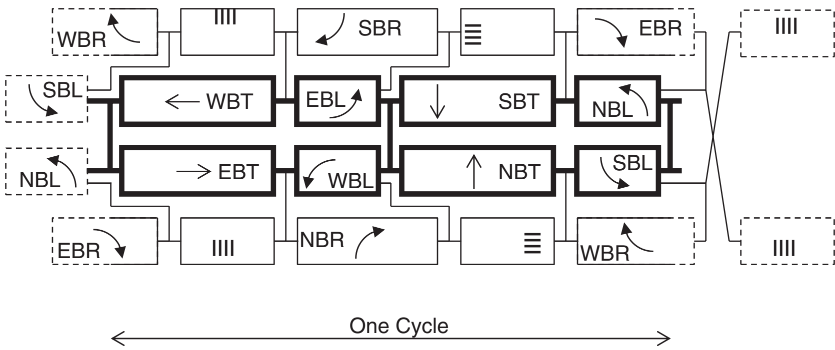


FIGURE 1 General quad-ring structure for a full set of protected yet concurrent crossings at a four-leg junction.

3. Compared with crossings with permitted conflicts or with all-pedestrian phases, how much does protected yet concurrent phasing, which requires right-turn lanes, affect road footprint?

QUAD RING FORMULATION FOR PROTECTED PHASING

Since about 1970, U.S. practice has structured signal phase sequences using a dual ring, a structure that is ideal for dealing with conflicts between through and left-turn movements. Providing separate phasing for right turns and crossings as well calls for a quad ring structure, as illustrated in Figure 1. Phases are identified by the movement they serve: eastbound (EB), westbound (WB), northbound (NB), and southbound (SB); and left (L), right (R), and through (T)—for example, NBL = northbound left. The two central rings in the diagram (drawn with heavy lines) are the standard dual rings, with the outer rings used for right-turn and crossing conflicts. The dashed lines indicate a phase that (partially) belongs to a previous or later cycle. The figure has been drawn with lagging lefts and leading rights; leading lefts and lagging rights are also possible. This control structure is common at intersections in the Netherlands, where most main roads have cycle tracks. In the United States, standard modern controllers allow for four or more rings.

As the figure shows, right-turn phases can overlap two central phases: a parallel left-turn phase from the cross street and a through phase from the same approach. Crossings are concurrent with a parallel through phase, but may begin later or end earlier than the through phase to allow more time for a conflicting right-turn phase. This ring structure has no barrier at which all phases must be red. It is also worth noting that the outer rings intertwine. In Figure 1, for example, WBR begins the cycle in the top ring but ends in the bottom ring, and EBR does the opposite.

Signal cycle length is governed by a critical conflict group, a set of mutually conflicting movements that must be served serially and require more time to be served that any other such group of movements. At most intersections, the right turns are not part of the critical conflict group, so the right-turn and crossing rings usually have some slack. Making effective use of this slack time is a key to creating efficient timing plans.

This paper examines several applications of protected yet concurrent phasing from the United States and the Netherlands. For some of the examples, because cycle tracks run along only one street or along one side of the street, the phasing sequence can be structured with fewer than four rings. The last example shows a potential quad ring application in the United States.

Example 1. Simple Right-Turn Overlap

Cyclists going southwest (labeled south in Figure 2) over the Broadway Bridge in Portland, Oregon, approach Lovejoy Street in a cycle track, where they have a conflict with a heavy right-turning movement for which the intersection angle allows higher-speed turns. The phases for the protected bike and pedestrian crossing and its conflicting right-turn movement are shown in the top ring of the figure. The phasing plan in Figure 2 characterizes signal operations before the recent expansion of streetcar service to this intersection. This example is a classic case in which the conflicting right-turn movement, SBR, can run concurrently with the cross street left turn (EBL), so that the time of the mainline through (SBT) phase can then be split between serving excess demand for SBR (if there is any) and serving bikes and pedestrians on the west side crossing. In the United States, this sort of configuration is commonly implemented with overlaps, essentially adding a third ring to the standard dual-ring structure. The SBR phase is actuated, yielding control when a gap is detected, and therefore consumes no more of the mainline through phase than is needed each cycle. That way, slack time goes to the bike crossing, helping lower cyclist delay.

