to make an initial determination of whether left-turn movements need to be protected. Do not include compound phasing in preliminary signal timing; this may be tried as part of a more comprehensive intersection analysis later.

2. Convert all left-turn and right-turn movements to equivalent through vehicle units (tvu's) using the equivalents of Tables 18.1 and 18.2, respectively.
3. Draw a ring diagram of the proposed phase plan, inserting lane volumes (in tvu's) for each set of movements. Determine the critical path through the signal phasing as well as the sum of the critical-lane volumes (V_c) for the critical path.
4. Determine *yellow* and *all-red* intervals for each signal phase.
5. Determine lost times per cycle using Equations 18-5 through 18-7.
6. Determine the desirable cycle length, C, using Equation 18-11. For pretimed signals, round up to reflect available controller cycle lengths. An appropriate *PHF* and reasonable target v/c ratio should be used.
7. Allocate the available effective green time within the cycle in proportion to the critical lane volumes for each portion of the phase plan.
8. Check pedestrian requirements and adjust signal timing as needed.

Example 18-1: Signal-Timing Case 1: A Simple Two-Phase Signal

Consider the intersection layout and demand volumes shown in Figure 18.13. It shows the intersection of two streets with one lane in each direction and relatively low turning volumes. Moderate pedestrian activity is present, and the *PHF* and target v/c ratio is specified.

Solution:

Step 1: Develop a Phase Plan

Given that there is only one lane for each approach, it is not possible to even consider including protected left turns in the phase plan. However, a check of the criteria of Equation 18-1 shows that no protected left turns are required for this case:

- EB: $V_{LT} = 10 < 200$
  xprod $= 10 * 315/1 = 3{,}150 < 50{,}000$
- WB: $V_{LT} = 12 < 200$
  xprod $= 12 * 420/1 = 5{,}040 < 50{,}000$
- NB: $V_{LT} = 10 < 200$
  xprod $= 10 * 400/1 = 4{,}000 < 50{,}000$
- SB: $V_{LT} = 10 < 200$
  xprod $< 10 * 375/1 = 3{,}750 < 50{,}000$

A simple two-phase signal, therefore, will be adopted for this intersection.

Step 2: Convert Volumes to Through-Vehicle Equivalents

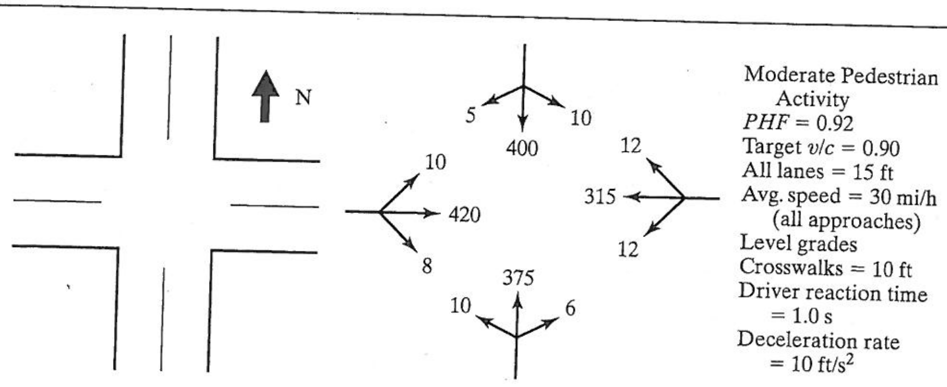

Figure 18.13: Signal-Timing Case 1

Table 18.4: Computation of Through Vehicle Equivalent Volumes for Signal Timing Case 1

Approach	Movement	Volume (Veh/h)	Equivalent Tables 18.1, 18.2	Volume (tvu/h)	Lane Group Vol (tvu/h)	Vol/Lane (tvu/h/ln)
EB	L	10	3.94	39	470	470
	T	420	1.00	420		
	R	8	1.32	11		
WB	L	12	5.50	66	397	397
	T	315	1.00	315		
	R	12	1.32	16		
NB	L	10	5.00	50	433	433
	T	375	1.00	375		
	R	6	1.32	8		
SB	L	10	4.69	47	454	454
	T	400	1.00	400		
	R	5	1.32	7		

The conversion of volumes to tvus is illustrated in Table 18.4. Equivalent values are taken from Tables 18.1 and 18.2, and are interpolated for intermediate values of opposing volume. Note that all through vehicles are equivalent to 1.0 tvu.

