White Paper: Introduction of Phase-time network representation for traffic signal timings

--Concept, formulation and applications

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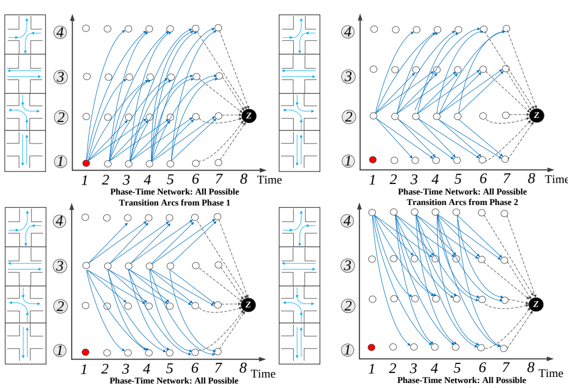
May-'2016



1. Background Introduction

Traditionally, traffic signal timing plans in North America are represented with the "Ring-Barrier" structure proposed by National Electronic Manufacture Association (NEMA). Although the Ring-Barrier structure is commonly used in practice, it also brings some unnecessary difficulties in modeling and optimizing traffic signal timings. Typically, the traffic signal optimization problem can be formulated as a *Mixed Integer Linear Programming* (MILP) in which decision variables are the phase lengths while the constraints reflect the hardware requirements in traffic signal controllers (e.g., barrier constraints, min/max green constraints, pedestrian constraints). Mathematically, those constraints are mostly nonlinear, making the traffic signal optimization very difficult at large scale.

The introduction of phase-time network aims to provide a flexible and straightforward signal timing representation. The proposed phase-time timing representation has the same flexibility of describing traffic signal control as the traditional ring-barrier structure at intersections while this new timing representation naturally requires fewer hard constraints than the ring-structure-based representation. This feature is critical in formulating and solving traffic signal control problems on the network level. We expect that the new phase-time network will offer a great potential for new adaptive signal control strategies and network-wide traffic signal strategies in the future. For full details of the phase-time network, readers are suggested to read the recently published journal paper:

Li, Pengfei, Pitu Mirchandani, and Xuesong Zhou. "Solving simultaneous route guidance and traffic signal optimization problem using space-phase-time hypernetwork." Transportation Research Part B: Methodological 81 (2015): 103-130.

2. Concept of phase-time network

A complete signal timing includes three components: phase, phasing sequence and phase duration. Figure 1 shows a standard NEMA phase set at a four-leg intersection. Any two NEMA phases on the same side of barrier and in two different rings can be concurrent, such as φ1 and φ 5 OR φ 1 and φ 6. Since the objective of ring-barrier structure is to define concurrent (i.e., compatible) movements. We proposed a new concept of signal phases each of which only include all concurrent movements within intersections. As shown in Figure 2, under the new concept of phase-time network, we can fully map NEMA phases (φX hereafter) and movement-based phases (Phase X hereafter) as:

- Phase 1= φ4+ φ8;
- Phase 2= φ3+ φ7;
- Phase 3= φ2+ φ6;
- Phase 4= φ1+ φ5;
- Phase 5= φ3+ φ8;

- Phase 6= φ4+ φ7;
- Phase 7= φ2+ φ5;
- Phase 8= φ1+ φ6;

At any time, only one movement-based phase can be allowed. The right side of Figure 2 shows a fully flexible phasing sequence in which any phase (i.e., node) can go any other phase while some arcs between nodes can also be removed if certain phase transitions are prohibited in practice. Obviously, this link-node type timing representation no longer needs barriers and rings to ensure compatible movements at intersections.