Because the geometry of the conflict requires a protected crossing of Lovejoy for pedestrians, providing a protected crossing for cyclists as well imposes no additional delay on motorists. What added delay does it impose on cyclists, compared with using a pocket bike lane, which would allow them to be served during the entire SBT phase? If Δd is defined as the difference in average delay

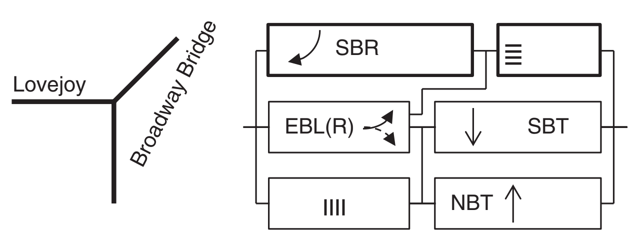


FIGURE 2 Phase sequences for Broadway Bridge at Lovejoy Street in Portland.

for bikes between operation with protected phasing versus with a pocket bike lane, then

$$\Delta d = \left[\frac{(C - g_{\text{bike}})^2}{2C} - \frac{(C - g_{\text{thru}})^2}{2C} \right] \left(\frac{1}{1 - \frac{v}{s}} \right) \quad (1)$$

where

C = cycle length;
g_{bike} and g_{thru} = effective green times for a protected bike phase and for the parallel through traffic phase, respectively; and
v/s = flow ratio for bicycles.

Example calculations assume that $v/s = 0.08$, $C = 80$ s, $g_{\text{thru}} = 44$ s, and that g_{bike} ranges from 37 s (as might happen if the right-turn movement is not much heavier than the EBL movement) to 24 s (as might happen when the right-turn movement is heavy and a pedestrian minimum governs the crossing phase). With a pocket bike lane, average bike delay is 9 s; with a cycle track and protected phasing, average bike delay is between 13 and 27 s, depending on the SBR volume. The additional delay of 4 to 16 s, depending on right-turn volume, can be considered the price cyclists pay for protection from right-turn conflicts. The price seems reasonable. When right-turn volume is low, a pocket bike lane might not be too onerous for cyclists to use, but the additional delay from protected phasing is small; substantial additional delay occurs only when right-turn volume is so heavy that pocket bike lane use would be unacceptable to most cyclists.

Example 2. One-Way Streets and Reservice

Examples of one-way streets with one-way cycle tracks positioned along the left side are 3rd Street in Long Beach, California, and 9th Avenue in New York City. The left-side position eliminates conflicts at bus stops and creates intersection conflicts with left-turning traffic that correspond to the right-turn conflict that occurs with right-side cycle tracks. Because one-way operation precludes the possibility of overlaps, protected yet concurrent phasing requires that the crossing and the conflicting left divide between them the half-cycle controlled by the mainline through movement.

A possible phasing plan is shown in Figure 3, with the mainline being WB. The lower ring shows the WB half-cycle divided between one interval for the bike and pedestrian crossing and two intervals for left turns; this phasing is similar to a conditional service operation (*4*).

Actual operation on 3rd Street at several cross streets follows a variation of this structure, in which the lagging left interval is skipped unless there is no initial call for the leading left, so left turns are never served twice in one cycle. During peak periods there is almost always a call for a leading left, and so the operation can be modeled simply as leading lefts. The additional delay to bikes compared with concurrent, unprotected phasing is about 7 s, assuming random bike arrivals, a 70-s cycle, a 40-s split for the mainline, and a 12-s average split for the conflicting turn.