Step 3: Determine Critical-Lane Volumes

The critical path through the signal phase plan is illustrated in Figure 18.14. As a two-phase signal, this is a relatively simple determination. For Phase A, either the EB or WB approach is critical. As the EB approach has the higher lane volume, 470 tvu/h, this is the critical movement for Phase A. For Phase B, either the NB or SB approach is critical; SB has the higher lane volume (454 tvu/h), so this is the critical movement for Phase B. The sum of the critical-lane volumes is, therefore, 470 + 454 = 924 tvu/h.

Step 4: Determine Yellow and All-Red Intervals

Yellow and *all-red* intervals are found using Equations 18-2 and 18-3. The average approach speed for all approaches is 30 mi/h. Thus, the $S_{85} = 30 + 5 = 35$ mi/h, and the $S_{15} = 30 - 5 = 25$ mi/h. As there are moderate numbers of pedestrians present, the all-red interval will be computed using Equation 18-3b, which allows vehicles to clear beyond the far crosswalk line. The distance to be crossed during the *all-red* clearance interval

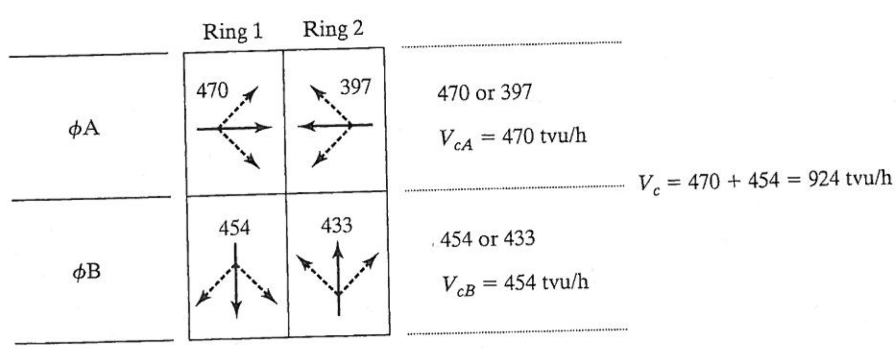

Figure 18.14: Determination of Critical Lane Volumes—Signal-Timing Case 1

is the sum of two 15-ft lanes and a 10-ft crosswalk, or $P = 15 + 15 + 10 = 40$ ft. Then:

$$y = t + \frac{1.47\, S_{85}}{2a + (64.4 * 0.01G)}$$

$$= 1.0 + \frac{1.47 * 35}{(2 * 10) + (0)}$$

$$= 3.6 \text{ s}$$

$$ar = \frac{P + L}{1.47 S_{15}} = \frac{40 + 20}{1.47 * 25} = 1.6 \text{ s}$$

Because both streets have the same width, crosswalk width, and approach speed, the values of y and ar are the same for both Phases A and B of the signal.

Step 5: Determination of Lost Times

Lost times are found using Equations 18-5 through 18-7. In this case, the recommended 2.0-s default values for start-up lost time (ℓ_1) and extension of effective green into yellow and all-red (e) are used:

$$Y = y + ar = 3.6 + 1.6 = 5.2 \text{ s}$$

$$\ell_2 = Y - e = 5.2 - 2.0 = 3.2 \text{ s}$$

$$t_L = \ell_1 + \ell_2 = 2.0 + 3.2 = 5.2 \text{ s}$$

As both phases have the same value, the total lost time per cycle, L, is $5.2 + 5.2 = 10.4$ s. Note that in all cases where the recommended default values for ℓ_1 (2.0 s) and e (2.0 s) are used, lost time per phase (t_L) is the same numerical value as the sum of the yellow and all red intervals (Y).

Step 6: Determine the Desirable Cycle Length

Equation 18-11 is used to determine the desirable cycle length:

$$C_{des} = \frac{L}{1 - \left(\dfrac{V_c}{1{,}615 * PHF * v/c}\right)}$$

$$= \frac{10.4}{1 - \left(\dfrac{924}{1{,}615 * 0.92 * 0.90}\right)}$$

$$= \frac{10.4}{0.31} = 33.5 \text{ s}$$

Assuming that this is a pretimed controller, a desirable cycle length of 35 s or a 40 s would be used. For the purposes of this signal timing case, the minimum value of 35 s will be used.