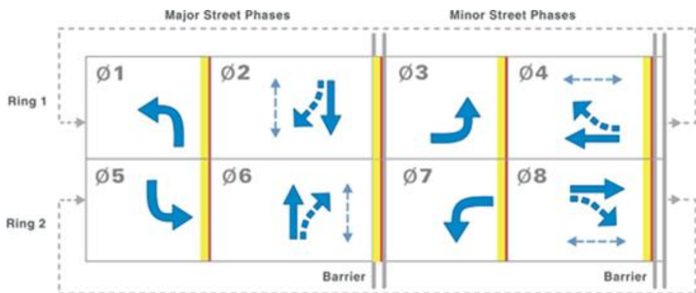


Figure 1: Standard NEMA phases

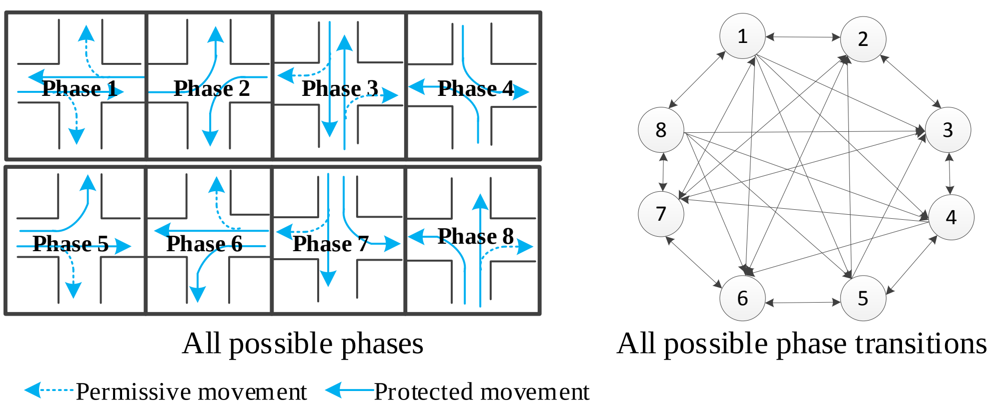


Figure 2 all (8) movement-based phases at a four-leg intersection

Even though it is straightforward to understand phase and phasing sequence as in Figure 2, it is not easy to identify phase durations just using the link-node representation. To address this issue, it is necessary to expand the link-node structure over time and we designed the concept of phase-time network. As shown in Figure 3-A, the left side illustrates the mapping between movement-based phases and the corresponding movements (i.e., controlled links) at a standard four-leg intersection. The right side of Figure 3-A explains the physical meaning if a feasible arc between two nodes is selected to in the signal timing representation. Note that those arcs are created only if the corresponding phase transition is feasible and min/max greens are satisfied. To formulate and solve a signal timing optimization problem, such representations can "pre-build" many hard constraints into the phase-time network model, significantly reducing the problem's complexity compared with the NEMA-phase representation. As an illustration, in Figure 3-B, in a cyclic phasing sequence (i.e., Phase 1 must be followed by Phase 2), if the summation of phase 1's min green, yellow and all-red clearance is 15 seconds while the summation of phase 1's max green, yellow and all-red clearance is 40 seconds, then the shadowed area represents all feasible timing plans from P1 to P2.

Note selection of any arc will incur a cost because all vehicles on all other conflict approaches must be stopped. As such, within the phase-time network, the traffic signal optimization is nothing but finding a minimum-cost path from origin to destination among all feasible arcs. The destination can be either the end of a cycle, if vehicle arriving pattern is stable over time, or the end of a time horizon (dynamic/adaptive signal timing optimization), if vehicle arriving pattern is dynamic over time.

In contrast, it is typical to use "IF-THEN" condition to represent the constraints of minimum green and maximum green in NEMA-phase-based formulation.

