Delay Estimation and Signal Timing Design Techniques for Multi-Stage Pedestrian Crossings and Two-Stage Bicycle Left Turns

Peter G Furth (corresponding author)
Northeastern University, room 400 SN
360 Huntington Ave
Boston, MA 02115
p.furth@neu.edu

Yue (Danny) Wang
Northeastern University, room 400 SN
360 Huntington Ave
Boston, MA 02115
wang.yue3@husky.neu.edu

For presentation at the Transportation Research Board Annual Meeting, January, 2015

Revised November 15, 2014

ABSTRACT

Signalized intersections sometimes involve multistage pedestrian crossings, in which signals direct pedestrians to cross to one or more islands and then wait there for a signal to continue. There are no widely accepted methods or tools for calculating pedestrian delay at multistage crossings, and perhaps as a consequence, traffic signals governing multistage crossings are sometimes designed in a way that results in very long pedestrian delays. This paper describes a numerical method for determining crossing delay that applies to crossings of any number of stages and multiple WALK intervals per cycle. It also covers diagonal two-stage crossings and bicycle two-stage left turns, a common way of providing for cyclist turns in Europe that American cities are beginning to adopt. This method has been implemented in the freely available Northeastern University Ped & Bike Crossing Delay Calculator. We also describe several signal control paradigms for reducing pedestrian and bike delay at intersections with multistage crossings including short cycles, pedestrian reservice, and bidirectional bicycle crossings. We also show how various lead / lag phasing sequences with pedestrian overlaps can results in good progression for selected pedestrian and bicycling movements. Examples show pedestrian delay reductions of up to 95 s.

Signalized intersections sometimes involve multistage pedestrian crossings, particularly where a wide street has to be crossed. In a multistage crossing, pedestrians cross to an island, and then wait there for a WALK signal there to resume crossing, perhaps to another island, repeating the process until the crossing is finished. Two-stage crossings are common; three- and four-stage crossings are also known.

A crossing island is almost always a welcome enhancement for pedestrians; even if they don't stop there, it lessens one's sense of exposure and offers a place of refuge in case one has to cross slowly. However, if the signal timing is such that all pedestrians are expected to pass through the island without stopping, it should still be considered at single-stage crossing. A stage is defined by the need to stop (the time dimension), not merely by the presence of an island.

While crossing islands almost always benefit pedestrians, making a crossing two-stage or multistage *in time* is usually done for the benefit of motor traffic. Pedestrians would almost always prefer to cross in a single stage. However, for long crossings, the time that would be needed for a single-stage crossing is sometimes considerably greater than what could be used effectively by concurrent traffic. The difference is essentially lost time, which increases delay to other traffic and reduces traffic capacity. Also, the much shorter clearance times associated with partial crossing phases, compared to a single-stage crossings, allows traffic signal control to be more responsive and efficient at serving motor traffic.

Regulations, such as those in the MUTCD (1), ensure that each crossing stage meets minimum safety standards; for example, they must include a minimum length WALK interval and a 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 – sometimes extremely long – delays for pedestrians. The Highway Capacity Manual (HCM) (2) has a scale by which pedestrian delay can be rated. Average delay above 60 s is considered Level of Service F, with high likelihood of pedestrian non-compliance; however, that scale can only be applied if pedestrian delay can be evaluated. And while the HCM offers a simple method for evaluating delay for single-stage crossings, it is silent on multistage crossings. Common intersection analysis software reports on delay and level of service to motorists, but is usually silent about level of service to pedestrians, and offers no means of evaluating multistage crossings.

The lack of an accepted method for evaluating pedestrian delay at multistage crossings means that where they are part of an intersection design, there is a good chance that delay to pedestrians was never estimated or considered in evaluating the design. Consequently, pedestrian delays that are well beyond acceptable norms can "sneak into" a project design. As one example, explored later in this paper, an intersection design was approved that involved a three-stage crossing. Only later was it discovered that average pedestrian delay would be 120 s, more than double the norm for a "failing" crossing.

Therefore, both designers and the public need tools for evaluating delay at multistage crossings. Public officials and citizens deserve to understand the crossing times involved in a proposed design so that they can make appropriate tradeoffs and decisions. At the same time, designers need guidance on designing multistage crossings that offer pedestrians a reasonable level of service. Sometimes designers have no choice but to use a multistage crossing solution; the challenge then is to find a design that serves pedestrians well, or at least holds pedestrian delay to a tolerable level, while satisfying traffic capacity needs.

One form of a two-stage crossing is the two-stage left turn for bicycling, also called a pedestrian-style left turn. At a two stage left turn, cyclists keep to the right on approaching the intersection. As a first stage, they cross the cross street, wait at the far corner, and then cross the street they approached on to complete their turn. Two-stage left turns have long been the norm in European countries with high levels of bicycle use. In Denmark, two-stage left turns are mandatory, since vehicular-style left turns are prohibited by law. The Netherlands has no such prohibition (some Dutch streets even have left-turn bike lanes), but its road design guidelines require provision for two-stage left turns (e.g., queuing places and bike signals) on all multilane roads. American cities have begun moving toward normalizing two-stage left turns. National guidelines have been published for two-stage queuing boxes, meaning a designated place for cyclists to wait after completing the first stage of their crossing (3). As cities seek to implement this lower-stress design, they need methods for evaluating cyclist delay and for designing intersections that help limit delay for left-turning bicycles.

The objectives, then, of this paper are (1) to describe a method for evaluating multistage crossing delay, including two-stage cyclist left turns, and (2) to identify and describe techniques, by means of several examples, for designing signal timing plans that provide good service for multistage crossings. This paper extends the state of the art by offering for the first time a method for evaluating delay for crossings of more than two stages, for multistage crossings in which one or more stages has more than one WALK interval per cycle, and for diagonal crossings involving path choice.

METHODS FOR ESTIMATING MULTISTAGE CROSSING DELAY

Delay to pedestrians at single stage crossings can be evaluated rather easily. Except where pedestrian volumes are so great that pedestrians queue up several people deep, pedestrians can be assumed to cross without regard to queuing or other interference from other pedestrians. The signal cycle can be divided into two intervals: effective ped green, in which pedestrians are allowed to start crossing, and the rest of the cycle, called effective ped red. Effective ped green consists of the WALK interval plus the first few seconds of Flashing Don't Walk (FDW). Legally, pedestrians are not supposed to begin crossing during the FDW interval, but experience indicates that most pedestrians are still willing to begin crossing a few seconds after FDW has begun. The HCM suggests 4 s as a default for this extra walk time, based on research done by Pretty in the 1970s (4).