Step 7: Allocate Effective Green to Each Phase

Given a 35-second cycle length with 10.4 s of lost time per cycle, the amount of effective green time to be allocated is $35.0 - 10.4 = 24.6$ s. The allocation is done using Equation 18-13:

$$g_A = g_{TOT} * \left(\frac{V_{cA}}{V_c}\right) = 24.6 * \left(\frac{470}{924}\right) = 12.5 \text{ s}$$

$$g_B = g_{TOT} * \left(\frac{V_{cB}}{V_c}\right) = 24.6 * \left(\frac{454}{924}\right) = 12.1 \text{ s}$$

The cycle length may be checked as the total of effective green times plus the lost time per cycle, or $12.5 + 12.1 + 10.4 = 35.0$ s. Effective green times may be converted to actual green times using Equation 18-14:

$$G_A = g_A - Y_A + t_{LA} = 12.5 - 5.2 + 5.2 = 12.5 \text{ s}$$

$$G_B = g_B - Y_B + t_{LB} = 12.1 - 5.2 + 5.2 = 12.1 \text{ s}$$

Again, note that when default values for start-up lost time (2.0 s) and extension of effective green into yellow and all-red (2.0 s) are used, the actual green time is numerically the same as effective green time.

Step 8: Check Pedestrian Requirements

Equation 18-15 is used to compute the minimum pedestrian green requirement for each phase. Because both streets have equal width and equal crosswalk widths and because pedestrian traffic is "moderate" in all crosswalks, the requirements will be the same for each phase in this case. From Table 18.2, the default pedestrian volume for "moderate" activity is 200 peds/h. The number of pedestrians per cycle (N_{ped}) is based on the number of cycles per hour (3,600/35 = 102.9, say 103 cycles/h). The number of pedestrians per cycle is then 200/103 = 1.94, say 2 peds/cycle. Then:

$$G_{pA,B} = 3.2 + \left(\frac{L}{S_p}\right) + (0.27 N_{ped})$$

$$= 3.2 + \left(\frac{30}{4.0}\right) + (0.27 * 2) = 11.2 \text{ s}$$

For this signal to be safe for pedestrians:

$$G_p < G + Y$$
$$G_{pA} = 11.2 < 12.5 + 5.2 = 17.7 \text{ s OK}$$
$$G_{pB} = 11.2 < 12.1 + 5.2 = 17.3 \text{ s OK}$$

The signal safely accommodates all pedestrians. No changes in the signal timing for vehicular needs is required.

Example 18-2: Signal Timing Case 2: Intersection of Major Arterials

Figure 18.15 illustrates the intersection of two four-lane arterials with significant demand volumes and exclusive left-turn lanes provided on each approach.

Step 1: Develop a Phase Plan

Each left-turn movement should be checked against the criteria of Equation 18-1 to determine whether or not it needs to be protected:

- EB: $V_{LT} = 35 < 200$
  xprod = 35 * (500/2) = 8,750 < 50,000
  No protection needed.
- WB: $V_{LT} = 25 < 200$
  xprod = 25 * (610/2) = 22,875 < 50,000
  No protection needed.
- NB: $V_{LT} = 250 > 200$
  Protection needed.
- SB: $V_{LT} = 220 > 200$
  Protection needed.

Given that the NB and SB left turns require a protected phase, the next issue is how to provide it. The two opposing left-turn volumes, 220 veh/h (NB) and 250 veh/h (SB), are not numerically very different. Therefore, there appears to be little reason to separate the NB and SB protected phases. An exclusive left-turn phase will be used on the N–S arterial. A single phase using permitted left turns will be used on the E–W arterial.

Step 2: Convert Volumes to Through Vehicle Equivalents

Through-vehicle equivalents are obtained from Tables 18.1 and 18.2 for left and right turns, respectively. The computations are illustrated in Table 18.5.

Note that exclusive LT lanes must be established as separate lane groups, with their demand volumes separately computed, as shown in Table 18.5. The equivalent for all protected left turns (Table 18.1) is 1.05.

