6. SUFFICIENCY OF CAPACITY

Learning objectives:
- Compute and interpret measures of capacity sufficiency for intersection performance
- Use the critical movement analysis to estimate intersection utilization

When designing a new intersection or evaluating the operation of an existing intersection, a common question to ask is: what is the capacity and is it sufficient to accommodate the traffic volume? A measure often used to determine whether there is sufficient capacity on an intersection approach is the volume-to-capacity ratio. A common method used to determine the volume-to-capacity ratio for an entire intersection is the critical movement analysis. Both the volume-to-capacity ratio and the critical movement analysis are described in this section.

6.1 Flow Ratio and Volume-to-Capacity Ratio

The *flow ratio* is defined as the ratio of the volume for a given movement to the saturation flow rate for that movement, or

Equation 1

$$Y = v/s$$

where
Y = flow ratio,
v = volume, veh/hr, and
s = saturation flow rate, veh/hr.

The flow ratio is the proportion of an hour that is required to serve a traffic movement. Thus the flow ratio determines the minimum effective green ratio required to serve that movement.

Example 9. Flow Ratio and Effective Green Ratio

Suppose that the volume on one approach of a signalized intersection is 600 veh/hr and the saturation flow rate for the approach is 1900 veh/hr. What proportion of the hour should be made available to serve this movement so that sufficient capacity is provided?

Using Equation 1, the flow ratio Y is determined to be

$$Y = \frac{600\ veh/hr}{1900\ veh/hr} = 0.32$$

This means that the effective green ratio must be at least 0.32 if sufficient capacity is to be provided to serve the demand on this approach.

The *volume-to-capacity ratio* is defined in Equation 2.

Equation 2

$$X = v/c$$

where
X = volume-to-capacity ratio,
v = volume, veh/hr, and
c = capacity, veh/hr.

Since the capacity is the product of the saturation flow rate and the effective green ratio, we can rewrite the definition of the volume-to-capacity ratio as

Equation 3

$$X = \frac{v}{s\left(\frac{g}{C}\right)} = \frac{v/s}{g/C} = \frac{Y}{g/C}$$

where
v = volume, veh/hr,
s = saturation flow rate, veh/hr,
g = effective green time, sec, and
C = cycle length, sec.

We can see from Equation 3 that if the flow ratio is less than the effective green ratio, then the volume-to-capacity ratio will be less than one. In this case, there will be sufficient capacity to serve the traffic demand. However, if the flow ratio is greater than the effective green ratio, there will not be sufficient capacity to serve the demand.

Example 10. Volume-to-Capacity Ratio
Suppose that the volume on an intersection approach is 750 veh/hr while the saturation flow rate is 1900 veh/hr. If the effective green ratio is 0.42, what is the volume-to-capacity ratio for the approach?

We first compute the capacity of the approach:

$$c = s\left(\frac{g}{C}\right) = 1900\ veh/hr\ (0.42) = 798\ veh/hr$$

The volume-to-capacity ratio is then:

$$X = \frac{v}{c} = \frac{750\ veh/hr}{798\ veh/hr} = .94$$

There are several interpretations of this result that are worth noting. First, there is just enough capacity to serve the demand, as *X* is just under one. However, if there is any variation in the demand (even small variations from one cycle to the next), the demand may exceed capacity. So, as we will see in the next section, it is prudent to provide some margin of safety in the design. Often a design value used for the volume-to-capacity ratio is 0.85 or less.

6.2 Critical Movement Analysis

While the definitions for volume-to-capacity ratio and flow ratio apply to an individual movement, we often want to determine the volume-to-capacity ratio for the entire intersection. If we know the volume-to-capacity ratio for the entire intersection, we can answer the question that began this section: is there sufficient capacity at the intersection to accommodate the traffic volume existing at or projected for the intersection?

The critical movement analysis method is commonly used for answering this question. The critical movement analysis method includes the five steps described below. The method is then illustrated with two examples, one for protected left turns and one for permitted left turns.

Step 1: Compute the flow ratio Y_i for each movement i present at the intersection. The standard movement numbers and notations are shown in Figure 1. Right turn volumes are combined with the through movement volumes.

