Barrier-Free Ring Structures and Pedestrian Overlaps in Signalized Intersection Control

Peter G. Furth, Theo H. J. Muller, Maria Salomons, Tomas A. Bertulis, and Peter J. Koonce

Compared with the ring-barrier framework used for ring structures (or phasing plans) in signalized control of intersections in the United States, the Dutch framework has no explicit barriers, but only a requirement to respect pairwise conflicts. This paper describes how ring structures can be modeled with pairwise conflicts as a starting point. Modeling techniques were extended to account for offset constraints such as leading pedestrian intervals in which the start or end of one traffic movement was constrained by the start or end of another one that was otherwise compatible. One practical drawback of the more flexible Dutch framework is that it permits so many more possible ring structures that it can be prohibitive to evaluate them all manually. Therefore, this paper describes VRIGEN, an automated method that overcomes this drawback by identifying and evaluating all possible ring structures. Finally, this paper presents several examples in which barrier-free ring designs allow signals to cycle more quickly and efficiently, with improvements in safety and delay for pedestrians and bicyclists. Most of these examples feature pedestrian phases that are allowed to overlap while their parent vehicular phases are not.

At signalized intersections, each traffic movement has its own need for time that is based on traffic demands and clearance needs. Movements that are in conflict with one another must run serially, while those that are compatible with one another may run in parallel. Within these constraints, a ring structure or phasing plan can be designed in many ways (i.e., the sequence and parallelism between traffic movements). Efficient structures take advantage of parallelism by serving multiple movements simultaneously; efficient structures also seek to minimize clearance time and, for actuated signals, maximize flexibility for handling fluctuating demand.

This paper compares the barrier-free approach to ring structure design used in the Netherlands with the ring-barrier framework commonly used in the United States, with three main contributions. One is to provide examples of how the barrier-free approach can lead to more efficient ring structures; most of those examples involve pedestrian overlaps. A second is to show how offset constraints such as leading pedestrian intervals can be incorporated into an activity network model of a signal cycle. A third is to describe a software tool that automatically identifies and evaluates all possible ring structures, a process that until now has been done manually (and not usually exhaustively). The hypothesis here is that the combination of a more flexible framework and a tool for taking better advantage of it should sometimes make possible the finding of more efficient ring structures, particularly at intersections that are complex or have critical pedestrian, bicycle, or transit phases.

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RING STRUCTURES WITH AND WITHOUT BARRIERS

Figure 1*a* shows a standard four-leg, 12-movement intersection with the movements numbered according to the Dutch coding scheme (clockwise beginning with westbound right). Coding movements that are based on their physical position in the intersection rather than on their expected position in a ring structure (the American coding scheme) lend themselves to greater flexibility when different sequences are tested.

In the United States, cycle structures usually follow a framework of rings and barriers (*1*), as illustrated in Figure 1*b.* Having two or more rings allows compatible movements to run in parallel. Within a ring, conflicting movements follow one another in series. At barriers, all traffic movements on one side of the barrier must end before the movements on the other side may begin, with provision for exceptions through the use of overlaps. Phases are numbered according to their sequence, with Phases 1 to 4 in the upper ring and Phases 5 to 8 in the lower ring.

The ring-barrier model is a powerful simplification well suited to common intersection configurations. However, it can also be constraining, as when a movement on one side of a barrier is in conflict with some, but not all, of the movements on the other side. In Dutch signal cycle design, there are no explicit barriers; the only requirement is that all conflicts be respected.

Figure 2 shows the layout of the intersection of Beacon Street with Park Drive in Boston, Massachusetts, in a possible future configuration with the west-side legs reduced to two lanes each. Five vehicular phases (2, 3, 8, 5, and 11, following the Dutch numbering scheme) are shown in the ring diagrams; the right- and left-turn movements not shown are treated as part of a through movement, with permitted conflicts. The four pedestrian movements (32, 34,

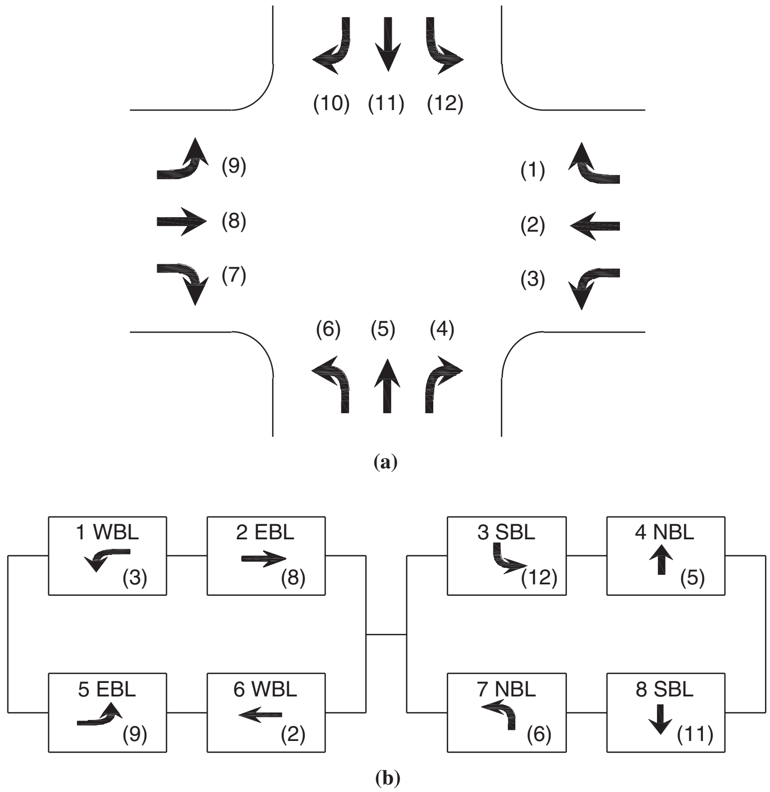

FIGURE 1 Ring-barrier structure with Dutch and American numbering schemes: (*a*) traffic movements with Dutch numbering scheme and (*b*) dual-ring structure with right turns as part of through movements (American numbering, with Dutch numbering given in parentheses at lower right; WBL = westbound left; EBL = eastbound left; SBL = southbound left; NBL = northbound left).