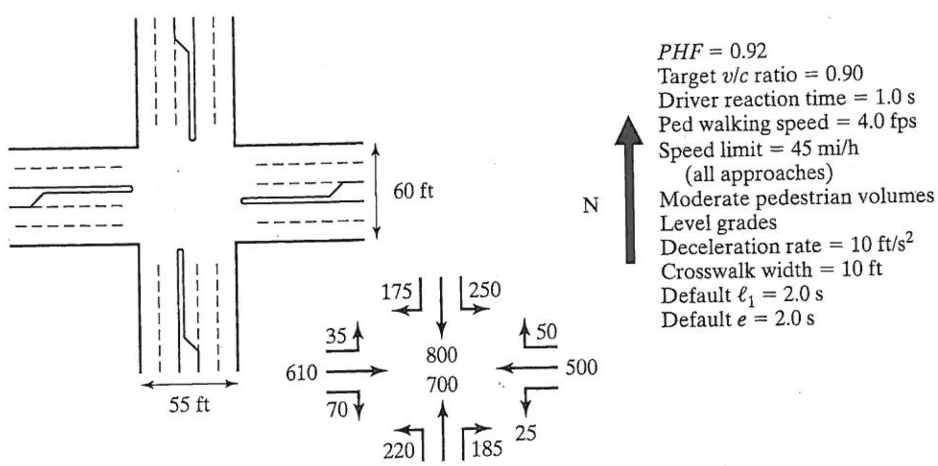

Figure 18.15: Signal-Timing Case 2

Table 18.5: Computation of Through Vehicle Equivalent Volumes for Signal-Timing Case 2

Approach	Movement	Volume (Veh/h)	Equivalent Tables 18.1, 18.2	Volume (tvu/h)	Lane Group Vol (tvu/h)	Vol/Lane (tvu/h/ln)
EB	L	35	4.00*	140	140	140
	T	610	1.00	610	702	351
	R	70	1.32	92		
WB	L	25	5.15*	129	129	129
	T	500	1.00	500	566	283
	R	50	1.32	66		
NB	L	220	1.05	231	231	231
	T	700	1.00	700	944	472
	R	185	1.32	244		
SB	L	250	1.05	263	263	263
	T	800	1.00	800	1,031	516
	R	175	1.32	231		

*Interpolated by opposing volume.

Step 3: Determine Critical Lane Volumes

As noted in Step 1, the signal phase plan includes an exclusive LT phase for the N–S artery and a single phase with permitted left turns for the E–W artery. Figure 18.16 illustrates this and the determination of critical lane volumes.

Phase A is the exclusive N–S LT phase. The heaviest movement in the phase is 263 tvu/h for the SB left turn. In Phase B, the heavier movement is the SB through and right turn, with 516 tvu/h. In Phase C, both E–W left-turn lane groups and through/right-turn lane groups move at the same time. The heaviest movement is the EB TH/RT lanes, with 351 tvu/h. The sum of critical-lane volumes, V_c, is, therefore, $263+516+351 = 1{,}130$ tvu/h.

Note that each "ring" handles two sets of movements in Phase C. This is possible, of course, because it is the same signal face that controls all movements in a given direction. The left-turn lane volume cannot be averaged with the through/right-turn movement as there are lane-use restrictions involved. All left turns must be in the left-turn lane; none may be in the through/right-turn lanes.

Step 4: Determine Yellow and All-Red Intervals

Equation 18-2 is used to determine the length of the *yellow* interval; Equation 18-3b is used to determine the length of the *all-red* interval. As a speed limit—45 mi/h—is given rather than a measured average approach speed, there will be no differentiation between the S_{85} and S_{15}.

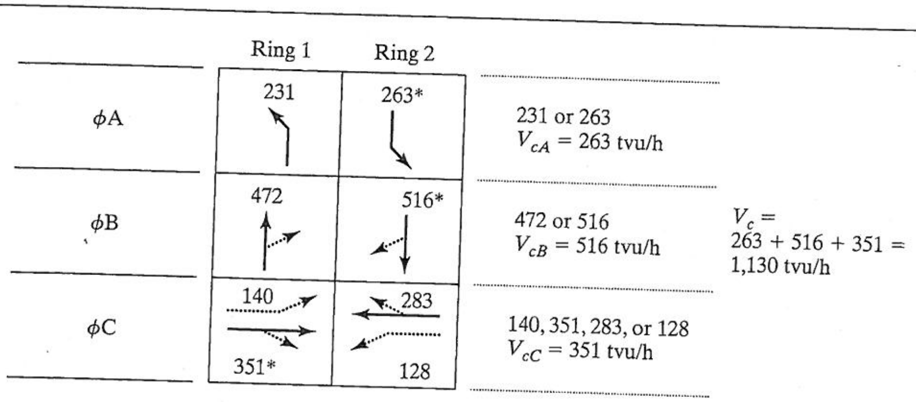

Figure 18.16: Determination of Critical-Lane Volumes—Signal-Timing Case 2

As the speed limits on both arteries are the same, the *yellow* intervals for all three phases will also be the same:

$$y_{A,B,C} = 1.0 + \frac{1.47 * 45}{(2 * 10) + (0)} = 4.3 \text{ s}$$

The *all-red* intervals will reflect the need to clear the full width of the street plus the width of the far crosswalk. The width of the N–S street is 55 ft, while the width of the E–W street is 60 ft. The width of a crosswalk is 10 ft. During the N–S left-turn phase, it will be assumed that a vehicle must clear the entire width of the E–W artery. Thus, for Phase A, the width to be cleared (*P*) is 60 +10 = 70 ft; for Phase B, it is also 60 +10 = 70 ft; for Phase C, the distance to be cleared is 55 +10 = 65 ft. Thus:

$$ar_{A,B} = \frac{70 + 20}{1.47 * 45} = 1.4 \text{ s}$$

$$ar_C = \frac{65 + 20}{1.47 * 45} = 1.3 \text{ s}$$

where 20 ft is the assumed length of a typical vehicle.

Step 5: Determination of Lost Times

Remembering that where the default values for ℓ_1 and e are both 2.0 s, that the lost time per phase, t_L, is the same as the sum of the yellow plus all-red intervals, Y:

$$Y_{A,B} = t_{LA,B} = 4.3 + 1.4 = 5.7 \text{ s}$$

$$Y_C = t_{LC} = 4.3 + 1.3 = 5.6 \text{ s}$$

Based on this, the total lost time per cycle, L, is 5.7 + 5.7 + 5.6 = 17.0 s.

Step 6: Determine the Desirable Cycle Length

The desirable cycle length is found using Equation 18-11:

$$C_{des} = \frac{17}{1 - \left(\frac{1{,}130}{1{,}615 * 0.92 * 0.90}\right)} = \frac{17}{0.155} = 109.7 \text{ s}$$

Assuming that this is a pretimed signal controller, a cycle length of 110 s would be selected.

Step 7: Allocate Effective Green to Each Phase

In a cycle length of 110 s, with 17 s of lost time per cycle, the amount of effective green time that must be allocated to the three phases is 110 − 17 = 93 s. Using Equation 18-13, the effective green time is allocated in proportion to the phase critical lane volumes:

$$g_A = 93 * \left(\frac{263}{1{,}130}\right) = 21.6 \text{ s}$$

$$g_B = 93 * \left(\frac{516}{1{,}130}\right) = 42.5 \text{ s}$$

$$g_C = 93 * \left(\frac{351}{1{,}130}\right) = 28.9 \text{ s}$$

The cycle length is now checked to ensure that the sum of all effective green times and the lost time equals 110 s: 21.6 + 42.5 + 28.9 + 17.0 = 110 OK. Note that when the default values for ℓ_1 and e (both 2.0 s) are used, actual green times, G, equal effective green times, g

Step 8: Check Pedestrian Requirements

Pedestrian requirements are estimated using Equation 18 15. In this case, note that pedestrians will be permitted t cross the E–W artery only during Phase B. Pedestrian will cross the N–S artery during Phase C. The number c pedestrians per cycle for all crosswalks is the defau pedestrian volume for "moderate" activity, 200 peds/h, di vided by the number of cycles in an hou (3600/110 = 32.7 cycles/h). Thus, N_{ped} = 200/32. = 6.1 peds/cycle. Required pedestrian green times ar

$$G_{pB} = 3.2 + \left(\frac{60}{4.0}\right) + (0.27 * 6.1)$$
$$= 3.2 + 15.0 + 1.6 = 19.8 \text{ s}$$

$$G_{pC} = 3.2 + \left(\frac{55}{4.0}\right) + (0.27 * 6.1)$$
$$= 3.2 + 13.8 + 1.6 = 18.6 \text{ s}$$

The minimum requirements are compared to the sum the green, yellow, and all-red times provided for vehicle

$$G_{pB} = 19.8 \text{ s} < G_B + Y_B = 42.5 + 5.7 = 48.2 \text{ s} \quad OK$$

$$G_{pC} = 18.6 \text{ s} < G_C + Y_C = 28.9 + 5.6 = 34.5 \text{ s} \quad OK$$

Therefore, no changes to the vehicular signal timing a required to accommodate pedestrians safely.