If the conflicting turning movement is actuated, bike delay is minimized if the bike phase lags. That way, the slack time in the half-cycle goes to the bikes, maximizing their green. This phasing can be especially valuable where the mainline half-cycle does not have a fixed ending time. With fixed time control (as on New York's 9th Avenue), sequence does not usually affect delay. Some consider it a psychological and safety advantage to lead with the bike and pedestrian crossing because pedestrians and cyclists are eager to cross as soon as the cross street phase ends.

On 3rd Street, compared with the previous regime in which WB lefts had a permissive green during the entire mainline half-cycle, having a short protected phase increases this movement's delay considerably. The secondary (lagging) left phase helps reduce left-turn delay during light traffic periods of the day and imposes no additional delay on bikes because it is applied only when the leading left is skipped. When the mainline half-cycle is long enough, the turning movement delay could be reduced substantially by allowing both leading and lagging turn phases each cycle. This reservice tactic, illustrated in Figure 3, roughly halves the length of the red periods facing the turning movement, and therefore roughly halves the delay.

Where protected phasing would be compromised by allowing left or right turn on red, a standard response is to simply prohibit turns on red. A less restrictive treatment is to have a part-time restriction on right turn on red, using blank-out signs indicating No Turn on Red during the protected crossing while allowing right turn on red during other parts of the cycle. Portland has used this technique effectively to minimize the added delay imposed on turning traffic from protecting bicycling movements.

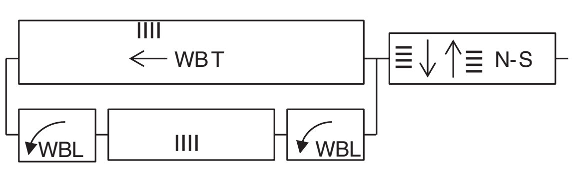


FIGURE 3 Ring structure with protected crossing for left-side cycle track and protected left turns with reservice (N-S = north–south).

Example 3. Arterial Coordination with Repeated Protected Crossings

New York's 9th Avenue is a one-way street with a left-side cycle track with protected yet concurrent crossings, with leading bike and pedestrian phases (in parallel) followed by a fixed duration lagging left. Because of the close intersection spacing and coordinated control with one-way progression, bicycles do not arrive at random, but rather arrive as they are released from upstream intersections. If signals progress at a speed greater than cyclist speed, through-going cyclists will arrive at successive intersections later and later within the green period until they arrive so late that they have to stop for a red. Using a continuous approximation and assuming a common effective bicycle green period g at all intersections, the distance x_{nonstop} that a cyclist can travel between stops is given by

$$x_{\text{nonstop}} = \frac{g}{\left(\frac{1}{u_b} - \frac{1}{u_p} \right)} \quad (2)$$

where u_b is bicycle speed and u_p is progression speed for the traffic signals (assuming $u_p > u_b$). Cyclist delay per unit distance, δ, is one red period's duration per distance x, or

$$\delta = \frac{C - g}{g} \left(\frac{1}{u_b} - \frac{1}{u_p} \right) \quad (3)$$

TABLE 1 Effect of Progression Speed on Incremental Bicycle Delay

	Progression Speed of 40 ft/s			Progression Speed of 22 ft/s		
	Bike Effective Green (s)			Bike Effective Green (s)		
Statistic	46	34	Difference	46	34	Difference
$x_{nonstop}$ (ft)	1,452	1,073	−379	4,057	2,999	−1,058
Average delay per mile (min)	2.1	3.8	1.7	0.7	1.3	0.6
Effective speed (mph)	8.5	6.8	−1.7	10.5	9.5	−1.0

Equation 3 shows that with arterial coordination, bike delay is doubly sensitive to cyclists' effective green time. Less green time means both more delay per stop (the numerator of the leading fraction) and more frequent stops (its denominator).