Equation 4

$$Y_i = \frac{v_i}{s_i}$$

where

Y_i = flow ratio for movement i
v_i = volume for movement i, veh/hr, and
s_i = saturation flow rate for movement i, veh/hr.

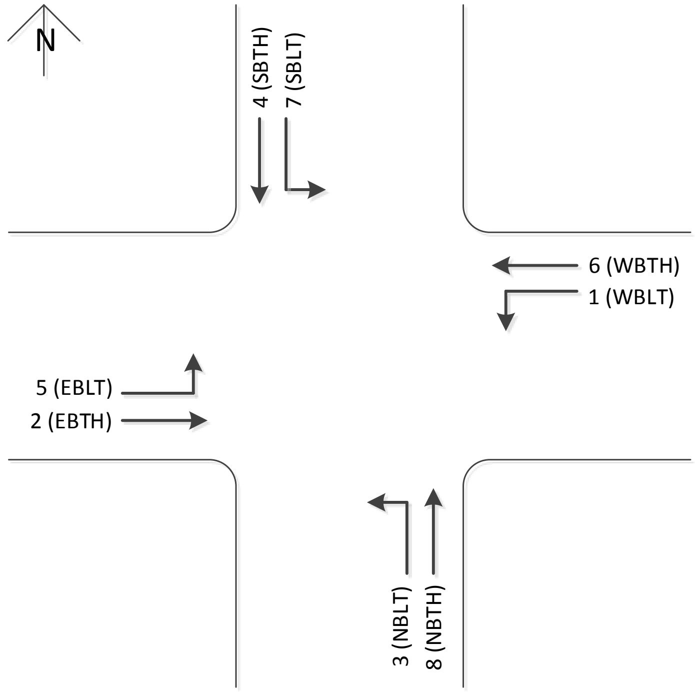

Figure 1. Numbering and notation of movements at a signalized intersection

Step 2: Determine the flow ratio sums for the phase sequences in each ring for each concurrency group (for the case of protected left turns only). (For permitted left turns, skip to step 3.)

Figure 2 and Figure 3 show the movements and phases from the east-west concurrency group.

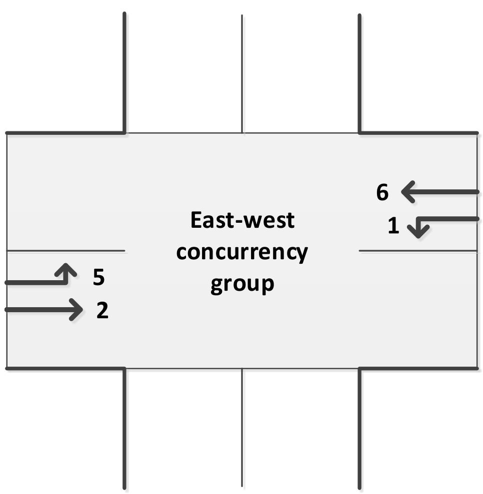

Figure 2. Movements served in east-west concurrency group

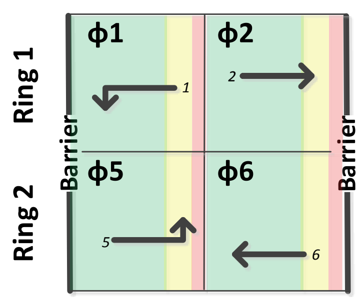

Figure 3. Phases served in east-west concurrency group

For the east-west concurrency group, the flow ratio sums for the movements served in rings 1 and 2 are given by Equation 5 and Equation 6.

Signalized Intersection Module – Excerpt: Critical Movement Analysis

Equation 5

$$Y_{EW1} = Y_1 + Y_2$$

Equation 6

$$Y_{EW2} = Y_5 + Y_6$$

where

Y_{EW1} = flow ratio sum for ring 1,
Y_{EW2} = flow ratio sum for ring 2, and
Y_i = flow ratios for movements 1, 2, 5, and 6

Figure 4 and Figure 5 show the movements and phases from the north-south concurrency group.