36, and 38) are modeled explicitly because their long crossing distances can make them critical in the signal cycle. Figure 2*a* shows afternoon peak-hour volumes and minimum pedestrian splits (walk interval plus clearance). Also included is a leading pedestrian interval (LPI), such that Movement 8 may not begin until at least 5 s after Movement 34 begins. Figure 2*b* shows the most efficient ring-barrier structure, which neatly divides the cycle into a time for the east–west street and a time for the north–south street. Figure 2*c* shows a barrier-free ring structure, which allows pedestrian phases from different streets to overlap because pedestrian phases do not conflict with one another. A simulation study described later shows how the barrier-free structure improves efficiency with a shorter cycle and less delay.

MODELING SIGNAL CYCLES

Time Requirements

In accordance with conventional practice (*2*), each vehicular movement i is modeled as having an arriving volume v_i and a maximum discharge or saturation flow rate s_i. For now, a cycle of fixed length C is assumed. A movement's split (green plus yellow) is modeled partly as lost time of length L_i, during which no discharge occurs, and the remainder as effective green of length g_i, during which queued vehicles depart at the saturation flow rate:

$$\text{split}_i = g_i + L_i \tag{1}$$

Vehicular movements typically have 3 to 5 s of lost time that account for start-up delay and not fully utilizing the yellow time. In many European countries, including the Netherlands, clearance time clear_{ij} is specified for each conflict pair i–j. It represents the time required from the end of Movement i's yellow until the start of Movement j's green and is determined as the difference between the time needed for a Movement i vehicle to pass the i–j conflict area and the time needed for a Movement j vehicle to reach that conflict area. Pairwise-specified clearance time cannot be counted as part of a stream's split. In American practice, all-red clearance periods are not specified pairwise but are applied to the exiting movement only. That exiting movement must be completed before any conflicting movement may begin. These one-sided clearance times are included in the yellow time, in which case $\text{clear}_{ij} = 0$.

For a given cycle length and green time, a vehicular movement's capacity is $s_i(g_i/C)$ and its degree of saturation X_i is the ratio of its arrival volume to its capacity:

$$X_i = \frac{\left(\frac{v}{s}\right)_i}{\left(\frac{g_i}{C}\right)}$$

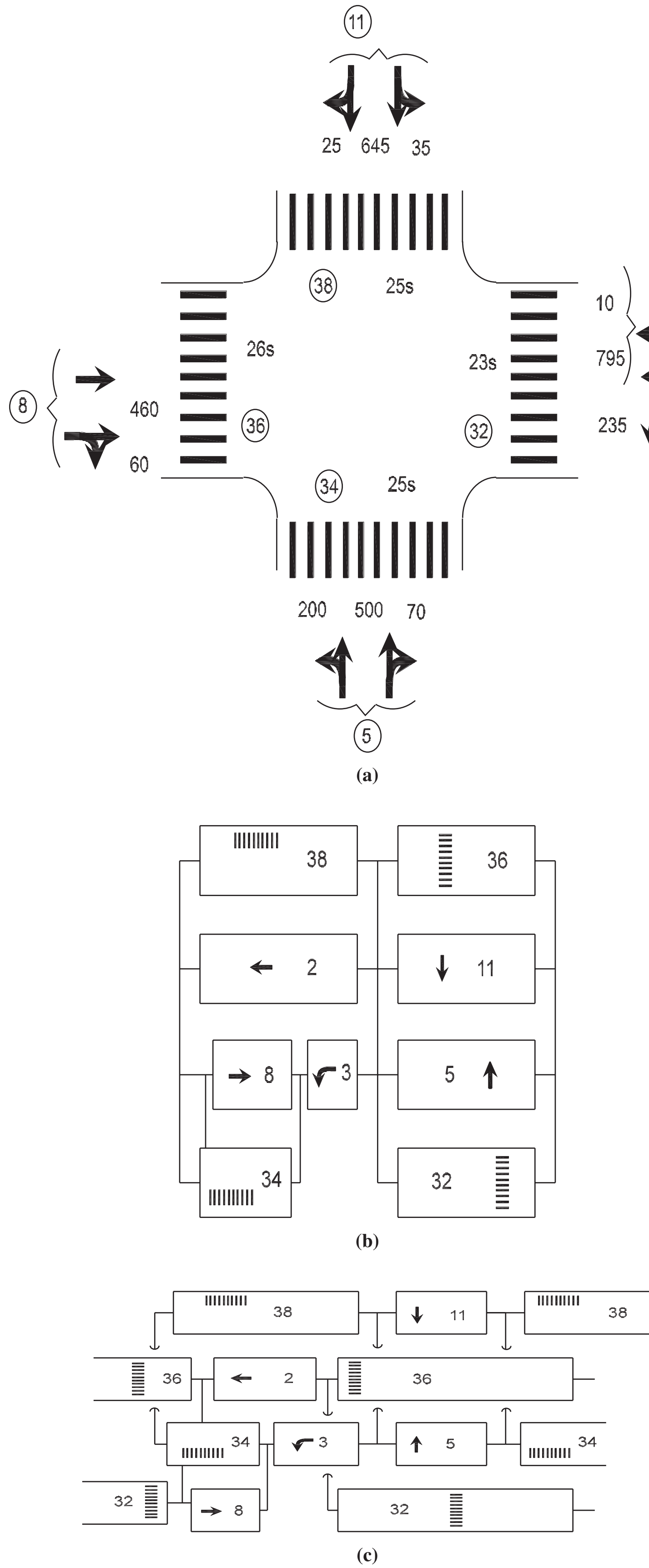

FIGURE 2 Ring diagrams with and without barrier constraint (Beacon Street at Park Drive): (*a*) movements, volumes (vehicles per hour), and minimum split for crosswalks; (*b*) barrier-constrained ring structure; and (*c*) barrier-free structure.

A degree of saturation less than 1 indicates some spare capacity, which in a fixed-time cycle helps limit the chance of overflow as demand fluctuates from cycle to cycle. Designers can specify a target degree of saturation $X_{\text{target},i}$ that should not be exceeded. Accounting for lost time as well, a movement's need for split becomes

$$\text{split}_i \geq C \frac{\left(\frac{v}{s}\right)_i}{X_{\text{target},i}} + L_i \tag{2}$$

Let minsplit_i, the minimum split needed by movement *i,* equal the right-hand side of Equation 2.

The needed split for pedestrian movements is fixed and consists of a minimum walk window of length W_i [7 s according to the *Manual on Uniform Traffic Control Devices* (*3*)] plus clearance time pedclear_i, which is crosswalk length divided by a standard pedestrian speed [3.5 ft/s (*3*)]. A pedestrian movement's need can therefore be modeled by using Equation 2 by specifying the following for crosswalks:

$$L_i = W_i + \text{pedclear}_i \tag{3}$$

$$\left(\frac{v}{s}\right)_i = 0 \tag{4}$$

Minimizing Cycle Length

Although many objectives could be advanced for designing a signal cycle, minimizing the required cycle length is a good objective to use for several reasons (*4*). Shorter cycles usually mean less delay, especially for pedestrians, cyclists, and transit vehicles, which do not progress at the speed of general traffic. A ring structure with a shorter minimum cycle uses time most efficiently and therefore tends to have the most to give toward meeting secondary objectives or responding to fluctuating demand.

Conflict Groups and Minimum Cycle Length

With traffic movements running partly in series and partly in parallel, the minimum cycle length needed to satisfy all their needs is not obvious. A lower bound is the summed needs of a conflict group, defined as a set of movements that are mutually conflicting and therefore may not overlap. For example, in Figure 1, {3–8–12–5} is a conflict group because each of those movements conflicts with all the others. Where pairwise clearance times are specified, those between immediate successors in the conflict group count as well; this statement means that clearance needs for a cycle depend on the sequence. For a four-member conflict group, there are $(4 - 1)! = 6$ sequences, each of which can have a unique clearance time for a given conflict group. Muller et al. show how ring structures with lagging lefts typically involve less clearance time—and therefore require a shorter minimum cycle length—than those with leading lefts (*5*).

The lower bound on cycle length, *C,* given by a conflict group cg with sequence cgseq is

$$C \geq \sum_{i \in \text{cg}} \text{minsplit}_i + \sum_{ij \in \text{cgseq}} \text{clear}_{ij} \tag{5}$$

where the pair *i–j* belongs to sequence cgseq if *j* immediately follows *i* in that sequence. When Equation 2 is substituted for minsplit_i,

$$C \geq \sum_{i \in \text{cg}} \left[C \frac{\left(\frac{v}{s}\right)_i}{X_{\text{target},i}} + L_i \right] + \sum_{ij \in \text{cgseq}} \text{clear}_{ij} \tag{6}$$

When Equation 6 is solved as an equality, it yields the following lower bound for *C* (*C*min) for a given conflict group and sequence:

$$C\min_{\text{cg,cgseq}} = \frac{\sum_{i \in \text{cg}} L_i + \sum_{ij \in \text{cgseq}} \text{clear}_{ij}}{1 - \sum_{i \in \text{cg}} \frac{\left(\frac{v}{s}\right)_i}{X_{\text{target},i}}} \tag{7}$$

The numerator in this formula is known as the internal lost time in Webster's formula (*6*).

When clearance time does not depend on sequence, as in American practice, references to sequence and to pairwise clearance times in Equation 7 can be dropped, and Equation 7 becomes the lower bound for cycle length associated with a given conflict group. When clearance time is a function of sequence, designers often choose the sequence with the least clearance time, which yields the most favorable lower bound for cycle length associated with a given conflict group:

$$C\min_{\text{cg}} = \min_{\text{cgseq}} \left[C\min_{\text{cg,cgseq}} \right] \tag{8}$$

Among all the possible conflict groups, the critical conflict group is the one that demands the longest cycle and yields a global lower bound that satisfies all conflict groups:

$$C \geq C\min_{\text{crit}} = \max_{\text{cg}} \left[C\min_{\text{cg}} \right] \tag{9}$$

In his seminal paper on signal cycle design optimization, Stoffers asserts that the minimum cycle length for a given cycle structure is always governed by a critical conflict group, (i.e., that Equation 9 holds as an equality) (*7*). For most intersections, this assumption is valid, but counterexamples show that it is not always the case (*8*). The authors have found several additional counterexamples that, for lack of space, are not shown.