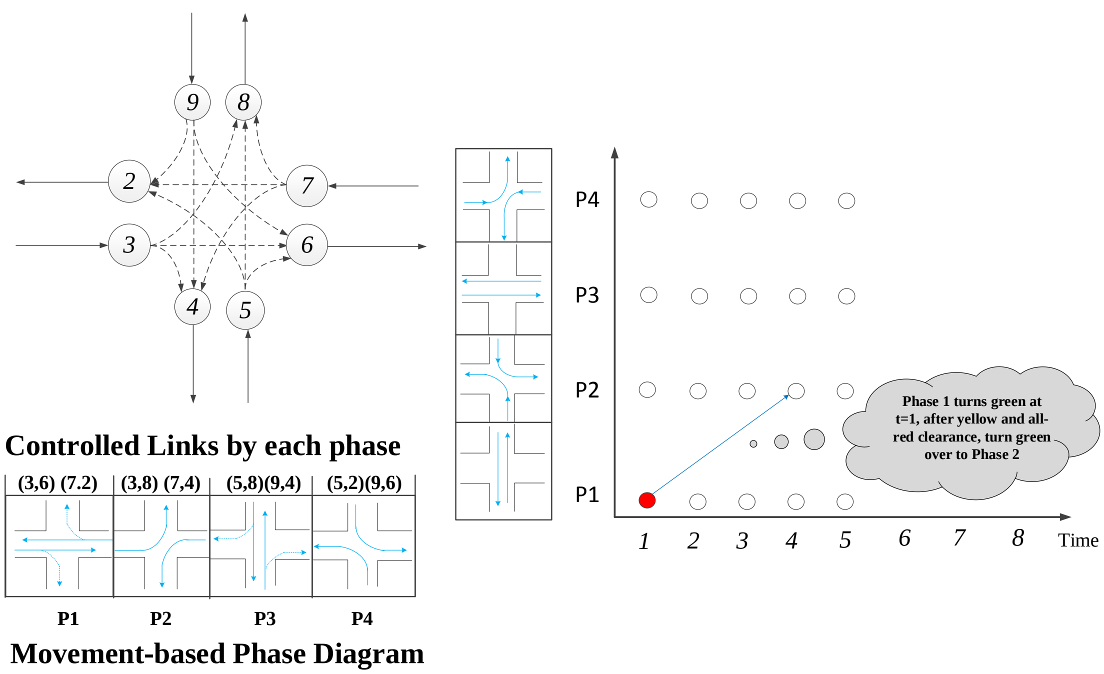


Figure 3-A Physical meaning of arcs in Phase-time network

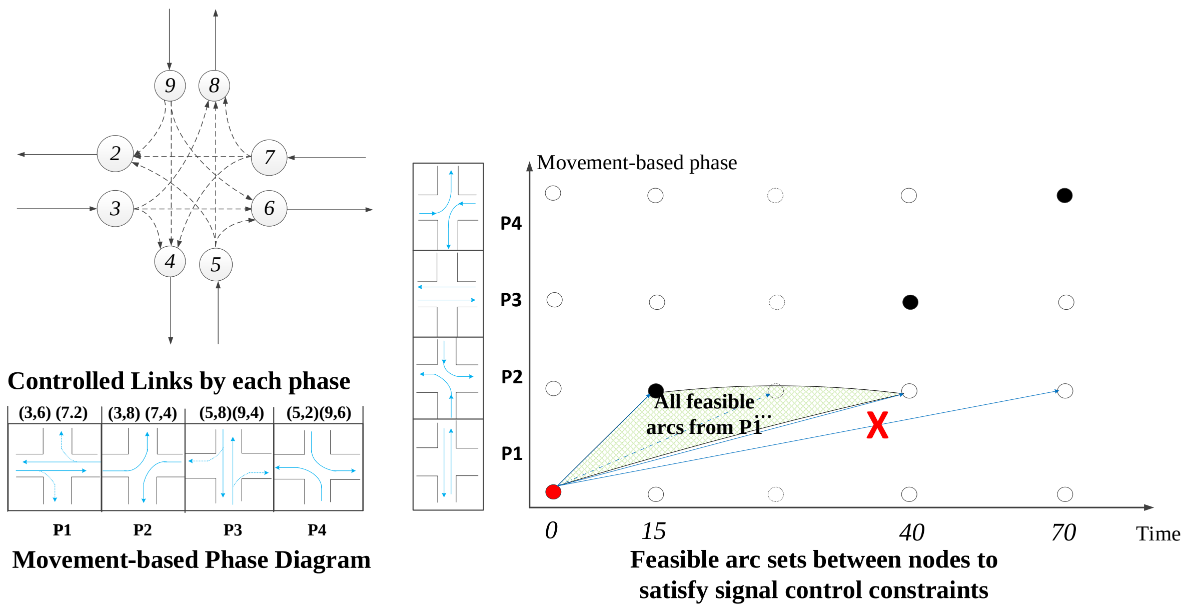


Figure 3-B Feasible arc sets between phases

3. Translation from Phase-time timing plan representation to NEMA-phase representation and Vice Versa.

Given that all the signal controllers in the field follow the NEMA's ring-barrier structure in North America, it is important to provide easy "translation" between NEMA-phase timing representation and phase time representation. In this section, a four-leg intersection is used as an example to demonstrate the full flexibility of translating from NEMA-phase representation to Phase-time network representation and vice versa.