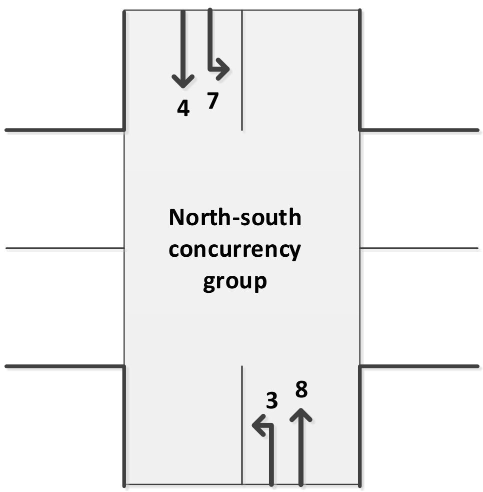

Figure 4. Movements served in north-south concurrency group

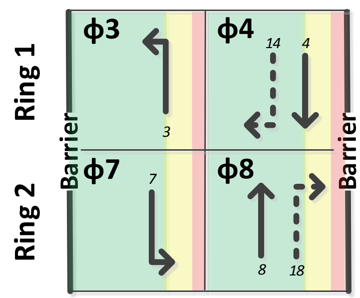

Figure 5. Phases served in north-south concurrency group

For the north-south concurrency group, the flow ratio sums are given by Equation 7 and Equation 8.

Equation 7

$$Y_{NS1} = Y_3 + Y_4$$

Equation 8

$$Y_{NS2} = Y_7 + Y_8$$

where

Y_{NS1} = flow ratio sum for ring 1,
Y_{NS2} = flow ratio sum for ring 2, and
Y_i = flow ratios for movements 3, 4, 7, and 8.

Step 3: Within each concurrency group, identify the movements with the maximum flow ratio sum (for protected left turns) or the movement with the

maximum flow ratio (for permitted left turns). These movements are the critical movements for each concurrency group.

For protected left turns, we use Equation 9 and Equation 10 to determine the critical movements for the east-west and north-south concurrency groups.

Equation 9

$$Y_{EW-critical} = Max(Y_{EW1}, Y_{EW2})$$

where

$Y_{EW\text{-}critical}$ = critical flow ratio for the EW concurrency group,
Y_{EW1} = flow ratio sum for ring 1, and
Y_{EW2} = flow ratio sum for ring 2.

Equation 10

$$Y_{NS-critical} = Max(Y_{NS1}, Y_{NS2})$$

where

$Y_{NS\text{-}critical}$ = critical flow ratio for NS concurrency group,
Y_{NS1} = flow ratio sum for ring 1, and
Y_{NS2} = flow ratio sum for ring 2.

For permitted left turns, we use Equation 11 and Equation 12 to determine the critical movements for each concurrency group.

Equation 11

$$Y_{EW-critical} = Max(Y_1, Y_2, Y_5, Y_6)$$

where

$Y_{EW\text{-}critical}$ = critical flow ratio for the EW concurrency group, and
Y_i = flow ratios for movements 1, 2, 5, and 6.

Equation 12

$$Y_{NS-critical} = Max(Y_3, Y_4, Y_7, Y_8)$$

where

$Y_{NS\text{-}critical}$ = critical flow ratio for NS concurrency group, and
Y_i = flow ratios for movements 3, 4, 7, and 8.

Step 4: Determine the critical volume-to-capacity ratio for the intersection.

Step 4a: Compute the lost time per cycle *L* as given in Equation 13.

Signalized Intersection Module – Excerpt: Critical Movement Analysis

Equation 13

$$L = \sum_{i=1}^{M} t_{Li}$$

where

L = lost time per cycle, sec,
t_{Li} = lost time for phase i, and
M = number of phases that serve the critical movements for one cycle.

If all left turn movements are protected, M is 4; if all are permitted, M is 2. If the left turn movements for one concurrency group are protected and if they are permitted for the other concurrency group, M is 3.

Step 4b: Compute the *critical volume-to-capacity* ratio considering the critical flow ratios and the lost time per cycle, using Equation 14.