For major arterial crossings, pedestrian sign would normally be provided. During Phase A, all ped trian signals would indicate "DON'T WALK." Dur

Phase B, the pedestrian clearance interval (the flashing DON'T WALK) would be L/S_p or 60/4.0 = 15.0 s. The WALK interval is whatever time is left in $G + Y$, counting from the end of Y: 48.2 − 15.0 = 33.2 s. During Phase C, L/S_p is 55/4.0 = 13.8 s, and the WALK interval would be 34.5 − 13.8 = 20.7 s.

Example 18-3: Signal-Timing Case 3: Another Junction of Major Arterials

Figure 18.17 illustrates another junction of major arterials. In this case, the E–W artery has three through lanes, plus an exclusive LT lane and an exclusive RT lane in each direction. In effect, each movement on the E–W artery has its own lane group. The N–S artery has two lanes in each direction, with no exclusive LT or RT lanes. There are no pedestrians present at this intersection.

Step 1: Develop a Phase Plan

Phasing is determined by the need for left-turn protection. Using the criteria of Equation 18-1, each left turn movement is examined.

- EB: $V_{LT} = 300$ veh/h > 200 veh/h
  Protected phase needed.
- WB: $V_{LT} = 150$ veh/h < 200 veh/h
  xprod = 150 * (1200/3)
  = 60,000 > 50,000
  Protected phase needed.
- NB: $V_{LT} = 50$ veh/h < 200 veh/h
  xprod = 50 * (400/2)
  = 10,000 < 50,000
  Protected phase not needed.
- SB: $V_{LT} = 30$ veh/h < 200 veh/h
  xprod = 30 * (500/2)
  = 7,500 < 50,000
  Protected phase not needed.

The results are fortunate. Had protected phasing been required for the NB and SB approaches, the lack of an exclusive LT lane on these approaches would have caused a problem.

The E–W approaches have LT lanes, and protected left-turns are needed on both approaches. As the LT volumes EB and WB are very different (300 veh/h vs. 150 veh/h), a phase plan that splits the protected LT phases would be advisable. A NEMA phase plan, utilizing an exclusive LT phase followed by a leading green for the EB direction, will be employed for the E–W artery.

Step 2: Convert Volumes to Through-Vehicle Equivalents

Tables 18.1 and 18.2 are used to find through-vehicle equivalents for left- and right-turn volumes respectively. Conversion computations are illustrated in Table 18.6.

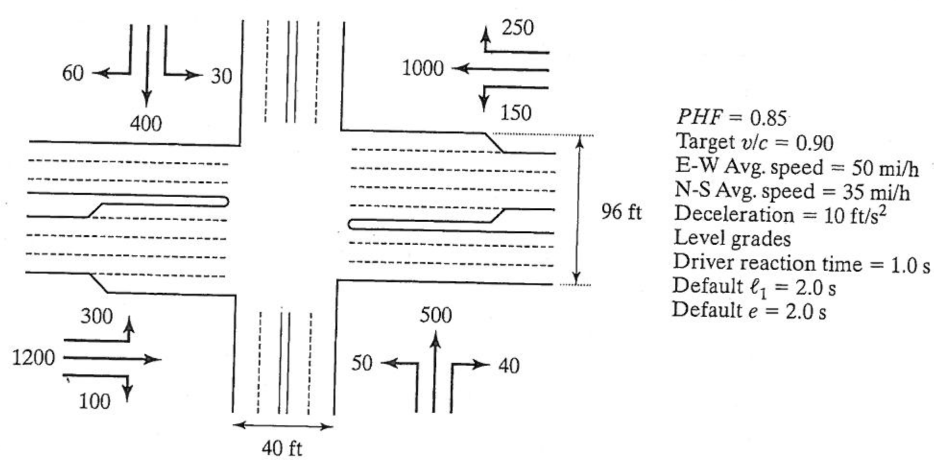

Figure 18.17: Signal-Timing Case 3

Table 18.6: Computation of Through Vehicle Equivalent Volumes for Signal-Timing Case 3

Approach	Movement	Volume (Veh/h)	Equivalent Tables 18.1, 18.2	Volume (tvu/h)	Lane Group Vol. (tvu/h)	Vol./Lane (tvu/h/ln)
EB	L	300	1.05	315	315	315
	T	1,200	1.00	1,200	1,200	400
	R	100	1.18	118	118	118
WB	L	150	1.05	158	158	158
	T	1,000	1.00	1,000	1,000	334
	R	250	1.18	295	295	295
NB	L	50	3.00	150		
	T	500	1.00	500	697	349
	R	40	1.18	47		
SB	L	30	4.00*	120		
	T	400	1.00	400	591	296
	R	60	1.18	71		

* Interpolated by opposing volume.