The well-accepted formula (2) for average pedestrian delay (d_{ped}) for a single-stage crossing is

$$d_{ped} = \left(\frac{r_{ped}}{C}\right)\left(\frac{r_{ped}}{2}\right) \tag{1}$$

where C = cycle length and r_{ped} = length of effective ped red. It is based on the assumption that pedestrians are equally likely to arrive at any moment in the cycle (uniform arrivals). The first ratio is the fraction of pedestrians arriving on red, and the second is the average delay to those that do arrive on red. Those who arrive during ped green, of course, have no delay.

Apart from microsimulation software, there is no intersection analysis software we know of that estimates pedestrian delay at multistage crossings. Microsimulation estimates pedestrian delay by modeling and tracking individual pedestrians. However, using microsimulation involves considerable time and expertise, so that there is still a need for simpler tools that correspond to those used to calculate average delay and level of service for motor traffic.

With multistage crossings, it would be wrong to evaluate by simply applying equation 1 to each partial crossing and summing, because pedestrians do not arrive uniformly at any stage after the first (5). Wang and Tian (6) and Ma et. al. (7) derived the formula for delay at a two-stage crossing. Wang and Tian develop formulas for six different cases, and Ma et. al. 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. Furthermore, the logic they follow is such that complexity will greatly expand when important generalizations are considered, including three that this paper considers – crossing with three or more stages, signal timing plans in which a crossing may get more than one WALK interval per cycle, and multistage crossings in which pedestrians have a choice of which path (which sequence of crossings) to follow.

Numerical Evaluation

We propose, instead of using analytical formulas, calculating delay numerically. A signal cycle is divided into a large number of timesteps; to limit aggregation error we use small steps of 0.1 s. Pedestrians are assumed to arrive with equal likelihood during every timestep. Then for each arrival moment, a pedestrian's trajectory is traced through the crossing, waiting or walking according to the signal indication until their departure at the end of the crossing. For any given trajectory, delay is the time in the system (from arrival until departure) minus walking time. This approach is like simulation in that discrete pedestrians (one per timestep) are tracked through a crossing; however, the method is deterministic. It is readily expandable to any number of stages, any number of walk intervals per cycle, and path choice. It is computationally fast. Another valuable feature is that this method lends itself well to graphical representation, making it easy to understand, easy to check for errors, and easy to explain to the public.

We have programmed this method using MatLab as the Northeastern University Ped & Bike Crossing Delay Calculator, freely available for download (8). The Calculator allows up to four stages and up to two walk intervals per cycle for each crossing stage. It has one module for linear crossings and another for diagonal crossings that may involve path choice. Users enter information on geometry (length of each crossing, distance to the next crossing) and signal timing (start time and duration of each walk interval). The output is average delay at each stage of the crossing and overall, and a progression diagram with selected trajectories showing how pedestrians progress through the different stages.

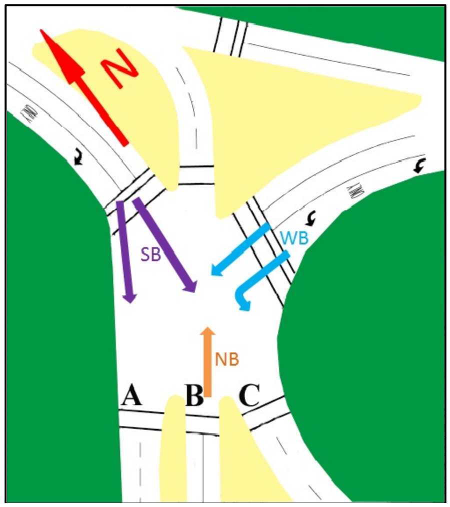
To avoid unnecessary complexity, some choices have to be made about parameters. One is pedestrian speed; we allow it to be user-set, with a default of 4.5 ft/s. We experimented with using a distribution of pedestrian speeds, but sensitivity tests showed that there was no meaningful difference in results. Another is the amount of extra time after the end of the WALK interval that belongs to the ped effective green. Again, we considered using a distribution, but chose to work with a fixed value which users may set for each stage of the crossing. The default value is 4 s.

Another issue is whether to account for pedestrian volumes. With low to moderate pedestrian volumes, queuing has no significant impact on delay, because pedestrians can spread out and advance almost as freely as they would if they were the only person crossing. Only with high crossing volumes does pedestrian queuing affect delay, and even then the effect is small. Therefore, like the HCM method for single-stage crossings that we aim to extend, we ignore pedestrian volume and the possible delays that pedestrians can impose on each other.