Equation 14

$$X_c = \frac{(Y_{EW-critical} + Y_{NS-critical})(C)}{C - L}$$

where

X_c = critical volume-to-capacity ratio,
$Y_{EW\text{-}critical}$ = critical flow ratio for the EW concurrency group,
$Y_{NS\text{-}critical}$ = critical flow ratio for the NS concurrency group,
C = cycle length, sec, and
L = total lost time per cycle for the critical phases, sec.

Step 5: Based on the value of X_c calculated in step 4, determine the sufficiency of capacity.

Table 1 gives four possible sufficiency ratings based on the critical volume-to-capacity ratio computed for the intersection. It is desirable, though not often possible during the peak period, for X_c to be less than 0.85.

Table 1. Sufficiency of capacity

X_c	Sufficiency of capacity rating
< 0.85	Intersection is operating under capacity. Excessive delays are not experienced.
0.85–0.95	Intersection is operating near its capacity. Higher delays may be expected, but continuously increasing queues should not occur.
0.95–1.00	Unstable flow results in a wide range of delay. Intersection improvements will be required soon to avoid excessive delays.
> 1.00	The demand exceeds the available capacity of the intersection. Excessive delays and queuing are anticipated.

Example 11. Critical Movement Analysis for Protected Left Turns
A standard 4-approach intersection has the geometric and volume characteristics shown in Figure 6. Figure 7 shows the phasing plan for this intersection, including leading protected left turns. The cycle length is 90 sec and the lost time is 4 sec/phase. The saturation flow rate is 1900 veh/hour/lane for through movements and protected left turn movements. Use the critical movement analysis method to determine whether the capacity is sufficient to serve the volume for this intersection.