Some example results are given in Table 1, assuming $C = 80$ s, 46-s effective green for the mainline through movement, and $u_b =$ 12 mph. With a progression speed of 40 ft/s (about 27 mph), introducing a protected left-turn phase that shortens bike green by 12 s increases delay to through bikes by a substantial 1.7 min/mi because it shortens $x_{nonstop}$ from 1,450 to 1,070 ft. However, cyclists' need for a long green period is less important if the progression speed is closer to bike speed; as the table shows, if progression speed is lowered to 22 ft/s (about 15 mph), the same shortening of the bike green increases the delay by only 0.6 min/mi. Lower progression speed also improves safety, progression for buses, and throughput (by compressing platoons after vehicles turn). For these reasons, Portland times its downtown traffic signals with a progression speed of 13 to 16 mph, depending on time of day. San Francisco, California, also uses low progression speeds on some of its corridors as part of its green wave program (*5*).

Example 4. Coordinating Bike Phases

At Broadway and North Williams Avenue in Portland, WB bikes along Broadway face a conflict from a heavy right-turn flow from Broadway onto North Williams en route to the I-5 freeway entrance. Until 2011, bikes had a pocket lane with a right-turn lane on their right and a through–right lane on their left—not a desirable layout. A new layout in 2011 gave Broadway dual right-turn lanes and shifted the bike lane to the right curb. At the same time, protected phasing—in this case, used with a bike lane—was introduced to separate bikes from right turns.

Because the heavy right-turning demand requires a fair amount of green time, the bike phase has to be short. If bikes arrived at random, that would result in rather long delays for bikes. Instead, a coordination scheme was developed in which a bike phase was also introduced at the upstream intersection, Broadway at Victoria, so that most bikes arrive at North Williams in a platoon. Offsets between bike phases at the two intersections are such that platoon arrivals at North Williams have no delay. The phasing scheme is shown in Figure 4. A third (downstream) intersection is also included in the coordination scheme.

At Victoria, WB bikes have an overlap with NBL, giving them a leading interval relative to other WB traffic. Most bikes depart from Victoria at the start of this leading bike interval. An in-pavement bike detector at the Victoria stop bar sends a call downstream, so that the bike phase at North Williams will be started in time for a platoon released at Victoria to cross North Williams without delay. A second bike detector at the North Williams stop line calls for a bike phase for bikes that arrive when the bike signal is red. A website has simulation videos that illustrate the bike coordination (*6*).

Example 5. Alternative Phase Sequences and Reservice

A two-way cycle track runs along the west side of Princes Beatrixlaan in Rijswijk, the Netherlands, where it intersects the northside ramps

