3. SEQUENCING AND CONTROLLING MOVEMENTS

Learning objectives:
- Define and apply the terms movement and phase
- Describe the sequencing and control of movements at a signalized intersection
- Determine left turn treatment
- Draw and interpret a ring barrier diagram that represents a particular phasing plan
- Define and apply the term stage

In the previous section, we considered traffic flow on one approach of a signalized intersection. In this section, we consider traffic flow at the entire intersection and how the movements on the individual approaches are sequenced and controlled. Safety and efficiency are the two primary goals of intersection control. Considering efficiency, as many movements as possible should be served concurrently. But for safety reasons, conflicting movements must be served during different periods of the signal cycle, separated in time by the yellow and red clearance intervals.

3.1 Movements

A standard intersection with four approaches can have up to twelve vehicular movements. These movements, and the way in which they are typically numbered and referred to, are shown in Figure 1. The numbering scheme is based on the National Electrical Manufacturers Association (NEMA) standard.

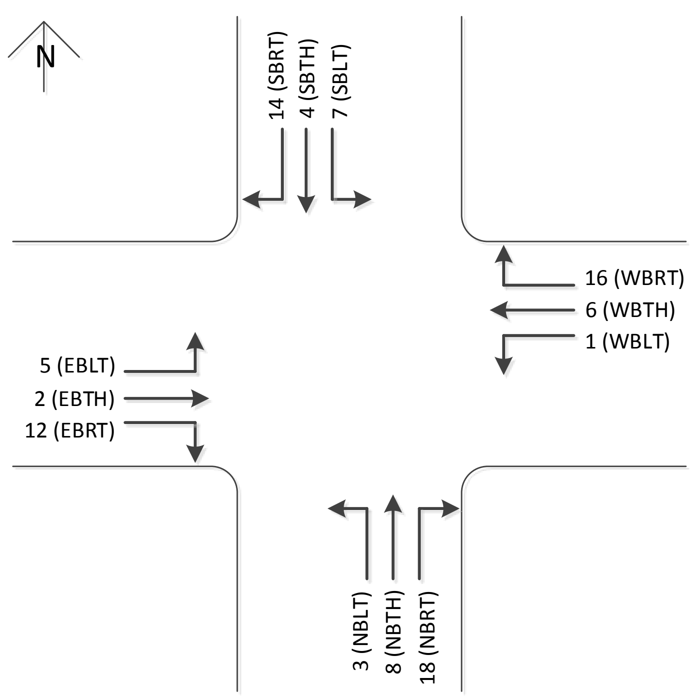

Figure 1. Numbering and notation of movements at a signalized intersection

Signalized Intersection Module: Sequencing and Controlling Movements

A *movement* is defined by the direction of travel from its origin and the turning maneuver that a vehicle completes to its destination. For example, movement 2 begins traveling in the eastbound direction and continues through the intersection in the eastbound direction. It is referred to as an eastbound through movement (abbreviated as EBTH). Or, movement 1 begins traveling in the westbound direction, making a left turn and continuing in the southbound direction. Movement 1 is referred to as a westbound left turn (WBLT) movement. As a final example, movement 14 is referred to as a southbound right turn (SBRT) movement.

A movement is also categorized by any restriction that may be placed on it. There are four such categories:

- An unopposed movement is just that: there is no other movement that opposes this movement. For example, a movement on a one-way street is unopposed.
- A protected movement may have a movement that can oppose it but the signal indication gives the protected movement the right-of-way. For example, a left turn movement may be protected if the signal indication is a green arrow while the opposing traffic movement has a red indication.
- A permitted movement is allowed to travel through the intersection, but must yield if a higher priority opposing movement is present. For example, a permitted left turn may enter and travel through the intersection as long as there are no opposing through movements also desiring to travel through the intersection at the same time.
- A movement can also be prohibited, or not allowed. This restriction can be complete or in effect only during certain periods of the day. For example, left turns can be prohibited (not allowed) during peak periods, especially if the left turn movement shares a lane with a through movement.