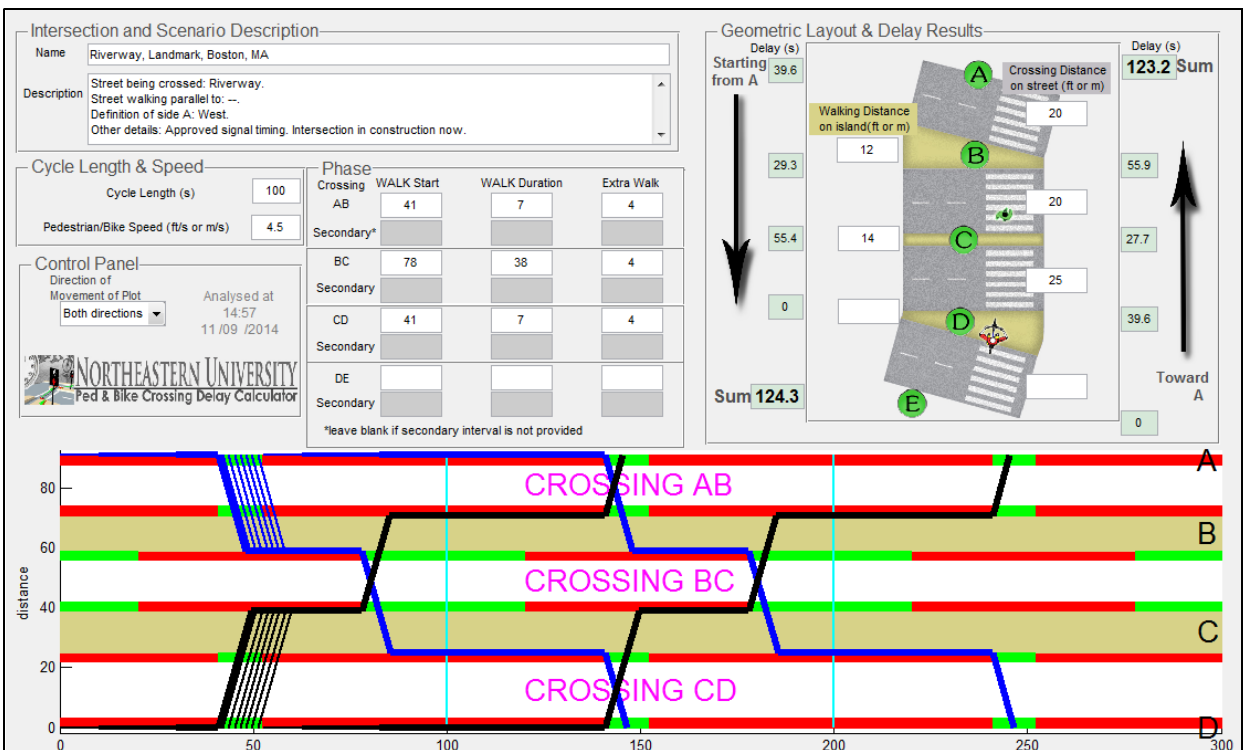
Finally, while our method, like those cited in the literature, treats cycle length and ped green time as parameters, many intersections use isolated-actuated logic in which the cycle length is not fixed, and many more use coordinated-actuated logic in which the cycle length is fixed, but the length of relevant intervals may not be. For such cases, our method (like the HCM method for single stage crossings) is approximate. For isolated actuated signals, expected values of cycle length and phase lengths can be estimated following the methods described in Furth, Cesme, and Muller (9). For coordinated-actuated signals, cycle length is fixed, but analysts may have to estimate the start time and duration of WALK intervals. During peak periods, for which evaluation is often most critical, actual operations often match nominal timings closely because all phases run to their maximum split. Where flexible control logic and actuation make the signal operation highly variable and hard to predict, microsimulation will be the only reliable way to estimate performance.

EXAMPLES WITH LINEAR MULTISTAGE CROSSING

For an example, consider the crossing of Riverway in Boston that is currently under construction shown in Figure 1. Pedestrians following an important and historic multiuse path (Olmsted's Emerald Necklace) will have a three-stage crossing. While each of the three sub-crossings involved is, in itself, compliant with governing standards for crosswalks, the crossing as a whole involves an average pedestrian delay of 124 s for pedestrians crossing eastbound and 123 s for those crossing westbound. On average, eastbound pedestrians (direction A-B-C) will wait 40 s to begin their crossing; they will cross to the first island, then wait 29 s there; then cross to the second island and wait an additional 55 s there before starting the final crossing. That such a plan could even be considered is evidence of the need for tools to evaluate and design multistage crossings.



a. Layout of Riverway crossing (currently under construction)



b. Delay calculation and progression graphics

Figure 1. Three stage crossing of Riverway, approved timing plan

Another way to express average delay is the difference between average departure time and average arrival time, minus time spent walking. If arrivals are uniform across the signal cycle, mean arrival time is simply the middle of the cycle. In many cases, mean departure time is readily calculated or comprehended. For the eastbound (A-B-C) crossing of Riverway, if the cycle start is taken to be time 52 (end of ped effective green for stage 1), mean arrival time will be 102 (because cycle length is 100s), and all peds will begin crossing stage 3 at time 241, for difference of 139 s. Subtracting 15 s for walking to the start of stage 3 (66 ft @ 4.5 ft/s) yields an average delay of 124 s.

To further confirm the calculator's logic, the two-stage crossing used as an example by Wang and Tian (5), crossing Boulder Highway along the north side of Flamingo Road in Las Vegas, was evaluated. They found the delay to be 55.8 s in each direction; our delay calculator, using the same parameters, finds the average delay to be 55.8 s eastbound and 55.9 s westbound. The 0.1 s discrepancy stems from aggregation error due to using finite timesteps.

DIAGONAL CROSSINGS WITH DIRECTIONAL CHOICE

Pedestrians crossing to a diagonally opposite corner of an intersection normally make their crossing in two stages, passing through another corner en route. Where such a movement is an important part of transportation planning – for example, for a major crossing from a railroad station – designers will be interested in calculating the delay and in seeking designs that minimize that delay.

Diagonal crossings usually involve path choice. If the corners of an intersection are labeled clockwise A-B-C-D, then a pedestrian crossing from A to C will typically have the choice of path A-B-C (clockwise) or A-D-C (counterclockwise). Where there is no choice – say, because one of the crossings is closed – a diagonal crossing can be treated as any other multistage, linear crossing. But where there is path choice, additional logic is needed.

We assume that pedestrian behavior is to identify the two feasible paths and to take whichever path offers a WALK signal first. With this assumption, there is a unique chosen path for every timestep, so that trajectories for each timestep can readily be constructed and delay calculated, as before, as (departure time – arrival time – walking time from origin to destination). The Northeastern University Ped & Bike Crossing Delay Calculator has been programmed with this logic, giving users the choice of specifying whether a diagonal crossing can be made in only clockwise, only counterclockwise, or in either direction. In the unlikely event that both paths offer WALK at the same time at the first stage, the calculator assumes that half of those facing the choice will take each path.

An example calculation is given in Figure 2 for a hypothetical intersection with 8-phase, dual ring control, leading lefts, and concurrent crossings. Relevant timing parameters are shown in the figure. As the figure shows, with path choice, average delay from corner A to corner C is 33. Another calculation (not shown) finds that if pedestrians were restricted to a single path, average delay would instead be 53 for path A-B-C and 52 s for path A-D-C.

It could be argued that for diagonal crossings, the undelayed travel time – against which control delay is calculated – should be based on the airline path between the origin and destination corners, rather than the square path that people actually walk. However, we do not accept this argument because the requirement for pedestrians to walk around, rather than directly through, intersections is inherent to roads with any significant amount of traffic, and not a product of traffic control.