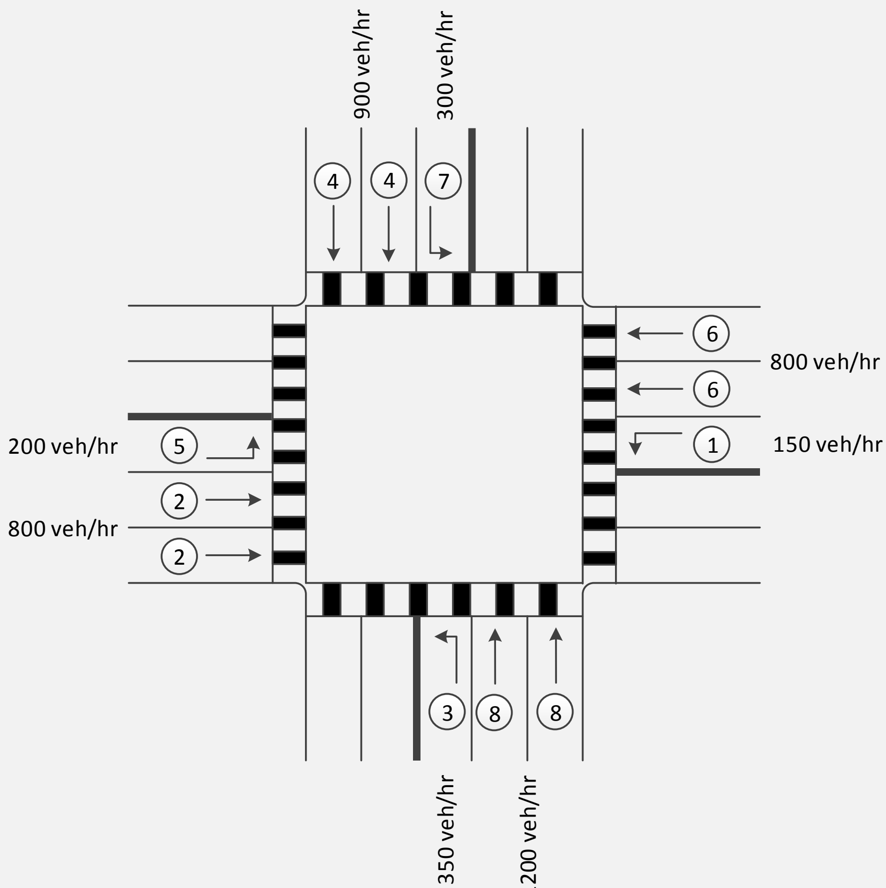

Figure 6. Intersection characteristics for Example 11

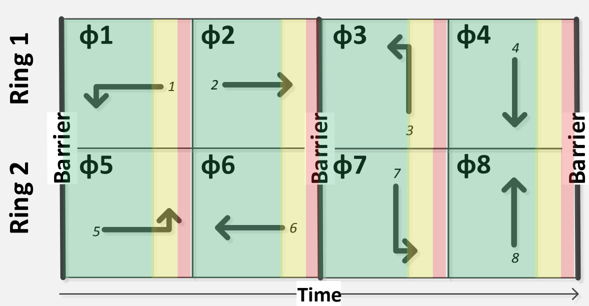

Figure 7. Phasing plan for Example 11

Step 1: Compute the flow ratio Y for each movement present at the intersection.
The flow ratios for each of the movements are calculated and shown in Figure 8.

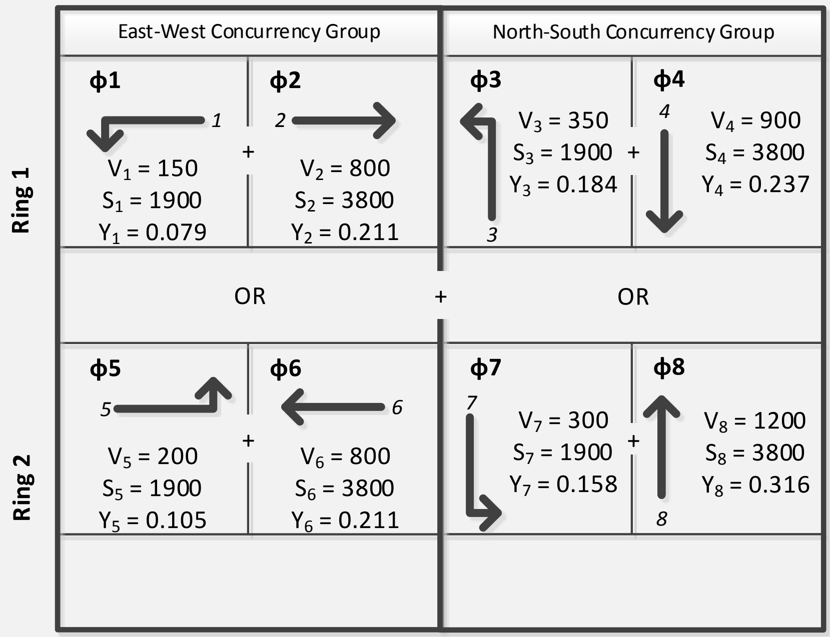

Figure 8. Flow ratios for each movement for Example 11

Step 2: Determine the flow ratio sums for the phase sequences in each ring for each concurrency group (for the case of protected left turns only).
The flow ratio sums for each ring within each concurrency group are shown in Figure 9. For example, for ring 1 in the east-west concurrency group, the flow ratios for movements 1 and 2 are .079 and .211, respectively. Their sum, noted as Y_{EW1}, is .290.