Groups of movements are also classified as either *compatible* or *conflicting*. In general, north-south movements conflict with east-west movements. North-south movements are part of a group called a *concurrency group* since these movements may travel concurrently; similarly east-west movements are part of the east-west concurrency group. The concept of the concurrency group is illustrated in Figure 2. Depending on the signal phasing plan (*phase* is defined in the next subsection) and restrictions on the movements, a movement in the north-south concurrency group may be served at the same time as any other movement in this group. The same concept applies to the movements in the east-west concurrency group.

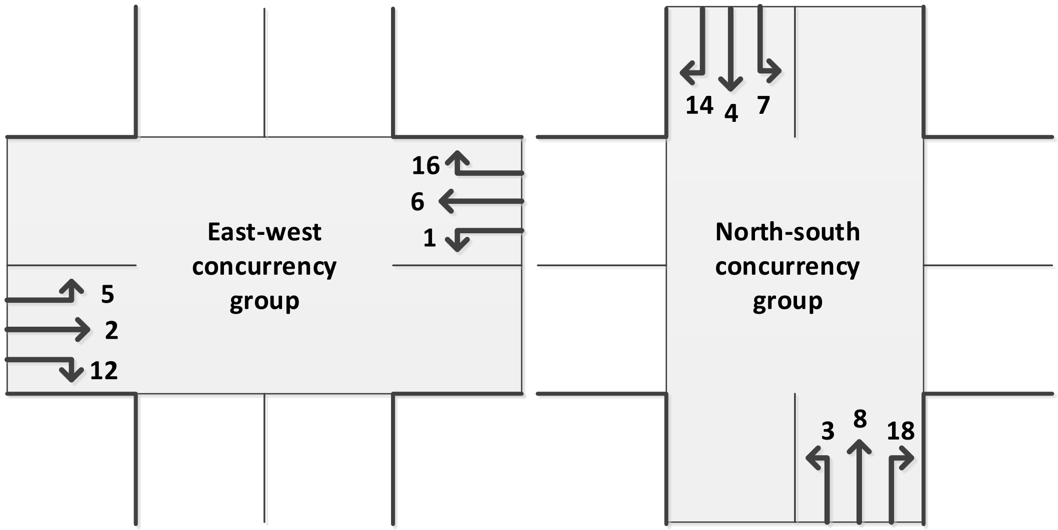

Figure 2. Concurrency groups

3.2 Phasing and the Ring Barrier Diagram

While stop and yield controlled intersections require judgment before a driver can safely enter the intersection, signal control gives an unambiguous indication whether a particular movement has the right of way or not. This right of way assignment is done through the signal display of a green ball, a green arrow, or a flashing yellow arrow.

A *phase* is a timing unit that controls one or more compatible movements at a signalized intersection. The timing unit consists of the consecutive displays of the green, yellow, and red indications shown to the movements controlled by the phase, as shown in Figure 3.

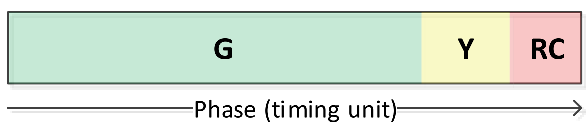

Figure 3. Phase

A *ring* is a sequence of phases that must be served one after the other. Phases are sequenced to separate conflicting movements and to make sure that those movements that are served concurrently are compatible.

A *ring barrier diagram* is the tool that is used to define those movements that are compatible and can be served concurrently, and those that conflict and must be served in sequence. The ring barrier diagram is built upon the concept of the concurrency group described above. The movements of the east-west concurrency group are served first, followed by service to the north-south concurrency group.

An example ring barrier diagram with eight phases and a two ring structure is shown in Figure 4. Barriers separate the two concurrency groups. The phase number is shown in the upper left corner of each square, and the movements that are controlled by that phase are shown with an arrow and movement number. A dashed line indicates permitted movements.