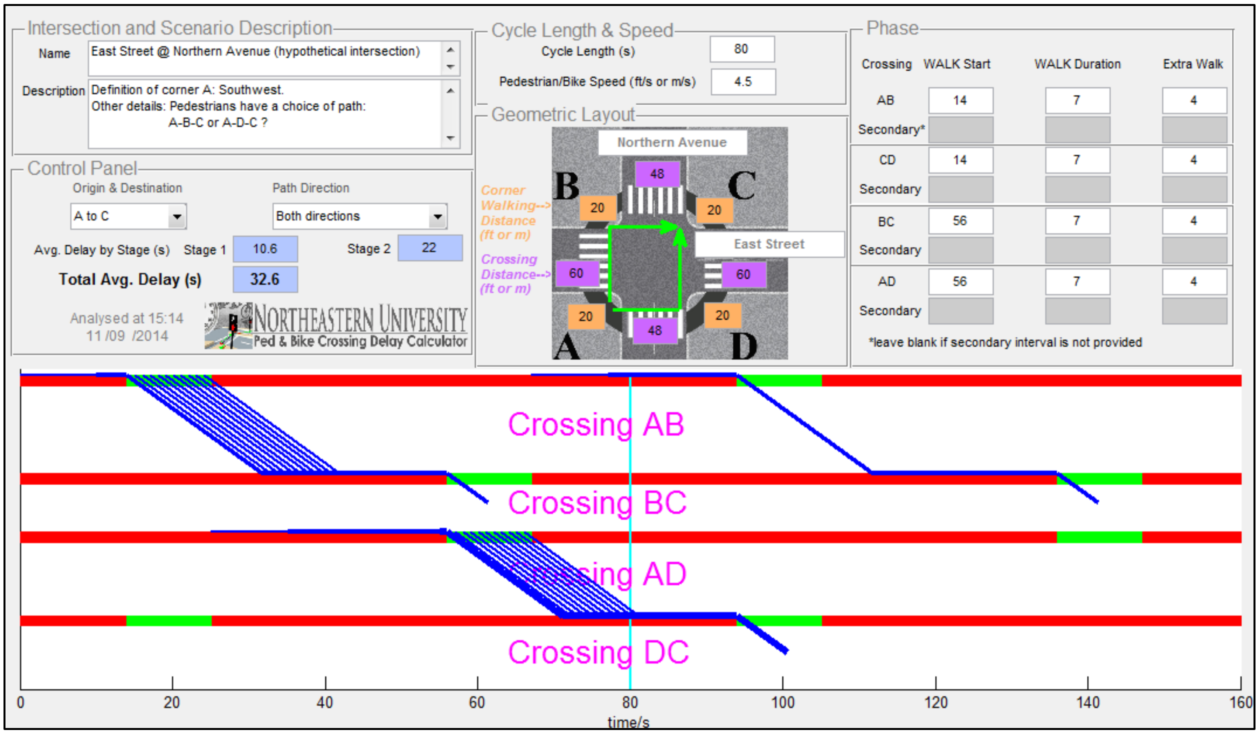


Figure 2. Delay calculation and progression graphics for diagonal crossing. Pedestrians are crossing from A to C, and are allowed to choose their path (via B or via D).

Bicyclist Two-Stage Left Turns

Where bicycle crossings are unidirectional, as is usually the case with bike lanes, a cyclist making a two-stage left turn has no path choice; the only legal path is counterclockwise. The delay for a two-stage left turn can then be calculated following the logic of a linear two-stage crossing. However, if bicycle crossing are bidirectional, cyclists can take advantage of path choice, reducing their delay. Making bike crossings bidirectional is a tactic recommended in the Dutch manual on bicycle traffic design (10).

Using the same example shown in Figure 3, the same calculations done for pedestrians making a diagonal crossing apply to bikes making a two-stage left turn, except that cyclist speed is set to 12 ft/s. If the cyclist crossings are bidirectional, their average delay from corner A to corner C will be 42 s. If instead the bicycle crossings are unidirectional, average delay from corner A to corner C will be 64 s.

It is interesting to compare these results with delay for a left-turn made in still a third way – a single-stage, vehicular left turn using the left turn lane. If overflow delay is ignored (because, facing possible overflow delay, cyclists will usually advance in the queue to ensure that they cross before the red), then, the uniform delay formula (2) may be used to estimate delay. Assuming that the left turn phase has 10 of effective green per cycle and a volume-capacity ratio of 0.8, average delay for a single-stage crossing will be 38 s, only slightly less than the delay for a two-way crossings.

SIGNAL CONTROL PARADIGMS THAT LIMIT PEDESTRIAN AND CYCLIST DELAY AT MULTI-STAGE CROSSINGS

This section will describe five paradigms for signal control by which pedestrian and cyclist delay can be reduced at multistage crossings. As stated earlier, multistage crossings are usually applied in order to reduce delay and increase capacity for motor traffic, at the expense of pedestrians. It is therefore incumbent on designers to mitigate the effect on pedestrians, adapting the multistage design so that pedestrians are served as well as possible.

Short Cycles with Offset Crossing Phases

Where signals are timed for arterial progression, cycles at some intersections can be far longer than they need to be to provide sufficient capacity. The additional delay to motor traffic from taking a signal out of coordination and offering a short cycle should be traded off against the delay reduction it offers to pedestrians who have to make a two-stage crossing. Shorter cycles mean shorter red periods and therefore less waiting time for pedestrians at their initial arrival point. If the crossing phases can be offset from one another enough that pedestrians can progress through the crossings without having to wait for the next cycle, there can also be little delay at the later stages of the crossing as well.

An example is the intersection of Opera Place, a minor street in Boston, at Huntington Avenue, a 2+2 lane road with a median reservation hosting a light rail line (see Figure 3a). The two-stage crossing of Huntington Avenue is heavily used, as the academic part of the Northeastern University campus lies on the south side of Huntington Avenue while residence halls, a dining hall, and restaurants lie on the north side. (There is also demand for crossing only half the street in order to access the light rail station in the median.)