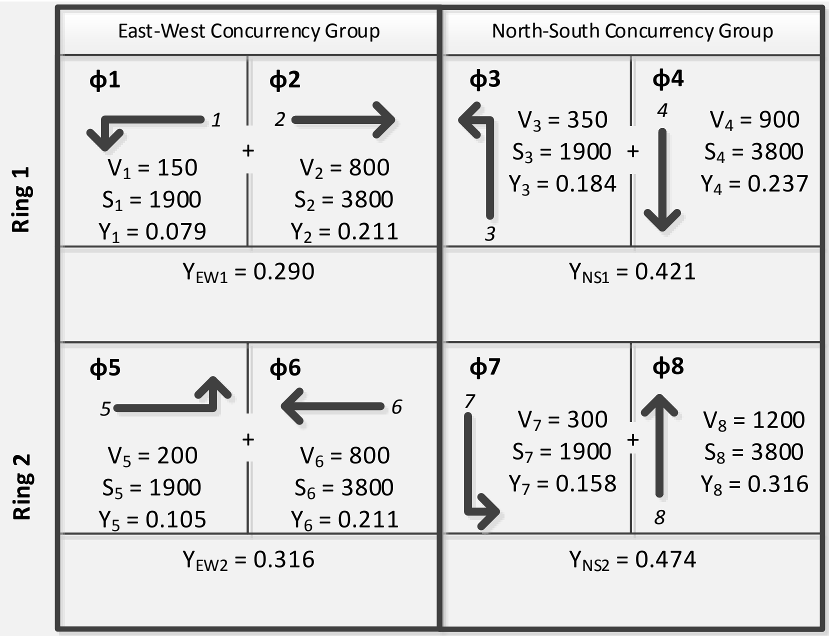

Figure 9. Flow ratio sums for Example 11

Step 3: Within each concurrency group, identify the movements with the maximum flow ratio sum (for protected left turns) or the movement with the maximum flow ratio (for permitted left turns). These movements are the critical movements for each concurrency group.

Since these are protected left turns, we identify the movements with the maximum flow ratio sum within each concurrency group (See Figure 10). For the east-west concurrency group, the movements served in ring 2 (movements 5 and 6) have the highest flow ratio sum (.316), as compared to the movements served in ring 1 (.290). For the north-south concurrency group, the movements served in ring 2 have the highest flow ratio sum (.474).

$$Y_{EW-critical} = Max(Y_{EW1}, Y_{EW2}) = Max(.290, .316) = .316$$
$$Y_{NS-critical} = Max(Y_{NS1}, Y_{SW2}) = Max\ (.421, .474) = .474$$

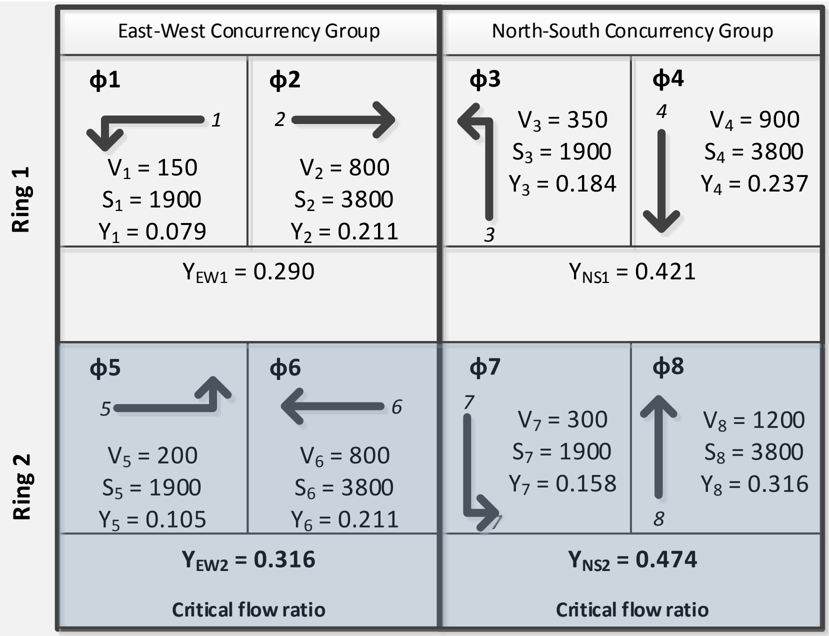

Figure 10. Critical flow ratios for Example 11

Step 4: Determine the critical volume-to-capacity ratio X_c for the intersection.

The critical flow ratios (Y_{EW2}=.316, Y_{NS2}=.474) were computed in step 3. The cycle length is given as 90 sec and the lost time per phase is 4 seconds. There are four critical phases since all left turns are protected, so the total lost time *L* is 16 sec. The critical volume-to-capacity ratio is computed using Equation 14:

$$X_c = \frac{(Y_{EW-critical} + Y_{NS-critical})(C)}{C - L} = \frac{(.316 + \ .474)(90\ sec)}{90\ sec - 16\ sec} = \ .96$$

Step 5: Based on the value of X_c calculated in step 4, determine the sufficiency of capacity.