3.1 From phase-time representation to NEMA-phase representation

Without loss of generality, Figure 4 shows four concurrent movements at a typical four-leg intersections and the timing plan represented by phase-time network model. If we assume the interphase loss time (yellow+ all-red clearance) is uniformly 5 seconds for each phase, we can easily translate the signal timing in Figure 4 into NEMA-phase-based signal timing as in Figure 5. Please note that such mapping can be easily to extend to a more general representation as in Figure 2.

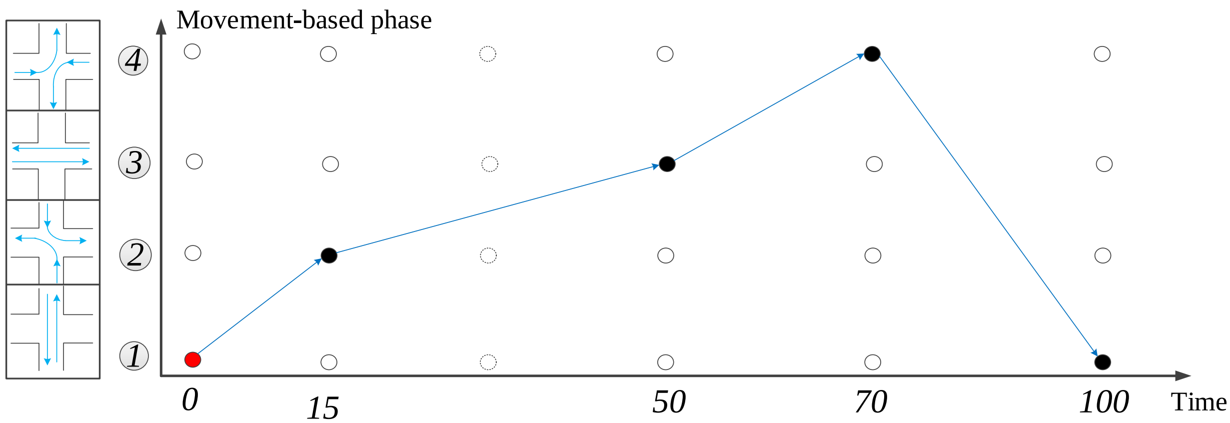


Figure 4 Signal timing representation in phase-time network model

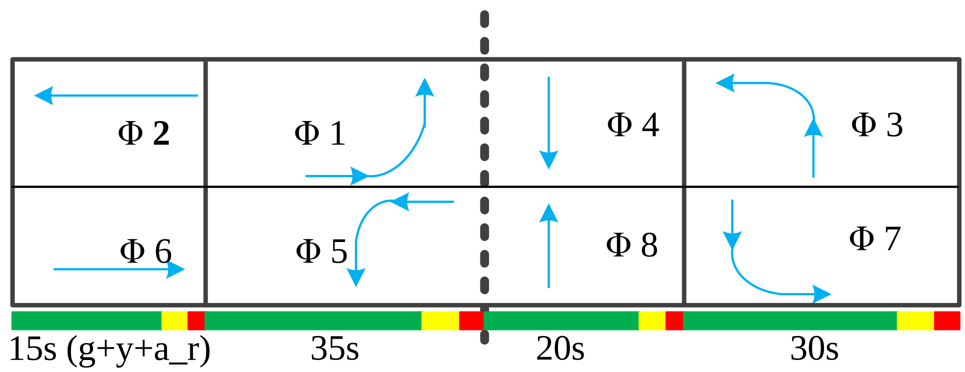


Figure 5 NEMA-phase-based signal timing translated from phase-time network representation

3.2 From NEMA-phase representation to phase-time representation

It is also possible to translate from NEMA-phase representation back to phase-time representation. Figure 6 shows a standard signal timing diagram based on NEMA phases and Figure 7 is the corresponding translation in phase-time timing representation.