Modeling Cycles with Directed Graph

Signal cycle design, which can be seen as a scheduling problem, can be modeled as an activity network or directed graph, as first suggested by Moeller (*8*). In this model, nodes represent traffic movements, arcs connect node pairs representing conflicts, and arc length represents the time from the start of one movement's split to the start of the next. Movement and clearance time needs are lower bounds on arc lengths.

If the ring structure has at least one barrier that can define the cycle's start and end, the minimum cycle length problem for a given ring structure is equivalent to finding the longest path or critical path from start to end. Among the many paths through the network are those through a conflict group, and the cycle length lower-bound formula (Equation 9) can be derived from this

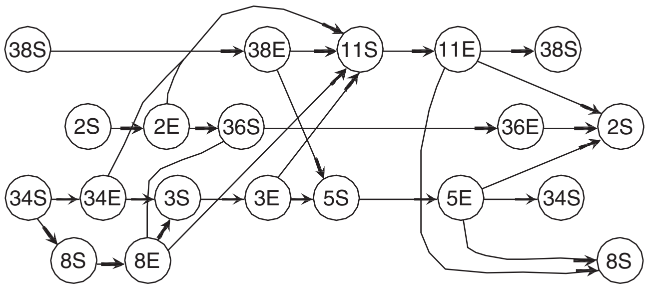

FIGURE 3 Network representation of ring structure (Beacon Street at Park Drive).

network representation. However, the longest path is not necessarily through a conflict group.

A useful generalization to the network model is to use separate nodes to represent the start and end of each movement's phase. The arc from a given movement's start node to its end node represents its split, whose length has a lower bound given by Equation 2; the arc from a given movement's end node to a conflicting movement's start node represents clearance time. Figure 3 is a network representation of the intersection and ring structure of the Beacon Street–Park Drive ring structure shown in Figure 2*c,* with S and E representing a movement's start and end, respectively.

Minimum-Green and Pedestrian Minimum Constraints

Minimum-green constraints can be modeled as an alternative lower bound on a movement's split. For greater transparency in the graphic representation, they can also be modeled by inserting an additional arc from each movement's start node to its end node, with minimum length equal to the minimum split. This arrangement is directly analogous to the minimum-green arc in the model of an actuated controller proposed by Head et al. (*9*). Because the longest path is being sought, inclusion of such an arc will ensure that the minimum split is respected.

Concurrent pedestrian phases that share all the same conflicts with a vehicular phase (the parent phase) can also be treated as minimum splits. However, because pedestrian phases do not conflict with one another, pedestrian phases do not share all the same conflicts as their parent phase. For greater flexibility, therefore, it is preferable to model pedestrian phases explicitly.

Offset Constraints

Safety and coordination goals can add offset constraints that apply to the starting or ending time of movements that are otherwise compatible. There are four general types:

- Start to start. An example is an LPI or a leading bike interval, in which a vehicular movement should not begin its green until a specified time after the timing of a parallel crosswalk or bike crossing has begun. This kind of offset constraint can be represented by an arc from *i*'s start node to *j*'s start node whose minimum length is the specified offset. Figure 3 has an example LPI: Movement 8 (a vehicular movement) waits until 5 s after Movement 34 (the parallel crosswalk) has started. In the conflict group framework, this kind of offset can be represented by a dummy movement that inherits all of *i*'s conflicts and is also in conflict with *j* and whose only time demand is a clearance time equal to the specified offset. In the Figure 3 example, the LPI could be modeled as a dummy Movement 34S that shares all Movement 34's conflicts and is in conflict with Movement 8.
- Simultaneous start. This special case of the start-to-start constraint is often specified for opposite-direction movements with permitted left turns. It is most easily represented by combining the two start nodes. In the conflict group framework, it is actually a pair of constraints (*i* waits for *j,* and *j* waits for *i*), each represented by a dummy movement that inherits its parent's conflicts and is also in conflict with the other movement.
- End to end. At large intersections where some vehicular movements face one signal to enter the intersection and another to leave, it is often specified (to prevent spillback) that the signal governing a major movement's entry should end at least a few seconds before the signal governing its departure ends. Such offset constraints can be modeled analogously to start-to-start constraints.
- Start to end. Where pedestrians make a two-stage crossing via a median refuge with each stage controlled by its own phase, a green wave is sometimes provided by specifying that the second-stage split should not end until a certain time after the first-stage split has begun. Pedestrian green waves can be specified for a single direction or for both directions. Offering of a pedestrian green wave in one direction along one side of the street, and in the other direction along the other side of the street, can sometimes be accomplished with little impact to the signal cycle by overlapping pedestrian phases with left-turn phases. Such an offset constraint can be modeled by arcs between the appropriate start and end nodes. However, it cannot be represented in the conflict group framework because the offset from *i*'s start to *j*'s end may overlap with both movements *i* and *j.*

Offset constraints also limit which sequences within the various conflict groups are feasible. With the LPI constraint, only sequences in which Movement 34 immediately precedes Movement 8 are allowed.