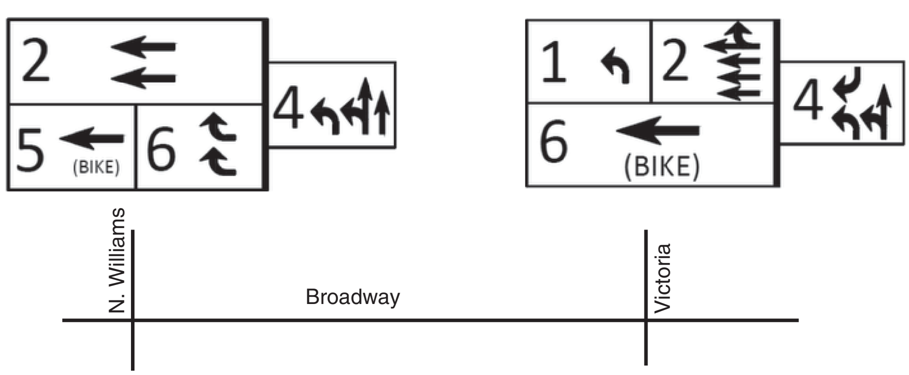
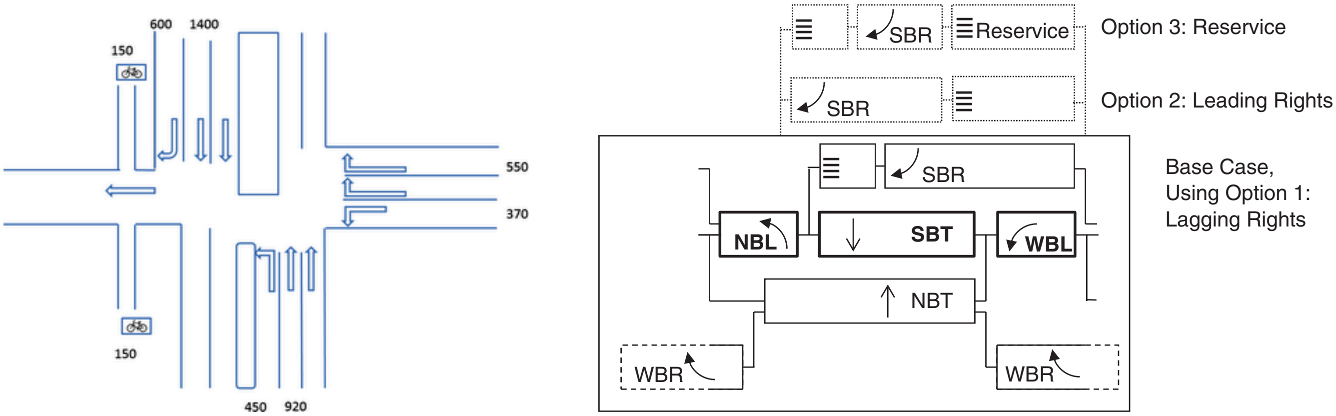


FIGURE 4 Coordinated, leading bike along Broadway at North Williams and at Victoria in Portland.



(a) (b)

FIGURE 5 Intersection layout, hourly traffic volumes, and control structures for A4 ramp junction in Rijswijk.

of the A4 motorway. This site was chosen for analysis because it has a flexible actuated and isolated control structure that allows various options to be tested. Figure 5 shows the intersection layout, the control structure, and the volumes used for simulation testing. With these volumes, the three critical phases are those in the ring beginning with NBL. The north–south street is Princes Beatrixlaan. The large box shows the base case ring structure; Options 2 and 3 represent alternative ways of sequencing the top ring.

Because the bike crossing and SBR conflict only with each other and with NBL, they divide between them the time NBL is red. This study tests three sequencing options for the bike crossing and SBR. Option 1, the base case, has a leading bike crossing. This option results in the greatest delay to bikes because they get a short green phase and a (potentially) long red. At the same time, it is most advantageous to the SBR movement, which gets all the slack time in the crossing–SBR ring.

Option 2 reverses the crossing–SBR sequence. SBR leads and, once it gaps out, yields to the bike crossing, which then enjoys all the slack time in the top ring. However, this sequence has the potential to create long queues in the SBR lane if the SBT and WBL phases run for a long time.

The third option shown is reservice, with the crossing both leading and lagging. With reservice, some green time is lost to the additional phase change, but because the bike–SBR ring is not critical, it can afford to lose some capacity to cut a long red interval in two, reducing delay. The bike reservice phase will be skipped if its start would occur after the start of WBL; otherwise the bike phase could still be timing its minimum green when WBL gaps out, delaying the start of the next signal cycle.

Simulation tests were performed with VISSIM 5.20; its ring-barrier controller was used to program signal control logic. Performance statistics are presented in Table 2. Bike delay changes as expected with the three options. Between Options 1 and 2, average delay for bikes and for SBR essentially switch places, depending on which has the favored (lagging) position. In Option 3, bike reservice, average bike delay is smallest, and SBR delay is unchanged from Option 2. Because of the bike phase's minimum green requirement, giving it a lagging position (Option 2 or 3) increases average cycle length by a few seconds, as it can be the constraining factor in switching control back to NBL to start a new cycle.