The critical volume-to-capacity ratio, X_c = .96, indicates that the intersection is operating in the region of unstable flow and that excessive delays and queuing will result, using the ratings from Table 1.

Example 12. Critical Movement Analysis for Permitted Left Turns
A standard four-approach intersection has the geometric and volume characteristics shown in Figure 11. The phasing scheme is shown in Figure 12. The cycle length is 90 sec and the lost time is 4 sec per phase. The permitted left turns have a saturation flow rate of 450 veh/hr while through movements have a saturation flow rate of 1900 veh/hr.

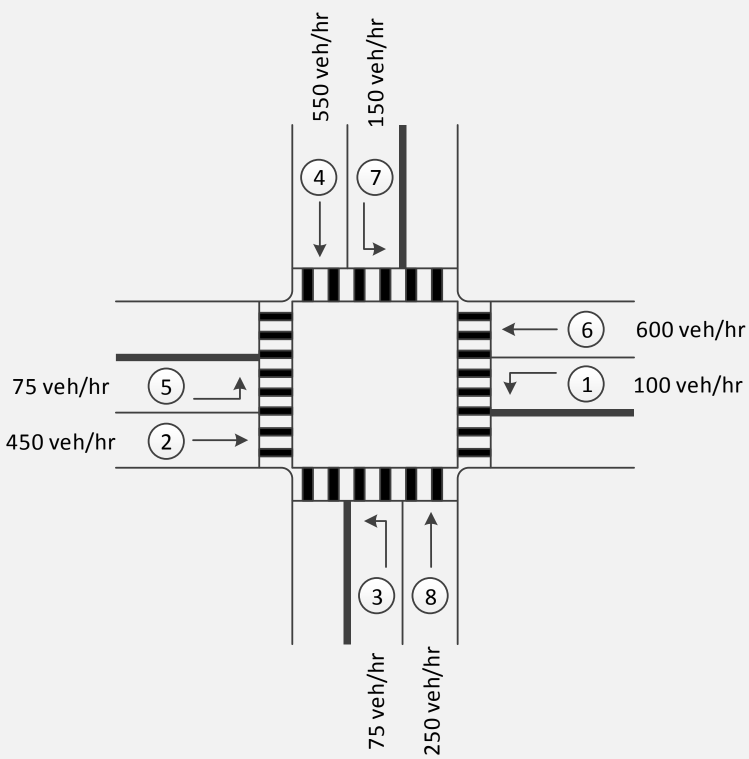

Figure 11. Intersection characteristics for Example 12

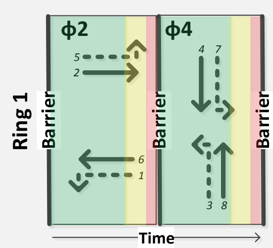

Figure 12. Ring barrier diagram for Example 12

Step 1: Compute the flow ratio Y_i for each movement i present at the intersection.
The flow ratios for each of the movements are calculated and shown in Figure 13.

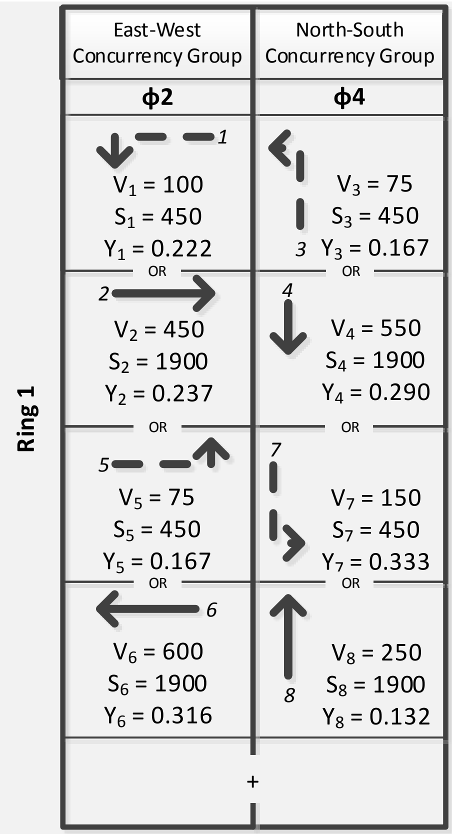

Figure 13. Flow ratios for each movement for, Example 12

Step 2: Determine the flow ratio sums for the phase sequences in each ring for each concurrency group (for the case of protected left turns only).
Since this example is for permitted left turns, we skip to step 3.