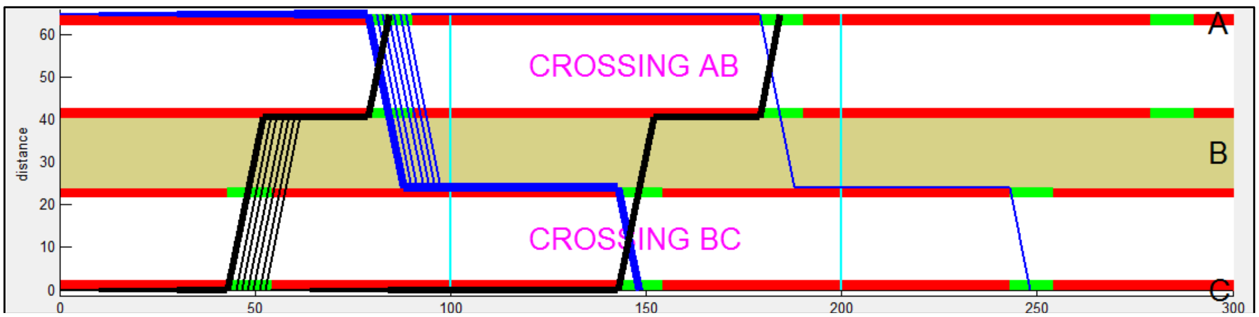
In the p.m. peak, the current cycle length, determined by traffic demands at a critical intersection half a mile away, is 100 s. Due to this long cycle and unfavorable offsets, average delay for the two-stage crossing is 94 s southbound (that includes a 54 s wait on the island) and 64 s northbound, as shown in Figure 3b. The Highway Capacity's Manual's suggestion that pedestrian compliance will be poor if average pedestrian delay exceeds 60 s is certainly borne out to any observer.

If the cycle length were reduced to 50 s, the maximum volume-capacity ratio on any approach leg would increase to only 0.8, making good level of service for motor traffic possible. With pedestrian phases for the two crossings offset relative to each other by half a cycle in order to provide good progression in both directions, average delay for the two-stage crossing falls to about 30 s for either direction (see Figure 3c). A shorter cycle length also means fewer people crossing per cycle, reducing congestion at the waiting areas.

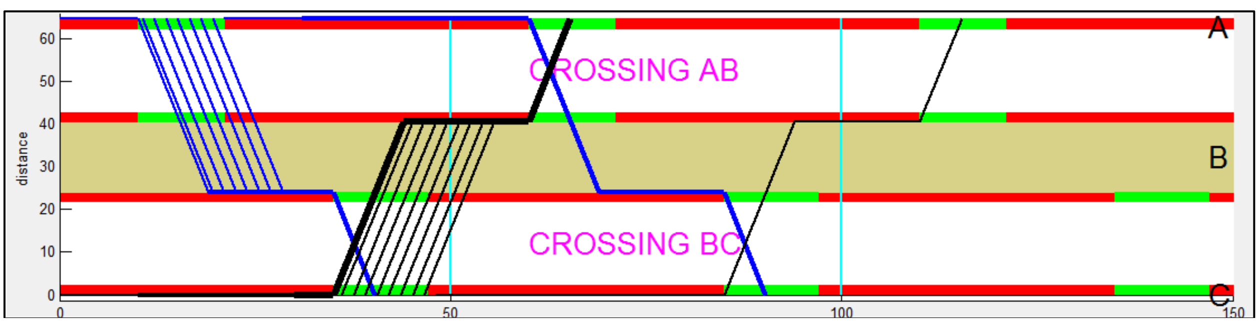
Reservice for Short Crossings

Where there are multistage crossings, often one of the crossings is a short crossing across a right turn lane. The small amount of time needed for a legal crossing interval, along with the excess capacity usually present on right turn lanes, means that it will often be possible to provide two intervals per cycle ("reservice") for the crosswalk across the right turn lane. Reservice, even for only one stage, can substantially reduce pedestrian delay facilitating good pedestrian progression in both directions. If the short crossing has one WALK interval timed to lead pedestrians into the main crossing, and the other timed to receive pedestrians coming from the main crossing, pedestrians will have excellent progression – essentially equivalent to a single-stage crossing – in both directions.

a. Layout



b. Existing timing plan and crossing trajectories

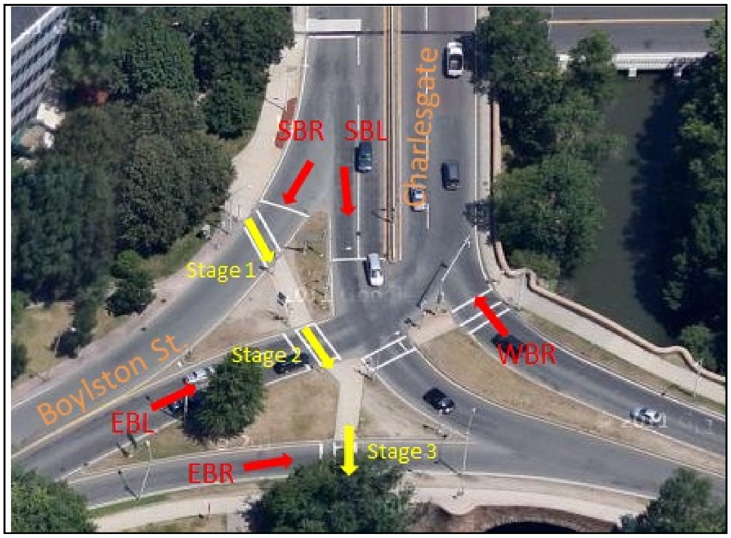


c. Proposed timing plan and crossing trajectories

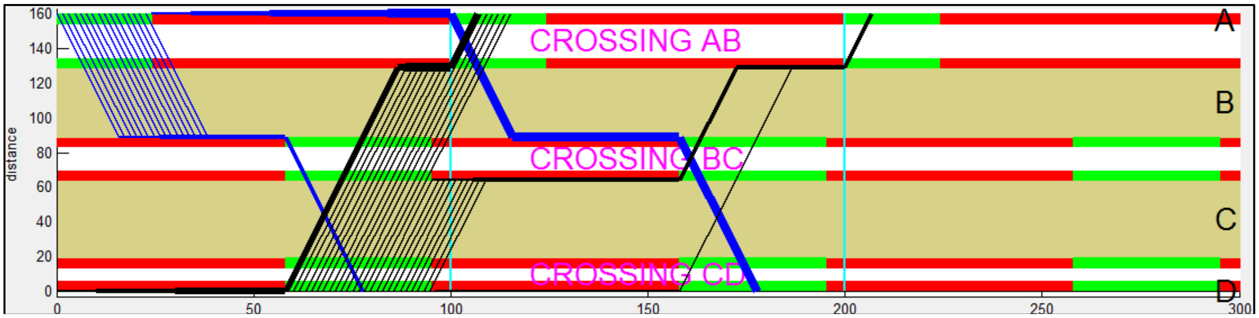
Figure 3. Shorter cycle length (50 s versus 100s) reduces pedestrian delay at a two-stage crossing, Huntington Ave @ Opera Pl, Boston

Boston's intersection of Charlesgate West with Boylston Street provides a good example of an opportunity to reduce pedestrian delay using this technique (see Figure 4). Pedestrians crossing Boylston Street along the west side of Charlesgate West face a three-stage crossing with average pedestrian delay of 68 s southbound and 41 s northbound. (The difference stems from the difference in pedestrian progression in the two directions.)