The intersection is actually run with an extended version of Option 3: the bike crossing leads, and after it, SBL and the bike crossing alternate back and forth until WBL has begun, after which no further switching is allowed. During long cycles, the bike crossing can be served in as many as three distinct intervals. This flexibility results in low delay to both bikes and SBR, and protected phases are maintained for safety.

Example 6. Footprint Impacts

Protected yet concurrent phasing requires right-turn lanes. What is its footprint impact compared with providing protecting crossings using an all-pedestrian phase or compared with not providing protected crossings?

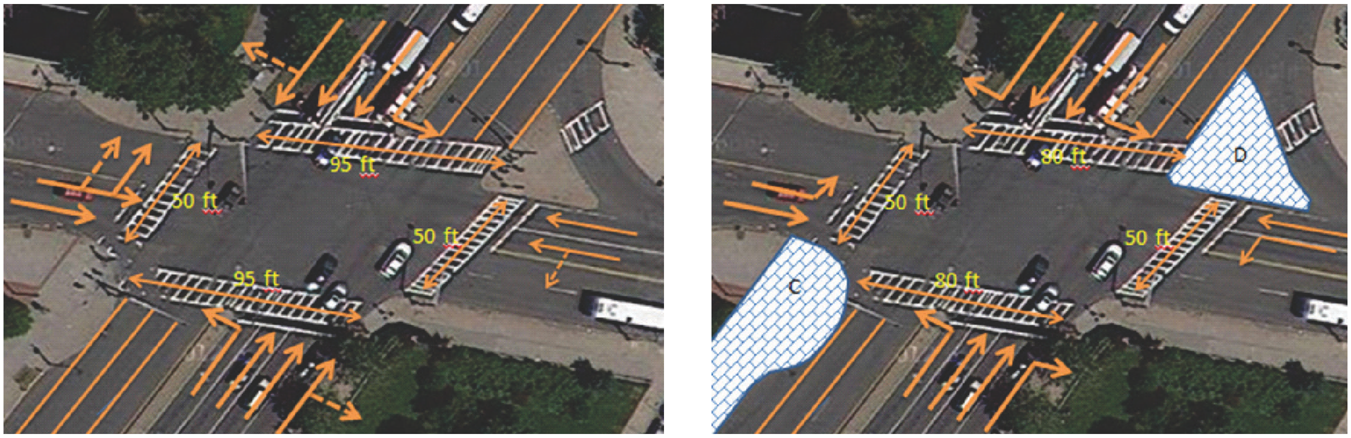
Roxbury Crossing, a busy junction in Boston, Massachusetts, that currently has an all-pedestrian phase, is one site chosen to study this impact. In the current layout, shown in Figure 6*a*, the north–south street has a left-turn lane plus three through lanes (one shared with right turns) per direction, resulting in 95-ft long crosswalks.

Evening peak volumes are shown in Figure 7. Pedestrian demand, fueled by an adjacent metro station, is strong on all crosswalks. A shared use path along the west side creates a strong bike demand across the west leg.

In the alternative layout, shown in Figure 6*b*, the curb lanes on the north–south street have been redesignated as right-turn lanes. With the number of receiving lanes per direction on the north–south

TABLE 2 Performance Statistics for Three Control Options at A4 Ramp Junction

Statistic	Leading Bikes (Option 1)	Lagging Bikes (Option 2)	Bike Reservice (Option 3)
Average bike delay (s)	21	12	7
Average delay, SBR (s)	13	20	21
Average delay, all vehicular movements (s)	14	14	15
Average cycle length (s)	55	58	60



(a) (b)

FIGURE 6 Existing and alternative layout for Roxbury Crossing in Boston.

street reduced from three to two, the length of its crossings falls from 95 ft to 80 ft.

Timing plans (fixed time) are shown in Figure 8. In the alternative with protected crossings, all left turns are protected only, unlike the current plan, which has some permitted lefts. The alternative allows a free right in the northeast corner and a permitted conflict between EBR and the south leg crosswalk because the sharp turning angle forces turning vehicles to go slowly. The alternative plan is able to meet demand with a 93-s cycle, in contrast to 135 s in the existing plan.