Enumerating Conflict Groups

The application of Equation 9 requires a method to search over conflict groups. For practically sized problems, the number of conflict groups is small enough that they can all be enumerated. For economy, conflict groups that are subsets of a larger conflict group can be skipped, and only maximal conflict groups, called cliques in graph theory, are left. Methods for enumerating cliques are well known, but because they do not appear (to the authors' knowledge) in the traffic signal control literature, a standard method is described in this section, with Beacon Street–Park Drive from Figure 2 as an example. The method is as follows:

1. List all conflict pairs. (Keep lists in lexicographic order to minimize processing and avoid duplicates.)
2. Find and list all three-member conflict groups. A three-member conflict group exists whenever 2 two-member groups have a common first member and last members that are a conflict pair. For example, the first two conflict pairs {2–5} and {2–11} do not form a three-member group because 5 and 11 are not in conflict. However, {3–5} and {3–8} form a three-member conflict group {3–5–8} because 5 and 8 form a conflict pair.

3. Find all four-member conflict groups. A four-member conflict group exists whenever two 3-member groups have all except their last member in common and have last members that form a conflict pair. For example, the three-member groups {3–5–8} and {3–5–34} form a four-member conflict group {3–5–8–34S} because both triplets begin with {3–5} and their last members, Movements 8 and 34, have an offset conflict (between Movement 8 and the start of Movement 34 or 34S).

4. Continue in this manner to find longer groups until no longer groups can be formed.

5. Erase all conflict groups that are a subset of a larger conflict group. The result is a list of the maximal conflict groups.

The calculations are shown in Table 1. To model the LPI, there is a dummy Movement 34S (start of 34) that is in conflict with Movement 8. The example in Table 1 has 12 maximal conflict groups. A review of Figure 2*c* shows that each of the 12 groups represents a path through a complete cycle.

A similar analysis with the eight-phase example of Figure 1*b* will show that four maximal conflict groups correspond to the four possible paths through the dual ring in Figure 1*b,* which is why the ring-barrier structure is ideal for standard configuration intersections. However, at more complex intersections that include (for instance) right-turn phases, pedestrian or bicycle phases that are protected from right turns, bus or tram lanes, or more than four legs, the pattern of maximal conflict groups can demand a more complex ring structure.

Software for Automatically Building and Evaluating Ring Structures

When pairwise conflicts are the only constraint, building a ring structure can involve a large number of choices about sequence. Different sequences can vary in efficiency because of differences in clearance times and opportunities for parallelism. In Dutch practice, alternative ring structures are usually created manually, with designers using intuition to select a limited number of promising structures, and sometimes missing the best solution.

Delft University of Technology has developed a program called VRIGEN that exhaustively enumerates ring structures by applying every possible sequence to each conflict group, discarding structures with internal inconsistencies. VRIGEN allows users to specify offset constraints as well as a variety of other signal control tactics, including priority to transit movements, various forms of recall, and double realization of certain movements within a cycle. For any selected ring structure, VRIGEN automatically generates code (in C++) for fully actuated control that can work in the traffic microsimulation program VISSIM.

TABLE 1 Calculations for Finding Set of Maximal Conflict Groups

Two-Member Groups (input)	Three-Member Groups	Four-Member Groups	Maximal Groups
2-5	3-5-8	3-5-8-34S	3-5-8-34S
2-11	3-5-34	3-8-11-34S	3-8-11-34S
2-32	3-8-11		3-5-34
2-36	3-8-32		3-8-32
3-5	3-8-34S		3-11-34
3-8	3-11-34		2-5
3-11	5-8-34S		2-11
3-32	8-11-34S		2-32
3-34			2-36
5-8			5-38
5-34			8-36
5-38			11-38
8-11			
8-32			
8-34S			
8-36			
11-34			
11-38			

Evaluation Criteria: Cycle Length and Flexibility

Because VRIGEN can easily generate dozens of ring structures for practically sized problems, it aids designers by evaluating each ring structure with respect to three criteria: minimum cycle length, Webster cycle length, and a flexibility score. First, the minimum cycle length has $X_{target} = 1$. Rather than relying on Equation 7, which is only a lower bound, the minimum cycle length finds the actual longest path from cycle start to cycle end. Second, the Webster cycle length (6), found by using Equation 7, has internal lost time amplified by 50% and supplemented by 5 s in an attempt to provide an optimal degree of slack for fixed-time control. Third, the flexibility score is important for efficiency under actuated control. One point is awarded for each movement that may run in parallel with a movement that belongs to the next stage, with stages defined as if each movement ran for exactly one stage. For example, in the dual-ring structure of Figure 1*a,* one flexibility point is awarded for Movement 3 (westbound left turn), which belongs to the first stage because it can run in parallel with Movement 2 (westbound through), which belongs to the second stage. Movements 9, 6, and 12 likewise garner points, giving Figure 1 a flexibility score of 4.

Figure 4 shows a VRIGEN input screen for the five-leg intersection of Boylston Street, Brookline Avenue, and Park Drive near Boston's Fenway Park, under a future configuration with the jughandle left turn replaced by a northeastbound left turn and with two pedestrian crossings added across Brookline Avenue. With VRIGEN, users specify movements and use a mouse to click and drag them to their correct location overlaying a satellite photograph. Other input screens, not shown, allow users to enter traffic parameters such as volumes, minimum and maximum greens, critical gaps, factors affecting saturation flow rate, and clearance times. A separate screen allows users to specify offset constraints and control tactics.