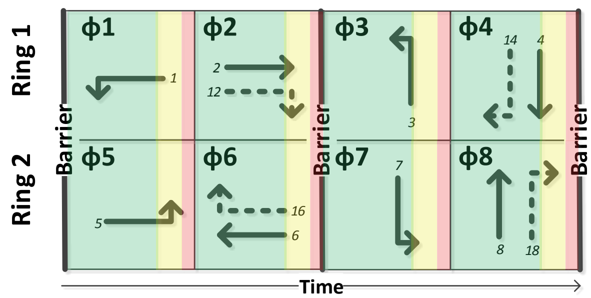

Figure 4. Ring barrier diagram for two ring, eight phase operation

The following rules apply to a ring barrier diagram:

- Each ring shows the order in which phases are sequenced.
- A phase in one ring can time concurrently with a phase in another ring as long as both phases are in the same concurrency group.
- A phase in one concurrency group cannot time concurrently with a phase in another concurrency group. (The exception to this rule is the concept of the *overlap*, which is beyond the scope of this module.)
- A barrier separates the north-south and the east-west concurrency groups. Both rings must cross the barrier at the same time.
- After a phase is served, a change and clearance interval (yellow indication and red indication) provides a time separation between that phase and the next conflicting phase.

3.3 Left Turn Phasing

There are several ways in which left turn movements can be served at a signalized intersection. Figure 4 showed the case of *leading left turns* (served before the through movements) that are *protected* (with no opposing through movements served at the same time). Protected left turns (shown with solid lines) are generally used when the combination of the left turn movement volume and its opposing through movement volume is high.

When left turn volumes are low, *permitted left turn* operation (shown with dashed lines) is possible. This results in a single ring two phase operation, as shown in Figure 5. Here, the left turn and through movements within each concurrency group are controlled by the same phase.

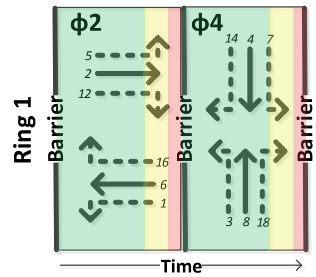

Figure 5. Two-phase ring barrier diagram

Another phase structure is called *split phasing*, in which each approach is served in sequence. Split phasing is used when safety or geometric restrictions don't allow opposing left turns to be served at the same time. This structure can be represented by a single ring, as shown in Figure 6.

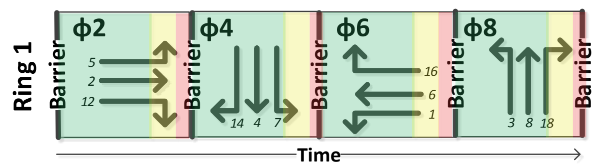

Figure 6. Split-phase ring barrier diagram

The decision whether to provide protected left turn phasing is based on the combination of the left turn and opposing through traffic volumes, the geometric layout of the intersection, the speeds of the opposing traffic, the number and kinds of traffic crashes that have occurred, and the delay and degree of queuing experienced by left turn traffic.

One common guideline is the "cross product" of the left turn volume and the sum of the opposing through and right turning volumes. The Highway Capacity Manual offers the following criterion for this guideline: the use of a protected left turn phase should be considered when, during the peak hour, the product of the left turning volume and the opposing traffic volume equals or exceeds:

- 50,000 if there is one opposing lane,
- 90,000 for two opposing lanes, and
- 110,000 for three or more opposing lanes.

Example 4. Left Turn Phasing

Consider the intersection shown in Figure 7, with one or two through lanes and an exclusive left turn lane on the four approaches. The hourly flow rates for each movement are also shown in the figure.