Table 3 summarizes the performance of existing and alternative plans as predicted with SYNCHRO, which uses standard delay formulas, and VISSIM, which measures individual vehicle delays in microsimulation. The models agree relatively well, with VISSIM predicting lower delays for the NB and SB movements in the alternative case. Depending on the model used, the alternative plan lowers average vehicular delay by 11 to 17 s and reduces pedestrian delay by 22 s. The alternative plan has a smaller footprint, shorter pedestrian crossing, substantially less delay for pedestrians and cyclists (which in turn lessens the incentive for noncompliance), and less delay for motorists.

FIGURE 7 Turning movements at Roxbury Crossing (vehicles per hour, evening peak) (st. = street; ave. = avenue; blvd. = boulevard).

A second study site was the two central intersections in the proposed Casey Arborway project in Boston. The intersections were analyzed to compare the footprint need of the base proposed operating plan, in which only one of their eight crossings is protected from right-turn conflict, with an alternative plan that provides protected-but-concurrent crossings for seven of eight crossings. (Those seven have predicted peak hour right-turning volumes exceeding 250; the eighth has a negligible right-turn volume.) The need to consider protected crossings is especially strong for the three crossings that will serve a two-way cycle track as well as pedestrians. Providing all-pedestrian phases was out of the question because of the capacity impact. Protected yet concurrent phasing was considered to be contrary to a project goal of minimizing the road footprint because it was initially imagined that doing so would require adding six right-turn lanes.

However, an analysis with SYNCHRO showed that many of the approaches would have sufficient capacity without the addition of a new lane. Instead, the curb lane could be redesignated as a right-turn lane. An important factor in capacity analysis is that with protected phasing, pedestrian blockage disappears. For the two intersections combined, providing protected yet concurrent crossings would increase the number of approach lanes by only two, from 24 to 26, which seems a small price to pay for six additional protected crossings.

CONCLUSION

Compared with crossing with permitted right-turn conflicts, protected yet concurrent phasing can offer improved safety for cyclists and pedestrians with only a small increase in delay. Factors and tactics that help limit incremental delay include the potential for right-turn overlaps; fewer phases and short cycles; and reservice (in a longer cycle) for bikes, right turns, or both. With arterial coordination, protected yet concurrent phasing adds little delay when the progression speed is close to the bike speed, but can add considerable delay when the progression speed is considerably faster than the bike speed. Coordinating bike phases can result in little delay to bikes despite short bike phases.

Because protected yet concurrent phasing makes efficient use of time, it is also economical with space. Compared with a solution