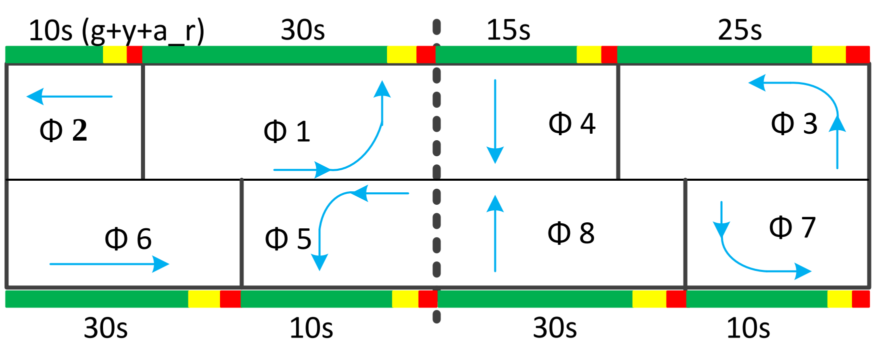


Figure 6 Signal timing representation using NEMA-phase

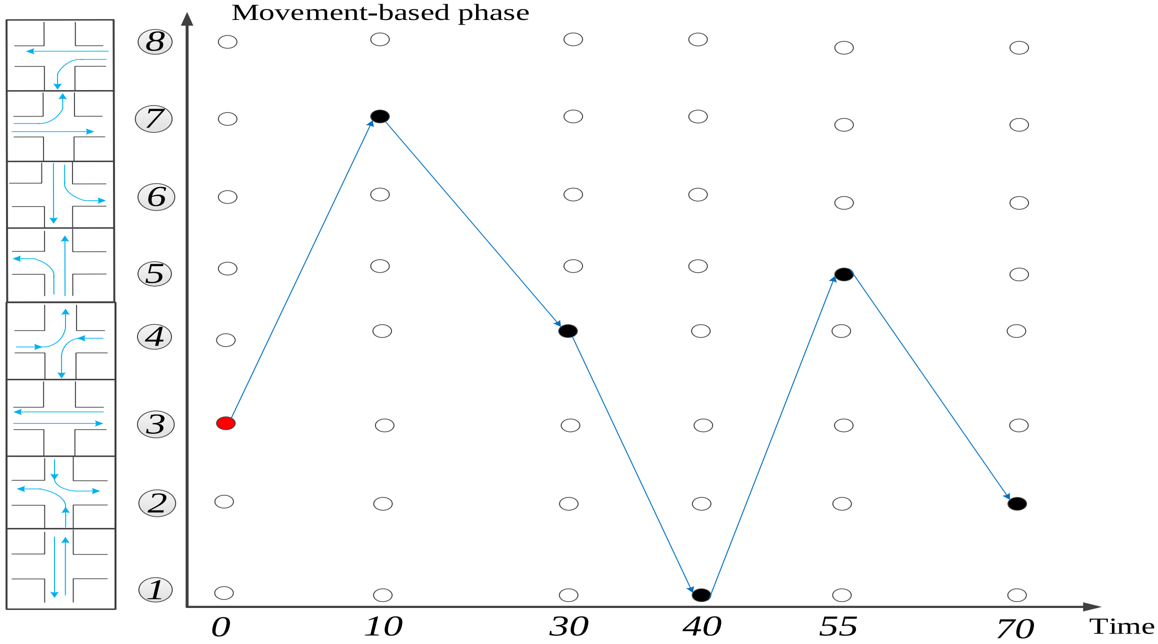


Figure 7 Phase-time representation translated from NEMA-phase signal timing

It should be pointed out that, dependent on the traffic controller's firmware, unnecessary yellow and all-red clearance may be automatically ignored. For instance, in Figure 7, when phase 3 turns over green to phase 7, Φ 6 (Figure 6) may be held in green all the time instead of switch to yellow, all-read and then switch back to green.

4 Example

The purpose of this section is to demonstrate how to set up the phase-time timing representation through input file. Specifically, it is necessary to map signal phase to movement within intersections and to set up possible phasing sequence, min/max greens, walk, pedestrian clearance, etc. for each phase. (file name in the example network: "input_timing_xxx.csv"). Without loss of generality, we ignore the right-turn links.

Using an example network as in Figure 8, the left side is the lane-based intersection created in VISSIM while the right side is the corresponding link-based intersection representation visualized in NexTA, an open-source graphic user interface program for DTALite mesoscopic simulator.