Figure 5 shows an output screen for which VRIGEN has enumerated and evaluated 24 feasible ring structures. They vary in minimum cycle length from 77.3 to 102.3 s, and in flexibility score from 3 to 7. This intersection has 16 maximal conflict groups, and the display format in Figure 5 has a column for each conflict group that shows its sequence and splits, calculated with Equation 2, for any user-selected structure (in Figure 5, Structure 1 is highlighted on the left side). Column 3 to the right, whose phase boxes are highlighted, is the critical conflict group {4–8–30–13}. In this solution, Movement 7

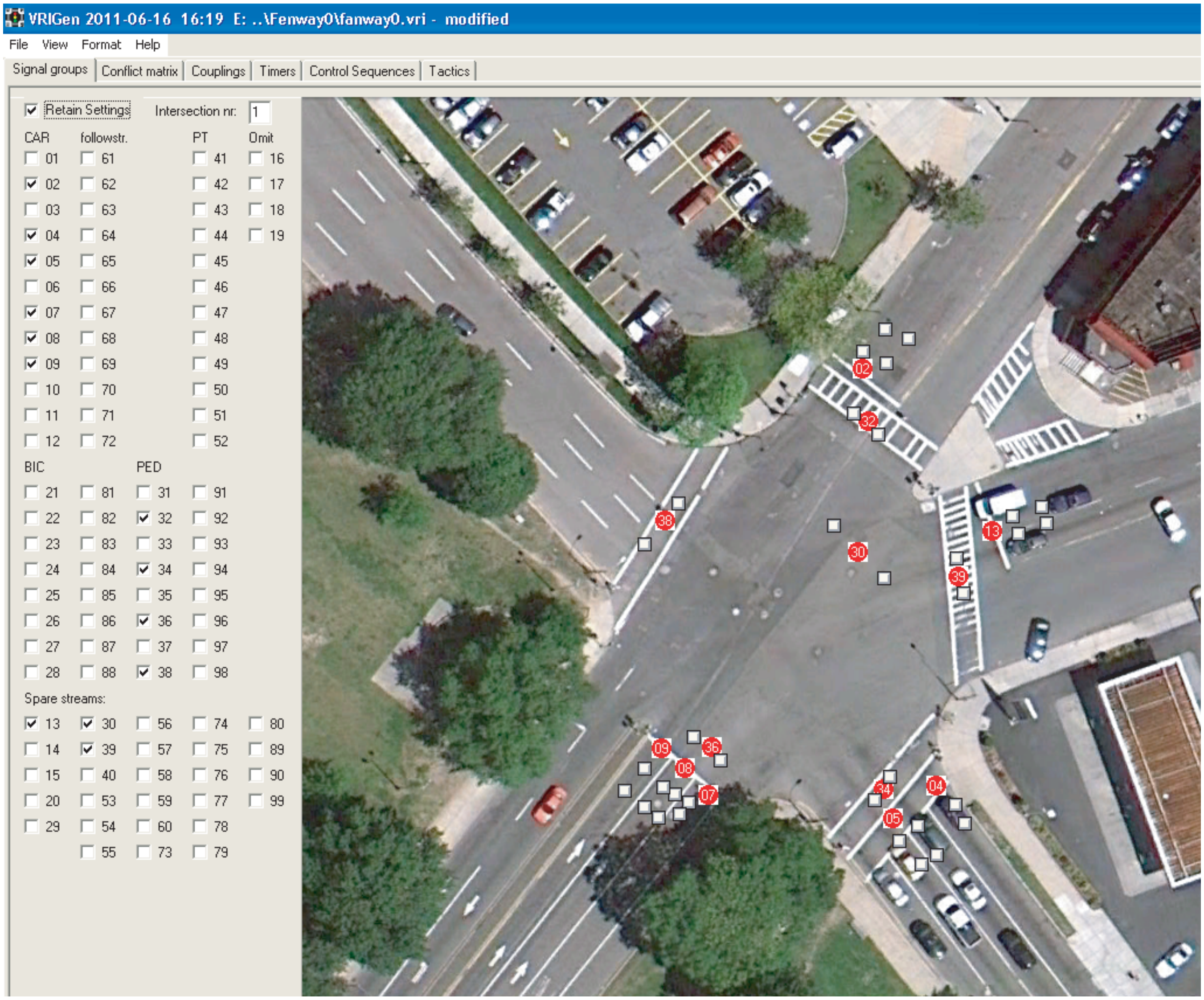

FIGURE 4 Traffic movements for Boylston Street, Brookline Avenue, and Park Drive (PT = public transit; BIC = bicycle; PED = pedestrian).

(northeastbound right turn in Figure 4), the most demanding vehicular movement, has two green periods per cycle.

Interface to Simulation Software

VRIGEN includes an interface to VISSIM so that traffic operations can be simulated with the selected ring structure and control tactics. The interface allows call and extension detectors to be located with a simple click and drag. Once a VISSIM model of an intersection is created, it can be run with a new ring structure or different control tactics and only a few clicks of the mouse. VRIGEN also has an interface to the simulation program TRAFCOD, which was developed at Delft University. TRAFCOD allows users to see how the signals behave when detectors are turned on and off manually; this simulation allows a way to check whether the desired control tactics were correctly specified. Together, these tools can help designers find a better ring structure than they might find by using either a constrained ring-barrier framework or a flexible framework with manual ring creation.

Example Ring Structures with Pedestrian Overlaps

Barrier-free cycle design serves the Netherlands well with its pairwise-specified clearance times and its common use of two-phase pedestrian crossings, tram and bus lane phases, bicycle path phases, and right-turn phases. American practitioners will naturally be interested in examples for which barrier-free cycles might improve operations of American intersections. This section offers four such examples: an overlapping right-turn phase, an overlap of two pedestrian phases, an overlap of a pedestrian phase with an LPI, and multiple intervals of pedestrian overlap.