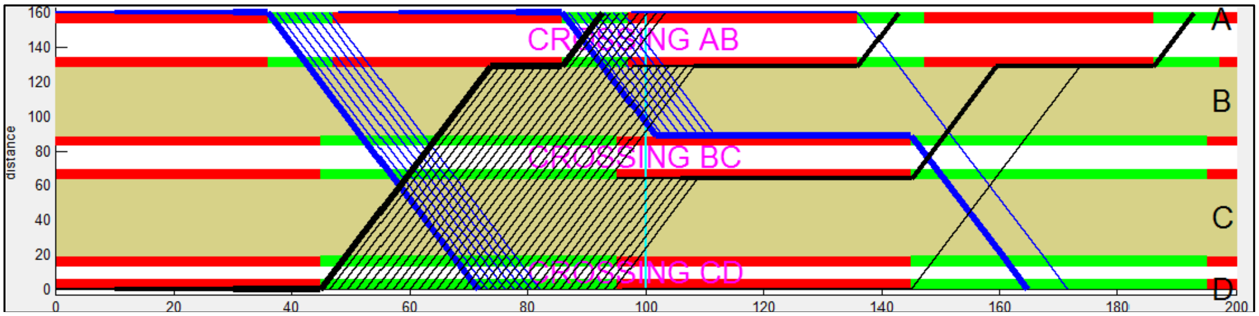
Because the right turn lane in the intersection's northwest quadrant has no conflicts except with the pedestrian crossing, it can easily afford to be stopped twice per cycle for a short crossing phase. The resulting progression offered to pedestrians lowers average pedestrian delay falls to 36 s southbound and 33 s northbound.



a. Layout,



b. Timing plan and crossing trajectories, existing



c. Timing plan and crossing trajectories, with pedestrian reservice in Stage 1 (proposed)

Figure 4: Pedestrian reservice for a one stage reduces two-stage crossing delay. Crossing Boylston Street at Charlesgate West, Boston

Lead-Lag Sequencing to Facilitate Two-Way Pedestrian Progression

At intersections with multistage crossings, some crossing stages can usually run concurrently with a left turn phase in an arrangement called an overlap. By carefully choosing how left turns are sequenced –

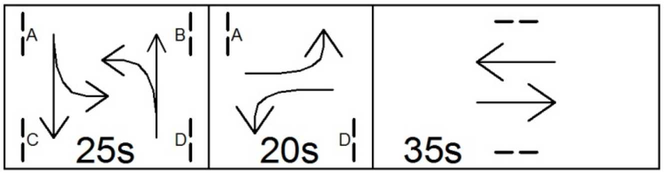
leading or lagging – and allowing pedestrian phases to overlap, interesting progression opportunities for multistage crossings can be created.

Consider as an example the intersection of Beacon Street in Brookline, MA with St. Paul Street. Beacon has a wide median hosting a light rail line that necessitates a two-stage crossing; it also has separate left turn phases. St. Paul is a relatively narrow street served with a single phase. Figure 5 shows the four possible ways of sequencing the Beacon Street left turn phases; it also shows splits for an 80 s cycle. When both lefts are leading (a), overlaps effectively extend the Beacon Street crossings for northbound pedestrians crossing on the west side, and for southbound pedestrians crossing on the east side. The resulting progression makes a single-stage crossing possible for the pedestrian movements shown in (b), which can be summarized this way: low-delay crossings if you walk along the left side of the street. When both lefts are lagging (c), the pedestrian movements shown in (d) can effectively be done in one stage (low-delay crossings if you walk along the right side of the street). Average delay for the two-stage crossings are between 27 and 30 s for the side of the street with progression (there are slight differences due to varying crossing distances) and 56 to 62 s for the side without.

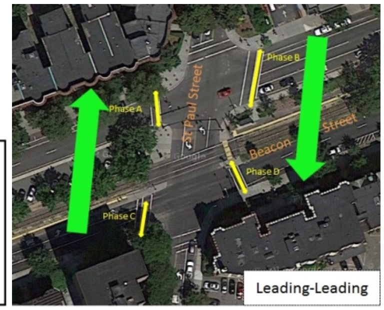
When the eastbound left turn leads and the westbound left turn lags, as in (e), both northbound crossings get good progression (f), while when eastbound left lags and westbound left leads (which is how the intersection is configured today), both sides of St. Paul get good progression southbound. Because lead-lag phasing with pedestrian overlaps allows far longer WALK intervals, average delay with a full complement of overlaps will be only about 14 s on the sides of the street with progression and about 38 s on those without. The final case, lag-lead, has similar results, but with northbound favored. Note that the far longer WALK intervals in this case mean that the delay in the non-favored direction compares well with the delay in the non-favored direction for lead-lead and lead-lag phasing.

Where phasing sequence favors pedestrians walking along a particular side of the street, an interesting question then is whether to provide that information to pedestrians, or to let them discover it for themselves.

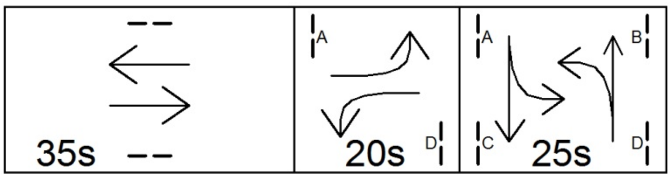
To ensure the full level of pedestrian progression described in this section, left turn phase splits must be at least as great as the pedestrian clearance interval for the overlapping crossing stage, and must not be skipped. Giving left turn phases a pedestrian-based minimum green and keeping them from being skipped is at variance with common practice in which left turn phases are only brought up when a call is detected, and end as soon as they gap out. Further research might be conducted to see what impact such a policy would have on motorist delay. (At this intersection, motorist impacts during peak periods are likely to be small, since the left turn phases always have considerable demand.)