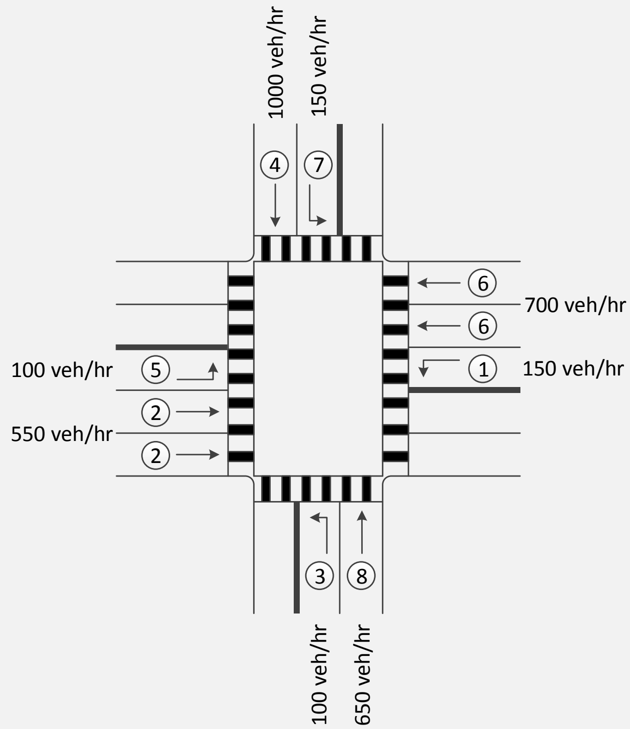

Figure 7. Flow rates for Example 4

Based on these flow rates and the intersection geometry, what left turn phasing would you recommend for each of the four approaches?

The flow rates for the left turn and through movement combinations are shown in Table 1. The cross products for each left turn-through movement combination are computed and also shown in the table. Finally, based on the criteria from the Highway Capacity Manual listed above, the recommended left turn phasing is given. In this case, the cross products are high enough for the north-south movements that protected left turn phasing would be recommended. However, permitted left turn phasing is sufficient for the east-west movements.

Table 1. LT-TH movement cross products and left turn phasing

Movement	Flow rate (veh/hr)	Cross product	HCM guideline	Recommended LT phasing
NBLT	100	100,000	50,000	Protected
SBTH	1000			
SBLT	150	97,500	50,000	Protected
NBTH	650			
EBLT	100	70,000	90,000	Permitted
WBTH	700			
WBLT	150	82,500	90,000	Permitted
EBTH	550			

Example 5. Creating a Ring Barrier Diagram
A signalized intersection has lagging protected left turns for the NB and SB movements and permitted left turns for the EB and WB movements. Create a ring barrier diagram for this case.

Figure 8 shows the ring barrier diagram that represents the conditions described above. For the east-west concurrency group, one phase (in this case phase 2), controls all of the movements. For the north-south concurrency group, phases 4 and 8 (controlling the through and right turn movements) "lead" the left turns (controlled by phases 3 and 7). The left turns "lag" the through movements.

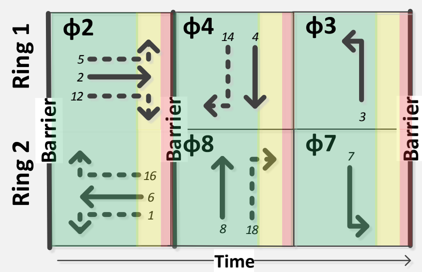

Figure 8. Ring barrier diagram for conditions in Example 5

3.4 Timing Stages

The ring-barrier concept allows compatible phases in different rings (within each concurrency group) to operate for different time durations based on the level of traffic volume. For example, if the traffic volume for the EBLT movement is greater than the volume for the WBLT movement, phase 5 (controlling the EBLT movement) can provide a longer green duration (or "time longer") than phase 1. Similarly, if the traffic volume for the NBLT movement is greater than the volume for the SBLT movement, then phase 3 can time longer than phase 7.

The conditions described above, represented in Figure 9 through the concept of the timing stage, show the intrinsic efficiency of the ring barrier process. A *timing stage* is an interval of time during which no signal displays change. The horizontal length of the phase is its relative time duration. Time moves from left to right.

- Stage 1 includes the concurrent timing of phases 1 and 5 serving the EBLT and WBLT movements. Because the volume for movement 1 is less than the volume for movement 5, phase 1 terminates before phase 5.
- The second stage is the concurrent timing of phases 2 and 5.
- When phase 5 terminates, phases 2 and 6 time concurrently in stage 3.
- The same process applies to the north-south concurrency group, shown in stages 4, 5, and 6.