Right-Turn Overlap with Protected Pedestrian–Bicycle Phases

To eliminate the conflict between right turns and pedestrians or a bike path running along a road, designers might wish to control the

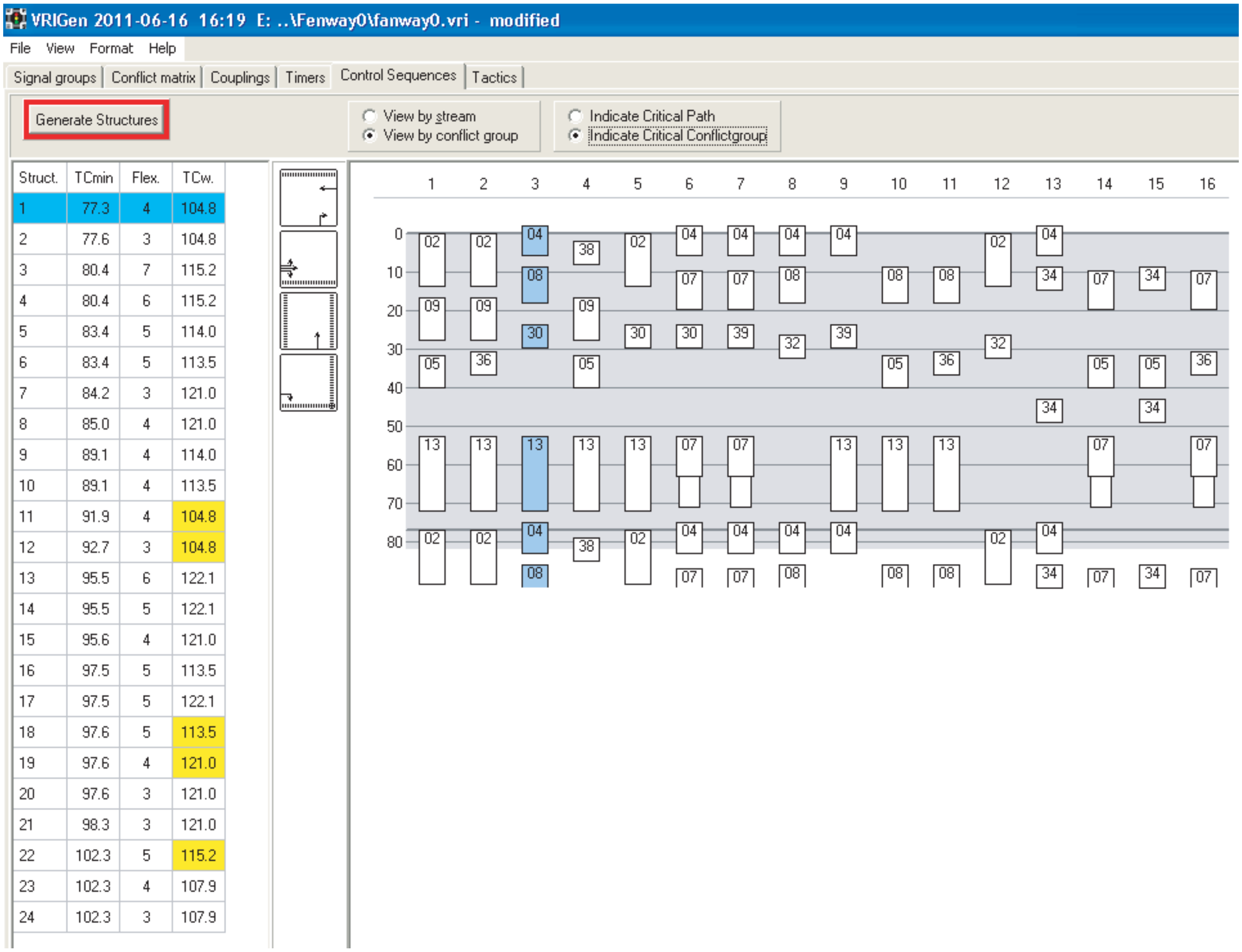

FIGURE 5 List of possible ring structures, with conflict group view used to display highlighted structure (struct. = structure; TCmin = minimum cycle length; flex. = flexibility score; TCw = Webster cycle length).

right-turn lane separately and provide either pedestrians or cyclists, or both, a protected crossing. Figure 6 shows an example of an intersection layout and possible ring structure. The pedestrian–bike crossing and the right-turn movement from which it is protected together share the time consumed by one street's through movement and the other street's left-turn movement. This paradigm is commonly used in the Netherlands to improve the safety of bicycle paths and can be programmed in most American controllers by using overlaps.

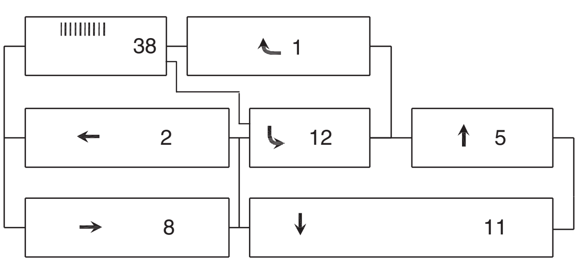

FIGURE 6 Overlap involving pedestrian phase protected from right turns.

Two Examples with Overlapping Pedestrian Phases

A simple two-phase intersection with long pedestrian crossings and moderate traffic can be considered as an example. In this example, each pedestrian crossing requires 30 s, and each vehicular movement needs 4 s for lost time plus 32% of the signal cycle, as shown in Figure 7. If pedestrian phases are constrained to run within the barriers of their parallel vehicular phase, both streets will need a 30-s split, so *C*min = 60 s. However, if the pedestrian phases are allowed to overlap, the needed cycle length is only 50 s. The critical conflict group consists of one pedestrian movement and the vehicular movement on the other street, with internal lost time = 34 s and combined $(v/s)/X_{target} = 0.32$ (Equation 7). The solution shown features two pedestrian overlaps of 5 s that incidentally double as LPIs.