Step 3: Within each concurrency group, identify the movements with the maximum flow ratio sum (for protected left turns) or the movement with the maximum flow ratio (for permitted left turns). These movements are the critical movements for each concurrency group.
Since this example is for permitted left turns, we identify the movement with the maximum flow ratio in each concurrency group. As shown in Figure 14, movement 2 has the highest flow ratio (.316) for the east-west concurrency group. For the north-south concurrency group, movement 7 has highest flow ratio (.333).

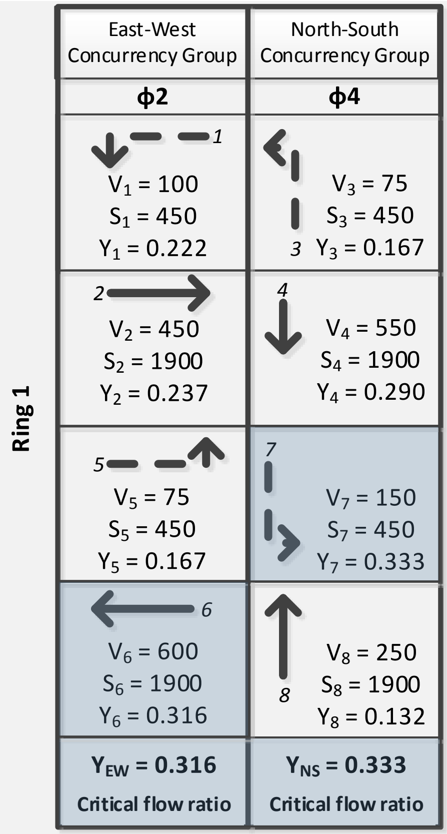

Figure 14. Critical flow ratios for Example 12

Step 4: Determine the critical volume-to-capacity ratio (X_c) for the intersection.
The critical flow ratios (Y_{EW}=.316, Y_{NS}=.333) were determined in step 3. The cycle length is given as 90 sec and the lost time per phase is 4 sec. There are two critical phases since all left turns are permitted, so the total lost time *L* is 8 sec. The critical volume-to-capacity ratio is computed using Equation 14.

$$X_c = \frac{(Y_{EW-critical} + Y_{NS-critical})(C)}{C - L} = \frac{(.316 + .333)(90\ sec)}{90\ sec - 8\ sec} = .71$$

Step 5: Based on the value of X_c calculated in step 4, determine the sufficiency of capacity.
The critical volume-to-capacity ratio, X_c = 0.71, indicates that the intersection is operating under capacity, using the ratings from Table 1.

6.3 Summary of Section 6

What You Should Know and Be Able to Do:

- Compute and interpret measures of capacity sufficiency for intersection performance
- Use the critical movement analysis to estimate intersection utilization

Concepts You Should Understand:

- Concept 6.1: Flow ratio and green ratio

The flow ratio shows the proportion of the hour needed to serve a traffic movement. The green ratio shows the proportion of an hour available to serve a traffic movement.

- Concept 6.2: Relationship between green ratio, flow ratio, and sufficiency of capacity

As long as the green ratio is greater than the flow ratio, there is sufficient capacity to serve the traffic demand.

- Concept 6.3: Critical movements in a concurrency group

For a concurrency group, the critical movements are those movements with the highest flow ratio sum considering each of the rings in the concurrency group (for protected left turns) or the movement with the highest flow ratio (for permitted left turns).

- Concept 6.4: Critical volume-to-capacity ratio

The critical volume-to-capacity ratio is the proportion of the available capacity at the intersection used by the critical traffic movements.