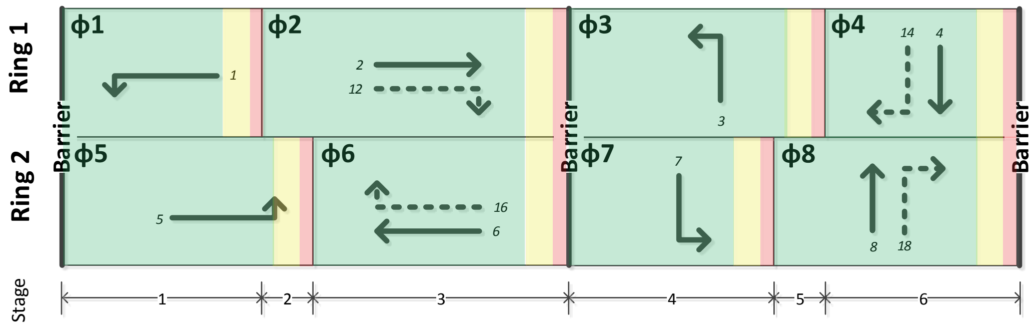

Figure 9. Ring barrier diagram and timing stages

Example 6. Phasing and Timing Stages

Consider the following timing requirements for the eight phases that serve a standard four leg intersection. If protected left turns are required, construct a ring barrier diagram for this intersection that shows the resulting timing stages. Assume also that the left turns lead the through movements.

Table 2. Phase durations

Phase	1	2	3	4	5	6	7	8
Duration, sec	15	30	10	25	10	35	10	25

The ring barrier diagram for leading protected left turns is shown in Figure 10.

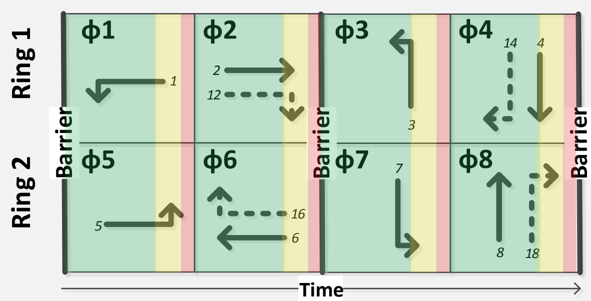

Figure 10. Ring barrier diagram

The ring barrier diagram can also be scaled based on the time required to serve each of the phases noted by the resulting timing stages (see Figure 11).

- For the east-west concurrency group, phases 1 and 5 time concurrently for 10 sec during stage 1
- But phase 1 times for an additional 5 sec. It times concurrently with phase 6 during stage 2.
- During stage 3, phases 2 and 6 time concurrently for 30 sec.
- When the barrier is crossed, phases 3 and 7 time concurrently for 10 sec, as part of stage 4. Here both phases end at the same time.
- Stage 5 consists of phases 4 and 8 timing concurrently for 25 sec.
- Note that the sum of the durations for phases 1 through 4 is equal to the durations for phases 5 through 8.

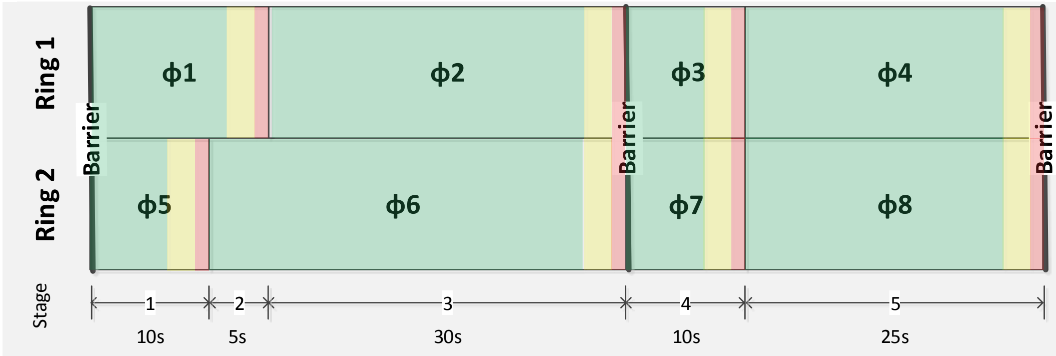

Figure 11. Ring barrier diagram with time scale

3.5 Summary of Section 3

What You Should Know and Be Able to Do:

- Define and apply the terms movement and phase
- Describe the sequencing and control of movements at a signalized intersection
- Determine left turn treatment
- Draw and interpret a ring barrier diagram that represents a particular phasing plan
- Define and apply the term timing stage

Concepts You Should Understand:

- Concept 3.1: Concurrency groups

Figure 12 shows the movements in the north-south and east-west concurrency groups. Movements in one concurrency group conflict with movements in the other concurrency group.

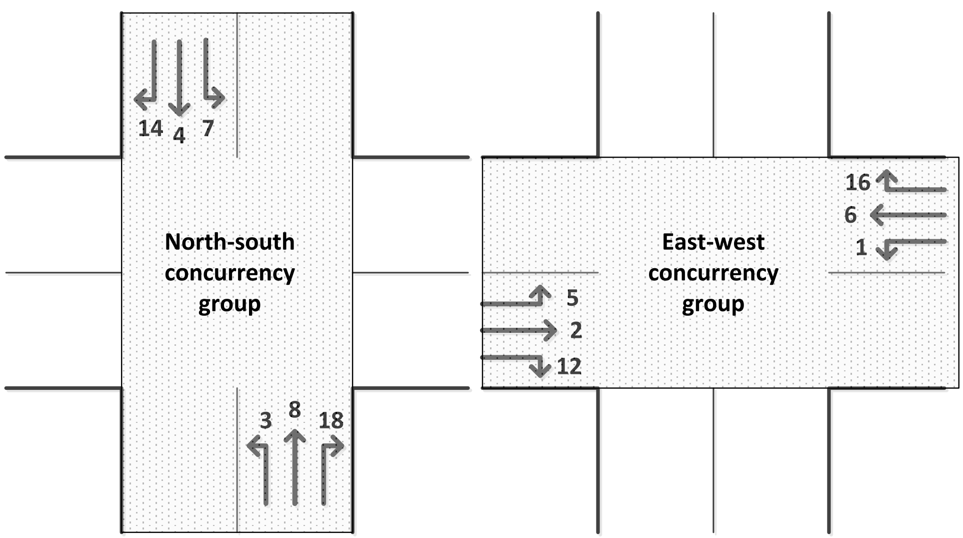

Figure 12. Concurrency groups

- Concept 3.2: Rings and the conflict and compatibility of phases in the same concurrency group:

Phases in the same ring conflict and must time sequentially. Figure 13 shows that phase 2 must time after phase 1 is completed.

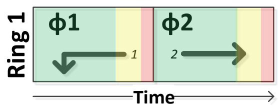

Figure 13. Phases timing sequentially

Phases in different rings are compatible and can time concurrently. Figure 14 shows that phase 1 can time concurrently with phases 5 and 6.

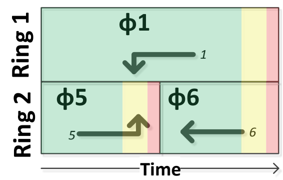

Figure 14. Phases timing concurrently

- Concept 3.3: Ring barrier diagram

The ring barrier diagram shows the phases in each ring that must time sequentially and the barrier that must be crossed at the same time by both rings. An example of a ring barrier diagram for leading protected left turns is shown in Figure 15:

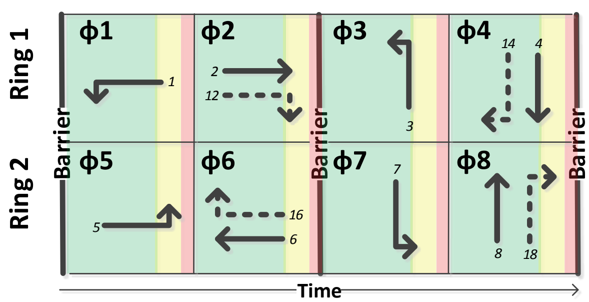

Figure 15. Ring barrier diagram