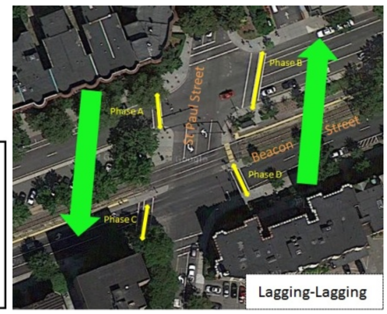
a. Lead-lead



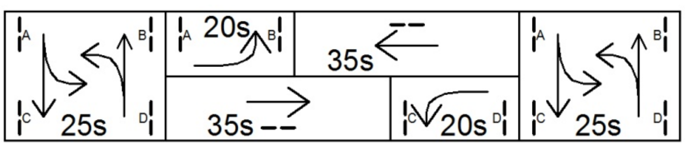
b. Movements with progression (lead-lead)



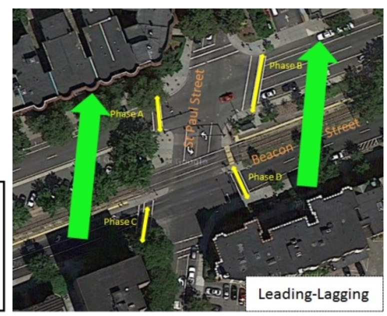
c. Lag-lag



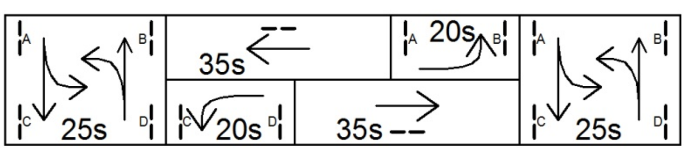
d. Movements with progression (lag-lag)



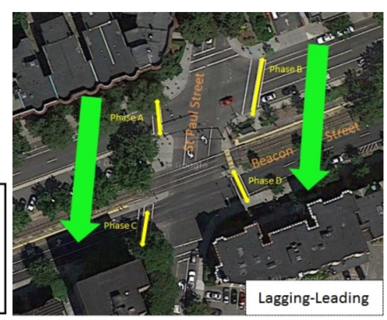
e. Lead-lag (Eastbound leads, westbound lags)
(ring diagram shows 1 ½ cycles)



f. Movements with progression, lead-lag



g. Lag-lead (Eastbound lags, westbound leads)
(ring diagram shows 1 ½ cycles)



h. Movements with progression, lag-lead

Figure 5: Sequencing left turn phases to enable single-stage crossings for some movements.

Lead-Lag Sequencing to Facilitate Two-Stage Cyclist Left Turns

Intersections with a full set of left turn phases often have long cycles, which can lead to long delays for cyclists making two-stage left turns. One way to mitigate that is to have good progression between the phases involved in the two-stage turn. This technique, recommended in the Dutch design guide (10) and often applied in the Netherlands, is being considered in Portland, Oregon.

Providing good progression for one or two dominant left turn movements is not difficult. Because the phases used by bikes are the through phases serving the arrival leg and departure leg, good progression is provided by making the *first leg through movement lag while the second leg through movement leads*. For example, consider the left turn whose legs, in order, are EBT-NBT (EBT stands for eastbound through, NBT for northbound through, and so forth). If EBT is lagging while NBT is leading, the second stage of the left turn will immediately follow the first.

With this technique, it is possible to provide good progression for both of the left turns that originate from the same street. For example, if EBT and WBT are both lagging while NBT and SBT are both leading, not only EBT-NBT but also WBT-SBT will be two-stage left turns with good progression. Offering good progression only to the left turns that originate on the same street can be a fine strategy if they are the dominant left turns, as is the case with many skew intersections.

However, if all four left turns are of concern, it turns out that the phase sequence that leads to good progression for left turns from one street leads to poor progression for left turns made from the other street. Continuing the previous example, the left turn whose legs are NBT-WBT involves first a movement that is leading, followed by one that is lagging. That means they won't directly follow one another; between them will be two left turn phases, resulting in poor progression and long delay. The fourth left turn (SBT-EBT) will suffer the same fate.

However, if bicycle crossings are bidirectional, it is possible to have good progression for all four two-stage left turns, as shown in Figure 6. The left turns from the east-west street have good progression (first leg lags, second leg leads) if cyclists move counterclockwise around the intersection, and the left turns from the north-south street have good progression if cyclists move clockwise around the intersection.

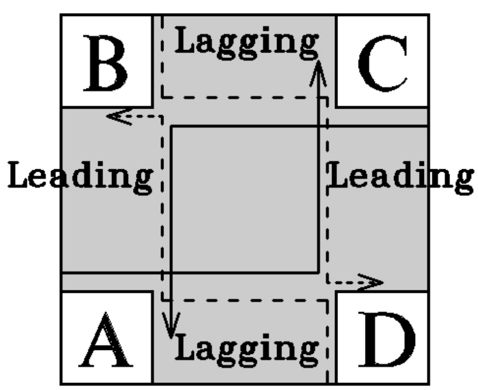


Figure 6: By having some through phases lead while others lag and providing bidirectional bicycle crossings, all four two-stage bicycle left turns get good progression (first leg lags, second leg leads)

Single Stage Crossing for Bikes with Multi-Stage Crossing for Pedestrians

Because bikes go faster than pedestrians, it should usually be possible to provide through cyclists with a one-stage crossing, even where pedestrians have a multi-stage crossing. In the Netherlands, through cyclists always have a one-stage crossing unless the median is at least 10 m wide. It is common there to see a green pedestrian signal at the same time the bike signal is red, meaning pedestrians are allowed to cross to a median island while cyclists are directed to wait until they can make a one-stage crossing. This is a primarily a matter of space –median islands are usually large enough to hold several pedestrians, but if several cyclists tried to queue up on the median island, they might spill back into the street.