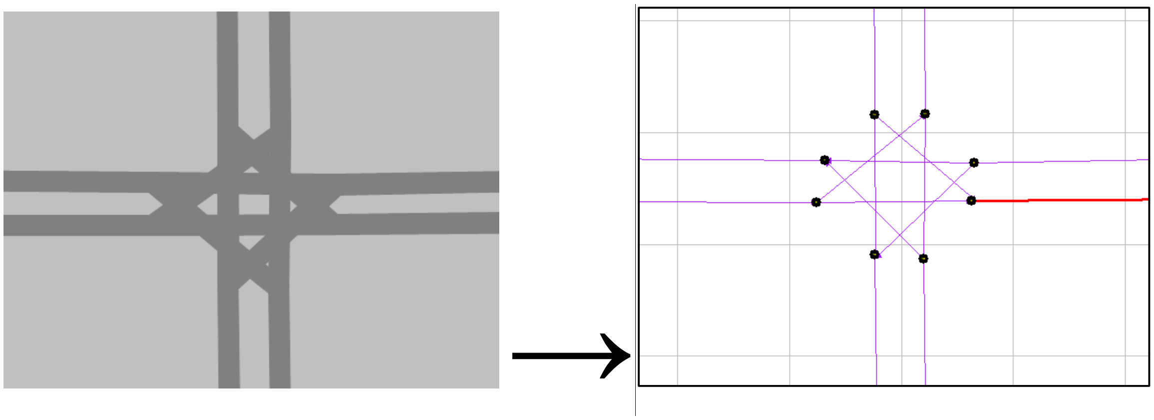


Figure 8 Example network generated in VISSIM and NexTA

In NexTA, after the network layout (link set, node set, etc.) is loaded, mapping between signal phases and corresponding links within intersections is specified. The data input format is shown as in Table 1 and 2. Please note that, although each phase is mapping two links (concurrent movements) within intersections in the example, it can be expanded to more movements with each phase for unconventional intersections.

Table 1 Phase-link matching and Phase Attributes Table (Fully flexible phasing sequence)

g_sig_index	int_id	no_of_phases	phase_id	signal_link1	signal_link2	signal_link3	signal_link_permissive1	signal_link_permissive 2	next_phase	min_green	max_green	yellow	all_red	walk	ped_clearance	veh_ext	start_phase	prefer_next_phase
1	1	4	1	14	10	--	--	--	2	5	20	3	2	5	10	3	1	2
2	1	4	1	14	10	--	--	--	3	5	20	3	2	5	10	3	1	2
3	1	4	1	14	10	--	--	--	4	5	20	3	2	5	10	3	1	2
4	1	4	2	15	11	--	--	--	3	10	50	5	2	5	15	5	0	3
5	1	4	2	15	11	--	--	--	4	10	50	5	2	5	15	5	0	3
6	1	4	2	15	11	--	--	--	1	10	50	5	2	5	15	5	0	3
7	1	4	3	16	12	--	--	--	4	5	30	3	2	5	10	5	0	4
8	1	4	3	16	12	--	--	--	1	5	30	3	2	5	10	5	0	4
9	1	4	3	16	12	--	--	--	2	5	30	3	2	5	10	5	0	4
10	1	4	4	6	13	--	--	--	1	15	30	4	2	5	20	5	0	1
11	1	4	4	6	13	--	--	--	2	15	30	4	2	5	20	5	0	1
12	1	4	4	6	13	--	--	--	3	15	30	4	2	5	20	5	0	1

Table 2 Phase-link matching and Phase Attributes Table (Cyclic phasing sequence)

g_sig_index	int_id	no_of_phases	phase_id	signal_link1	signal_link2	signal_link3	signal_link_permissive1	signal_link_permissive2	next_phase	min_green	max_green	yellow	all_red	walk	ped_clearance	veh_ext	coordinated_phase_flag	Offset	start_phase	prefer_next_phase
1	1	4	1	14	10	--	--	--	2	5	20	3	2	5	10	3	0	5	1	2
4	1	4	2	15	11	--	--	--	3	10	50	5	2	5	15	5	1	5	0	3
7	1	4	3	16	12	--	--	--	4	5	30	3	2	5	10	5	0	5	0	4
10	1	4	4	6	13	--	--	--	1	15	30	4	2	5	20	5	0	5	0	1

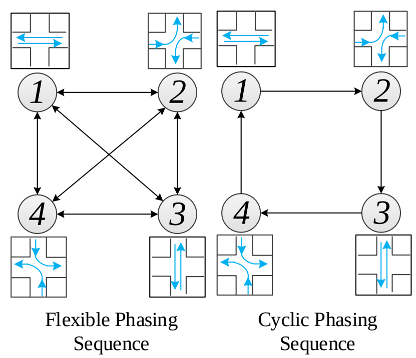


Figure 9 the corresponding sequence defined in Table 1 and 2

Explanations of each field in Table 1 and 2 are as follows:

- g_sig_index: Global ID of each movement-based phase;
- int_id: Intersection ID;
- no_of_phases: the total number of phases at that intersection;
- sig_linkX: the corresponding link of that phase to allow or prohibit protected vehicle movements within intersections
- signal_link_permissiveX: the corresponding link of that phase to allow permissive vehicle movements within intersections, such as permissive left turn movements; Note that the same link can be both a protected sig_link and a permissive sig_link for the same phase.
- next_phase: to which phase the green should be turned over after the current green ends;
- min_green: minimum green of this phase;
- max_green: maximum green of this phase;
- yellow: yellow time of this phase;
- all-red: all-red clearance for this phase
- walk: concurrent walk time for this phase;
- ped-clearance: concurrent pedestrian clearance for this phase;
- veh_ext: vehicle extension for this phase (vehicle extension is to, after the last vehicle leaves the stop line, hold the current phase for another few seconds until either a new vehicle reach the stop line resetting the extension timer or "gap out" the current green). It is an important function of actuated signal control strategies.
- coordinated_phase_flag: (cyclic phasing sequence only) 1 means this phase is the coordinated phase; 0 other wise;
- offset: (cyclic phasing sequence only) negative, zero or positive. The time difference of the local clock with the master clock;
- start_phase: 1 means this phase should be started first when a simulation run is launching
- prefer_next_phase: Identify which phase the current green should be turned over after maximum green is reached or just "REST" (i.e., "prefer_next_phase" is set to itself), if there are no vehicle or pedestrian calls from the conflict movements.

Figure 9 visualizes two types of phasing sequence in Table 1 (fully flexible phasing sequence) and Table 2 (cyclic phasing sequence). It should also be pointed out that, compared with vehicle calls, pedestrian calls are relatively rare events in most places and, in case there are pedestrian calls, the min green should be the larger value of programmed min green and "walk+ped_clearance" and "walk+ped_clearance" should always be equal to or shorter than the programmed maximum green. In case there are no pedestrian calls, we may just set zero walk and zero pedestrian clearance. In order to implement fixed timing plans, the green durations should always refer to the max green of each phase following the convention of traffic signal operations.

5. Comparison between SYNCHRO signal timing format and Phase-time timing representation

In SYNCHRO, it will need at least three information sections to represent a complete signal timing plan, LANES, PHASES AND SIGNAL TIMINGS (Table 3). They are never straightforward and often difficult to translate into other traffic simulators. In contrast, the phase-time timing representation only needs users to identify those concurrent signal groups and provides additional information like Table 1 or 2.

Table 3-A Lanes data format in SYNCHRO (partial)

RECORDNAME	INTID	SBL	SBR	EBL	EBT	WBT	WBR	PED	HOLD
Up Node	100	200	200	3	3	120	120		
Dest Node	100	120	3	200	120	3	200		
Lanes	100	1	0	0	3	0	0		
Shared	100	0		0	0	0			
Width	100	12	12	12	12	12	12		
Storage	100								
Taper	100								
StLanes	100								
Grade	100								
Speed	100	30			30	30			
Phase1	100	4			2				
LostTime	100	4	4	4	4	4	4		

Table 3-B Phases data format in SYNCHRO (partial)

RECORDNAME	INTID	D1	D2	D3	D4	D5	D6	D7	D8
BRP	100	111	112	211	212	121	122	221	222
MinGreen	100		4		4				
MaxGreen	100		29		23				
VehExt	100		3		3				
TimeBeforeReduce	100		0		0				
TimeToReduce	100		0		0				
MinGap	100		3		3				
Yellow	100		3.5		3.5				
AllRed	100		0.5		0.5				
Recall	100		3		0				
Walk	100		5		5				
DontWalk	100		11		11				
PedCalls	100		0		0				
MinSplit	100		20		20				
DualEntry	100		1		1				

Table 3-C Signal Timing data format in SYNCHRO (partial)

RECORDNAME	INTID	DATA
Control Type	100	3
Cycle Length	100	60
Lock Timings	100	0
Referenced To	100	0
Reference Phase	100	2
Offset	100	36
Master	100	0
Yield	100	0
Node 0	100	100
Node 1	100	0