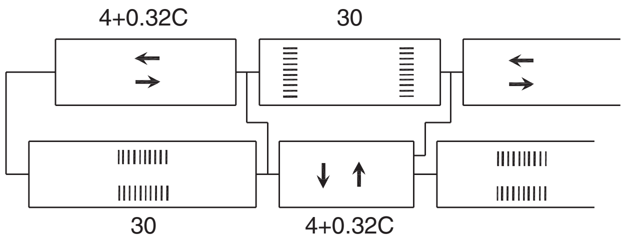

FIGURE 7 Example in which overlapping pedestrian phases lower the needed cycle length (C = signal cycle).

The shorter cycle allowed by these overlaps means less delay for pedestrians and shorter traffic queues. It can also be expected to improve safety, because lengthening vehicular phases to meet pedestrian minima can lead to long periods of unsaturated green, which tend to promote speeding and dangerous conflicts with left turns and pedestrians. If one assumes a 4-s yellow period, green intervals in the structure with overlaps are only 16 s long, and those in the structure with barriers are 26 s long.

Another two-phase example (Figure 8) is the Beacon Street–Harvard Street intersection in Brookline, Massachusetts. Pedestrian needs dominate the north–south phase because it is a long crossing, and an LPI is part of the critical path for the east–west phase. If pedestrian movements are kept on their respective sides of a barrier, the critical movements' combined lost time is 44 s, and $C\text{min} = 44/(1 - 0.34) = 67$ s. Without the constraint of barriers, the east–west LPI can overlap the north–south pedestrian phase, as shown in Figure 8*b*. The upper ring becomes the critical conflict group, with lost time reduced by 5 s and *C*min reduced by 8 s, or 11%. The shorter cycle would not only decrease delay for pedestrians and transit vehicles; it would also lead to shorter queues and to smaller platoons at downstream pedestrian crossings.

Actuated Signal Performance With and Without Pedestrian Overlaps

Although the previous examples have assumed pretimed control, barrier-free ring structures apply equally well to actuated operation. A final example, the Beacon Street–Park Drive intersection, introduced in Figure 2, was analyzed with traffic microsimulation (VISSIM) to compare actuated signal operations that have explicit barriers (Figure 2*b*) with those that have the ring structure shown in Figure 2*c,* which allows pedestrian overlaps. Pedestrian overlaps would be expected to be the most important outside peak hours, when lower vehicular demand can make the pedestrian phases become critical. Pedestrian phases are served every cycle, in keeping with the urban context; only the left-turn movement is subject to being skipped for lack of demand.

TABLE 2 Actuated Signal Performance Based on Simulation: Beacon Street at Park Drive

Volume	Average Cycle Length (s)	Average Pedestrian Delay (s)	Average Motorist Delay (s)
p.m. peak			
With barriers	67	27	12
With pedestrian overlaps	59	23	13
Off-peak (50% of peak)			
With barriers	61	24	7
With pedestrian overlaps	50	18	7

Results for the afternoon peak and off-peak (50% of afternoon peak) volumes are shown in Table 2. Compared with the ring-barrier design, pedestrian overlaps allowed cycles to be shorter in both periods, averaging only 50 s off peak. The shorter cycles lowered pedestrian delay by about 5 s in both periods. Average motorist delay was virtually unchanged because of the offsetting effects of a shorter cycle and less green time.

CONCLUSION

Although the ring-barrier framework is a powerful simplification that is helpful for many intersection configurations, it can be overly constraining at intersections with critical conflicts that include pedestrian, bicycle, right-turn, or transit movements or that involve offset constraints between movements that are otherwise compatible. Designing ring structures without explicit barriers offers more flexibility, but the larger number of sequence options makes it impractical to evaluate them all manually. The use of an automated means of identifying and evaluating all the possible ring structures makes it possible to find the most efficient ring structure for both fixed-time and actuated control. Finally, the greater efficiency that

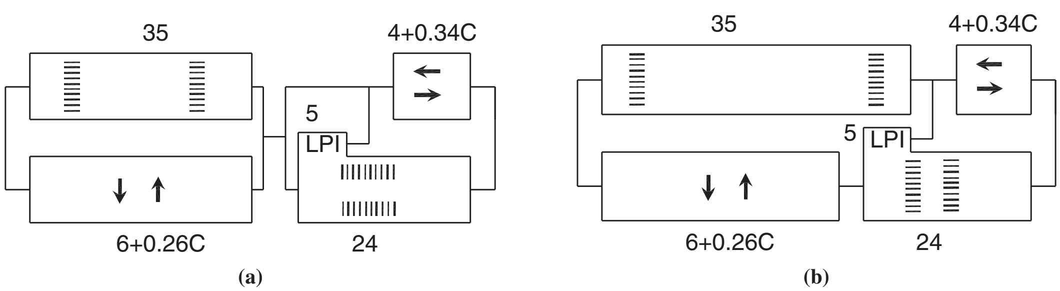

FIGURE 8 Overlapping pedestrian phase with leading pedestrian interval: (*a*) barrier-constrained structure (*C*min = 67 s) and (*b*) with pedestrian overlap (*C*min = 59 s).

is possible with pedestrian overlaps may make it more feasible to include protected pedestrian and bicycle phases at signalized intersections.

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