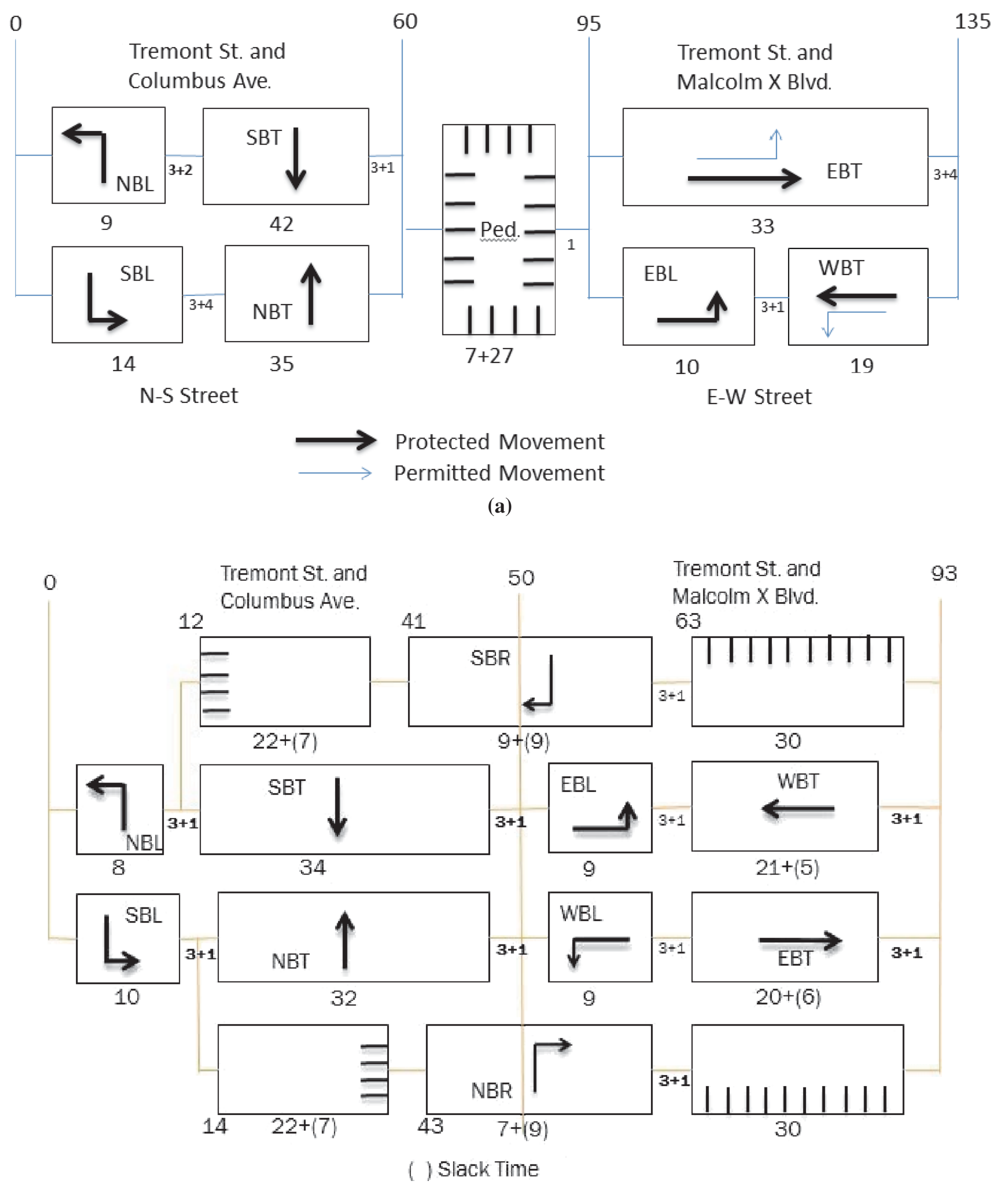


FIGURE 8 Existing and alternative timing plans for Roxbury Crossing: (*a*) existing phasing sequence and splits and (*b*) phasing sequence for the alternative layout with protected–concurrent crossing (splits indicate minimum needed to achieve a degree of saturation of 0.92, plus slack time for the noncritical phases; ped. = pedestrian).

TABLE 3 Average User Delay for Current versus Alternative Plans

	Delay (s)					
Plan	EB	WB	NB	SB	All Vehicles	All Pedestrians
SYNCHRO model						
Current	50	58	52	50	51	na
Alternative	40	35	35	47	40	na
VISSIM model						
Current	45	61	50	45	49	63
Alternative	39	32	30	32	32	41

NOTE: na = not applicable.

with an all-pedestrian phase, it provides protected crossing with a smaller roadway footprint, and compared with a solution in which crossings were not protected from right-turn conflicts, six protected crossings could be provided at the cost of only two additional approach lanes. As more American cities plan cycle tracks, making good use of protected yet concurrent phasing could be important to achieving safety and service objectives while maintaining road capacity and avoiding increased street footprints.

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The Traffic Signal Systems Committee peer-reviewed this paper.