Returning to the example of the Riverway crossing (Figure 1), while it would probably consume too much intersection capacity to provide a one-stage pedestrian crossing across all three roadway segments, we show below (Figure 7) how drastically bicycle and pedestrian service can be improved by deliberately fashioning a timing plan with a single-stage bike crossing and good progression for the pedestrian crossing. The proposed change is stopping traffic at crosswalks A and C for an additional 15 s interval coinciding the crosswalk B's WALK interval, resulting in a single-stage crossing for bikes and good progression for pedestrians. With this modification, average delay for cyclists is reduced by 95 s (from 133 to 38 s), and pedestrians get an average delay reduction of 79 s (from 123 to 44 s).

We were unable to estimate the impact on motor traffic because we lacked data on traffic volumes (and they cannot be counted because they are projections for a future condition). This modification is therefore only a suggestion of what might be done in keeping with the principle that a signalization design that favors motor traffic by forcing pedestrians to have a multi-stage crossing should mitigate that by offering pedestrians a timing plan with good progression and tolerable delay.

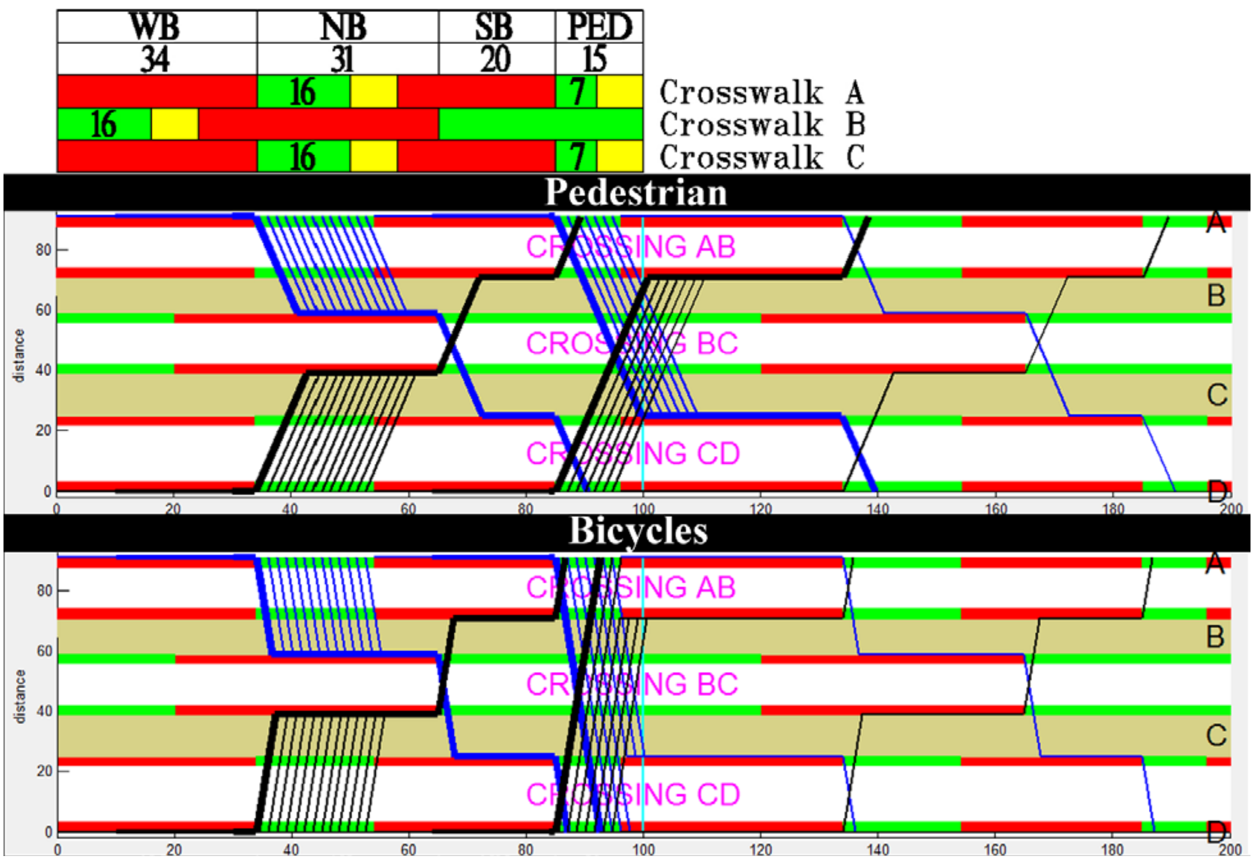


Figure 7: Crossing trajectories if a second walk phase for Crosswalks A and C is added

CONCLUSION

The lack of existing methods for calculating pedestrian delay at multistage crossings means that signal timing plans are sometimes developed that lead to very long pedestrian delays. We have demonstrated the feasibility of using a simple numerical method for calculation multistage pedestrian delay, and introduced a software tool that can be used for that purpose. If pedestrian delay is estimated and reported as part of the analysis that goes into intersection designs involving multistage crossings, it is likely that more attention will be given to reducing pedestrian delay.

One special form of a multistage crossing is a two-stage left turn made by cyclists. Among bicycle planners, some concern that two-stage turns, good as they are at eliminating the need for cyclists to weave through traffic, may impose an unacceptable burden of delay on cyclists. However, until now there has been no method that we know of for estimating delay for two-stage left turns. We show how that delay can be substantially reduced by providing bidirectional bike crossings.

At intersections with multistage crossings, there are several design paradigms that can be followed to help limit pedestrian and bike delay. Several such paradigms are presented with examples showing substantial delay reductions. Examples are also presented in which average delay for two-stage crossings is only 30 s or even 14 s.

REFERENCES

1. FHWA. *Manual on Uniform Traffic Control Devices.* Washington, D.C. 2009.
2. *Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 2000.
3. *Urban Bikeway Design Guide.* National Association of City Transportation Officials, New York, 2011.
4. Pretty, R. The Delay to Pedestrians and Vehicles at Signalized Intersections. *ITE Journal*, May 1979, pp. 20–23.
5. 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.
6. Wang, Xuan and Zong Tian. Pedestrian Delay at Signalized Intersections with a Two-Stage Crossing Design. *Transportation Research Record* 2173, 2010, pp. 133-138.
7. 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.
8. Northeastern University Ped & Bike Crossing Delay Calculator. http://www.northeastern.edu/peter.furth/delaycalculator/
9. 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.
10. *Design manual for bicycle traffic*. CROW, Ede, Netherlands, 2007.