Note that the EB and WB approaches have a separate lane group for each movement, while the NB and SB approaches have a single lane group serving all movements from shared lanes.

Step 3: Determine Critical-Lane Volumes

Figure 18.18 shows a ring diagram for the phase plan discussed in Step 1 and illustrates the selection of the critical-lane volumes.

The phasing involves overlaps. For the combined Phase A, the critical path is down Ring 1, which has a sum of critical-lane volumes of 649 tvu/h. For Phase B, the choice is simpler, as there are no overlapping phases. Ring 2, serving the NB approach, has the critical-lane volume of 349 tvu/h. The sum of all critical-lane volumes (V_c) is 649 + 349 = 998 tvu/h.

Note also that overlapping phases have a unique characteristic. In this example, for overlapping Phase A, the largest left-turn movement is EB and the largest through movement is EB as well. Because of this, the overlapping phase plan will yield a smaller sum of critical lane volumes than one using an exclusive left-turn phase for both left-turn movements. Had the largest left-turn and through movements been from opposing

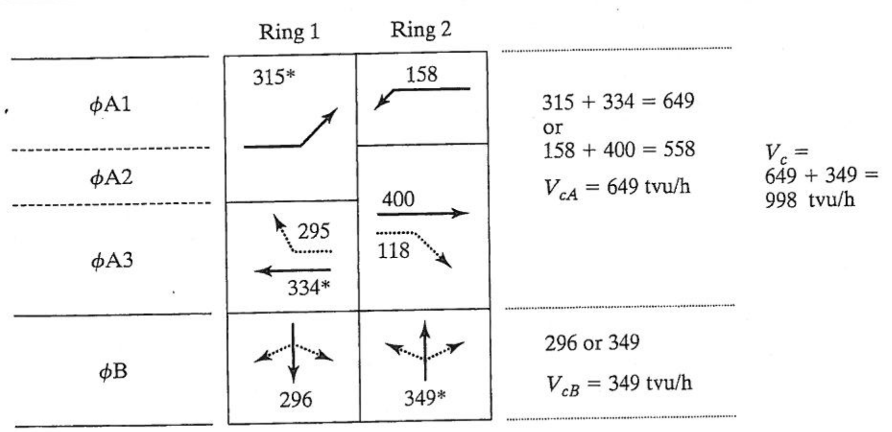

Figure 18.18: Determination of Critical-Lane Volumes—Signal-Timing Case 3

approaches, the sum of critical-lane volumes would be the same for the overlapping sequence and for a single exclusive LT phase. In other words, little is gained by using overlapping phases where a left turn and its opposing through (through plus right turn) movement are the larger movements.

Step 4: Determine Yellow and All-Red Intervals

Equation 18-2 is used to determine the appropriate length of the *yellow* change intervals. Note that the signal design is a *three*-phase signal and that there are three transitions in the cycle. Because of the overlapping sequence, the transition at the end of the protected EB/WB left turns occur at different times on Ring 1 and Ring 2. For simplicity, it is assumed that left-turning vehicles from the EB and WB approaches cross the entire width of the N–S artery. *All-red* intervals are determined using Equation 18-3a, as there are no pedestrians present.

Percentile speeds are estimated from the measured average approach speeds given:

$$S_{85EW} = 50 + 5 = 55 \text{ mi/h}$$
$$S_{15EW} = 50 - 5 = 45 \text{ mi/h}$$
$$S_{85NS} = 35 + 5 = 40 \text{ mi/h}$$
$$S_{15NS} = 35 - 5 = 30 \text{ mi/h}$$

Then:

$$y_{A1,A2,A3} = 1.0 + \frac{1.47*55}{(2*10) + (0)} = 5.0 \text{ s}$$
$$y_B = 1.0 + \frac{1.47*40}{(2*10) + (0)} = 3.9 \text{ s}$$
$$ar_{A1,A2,A3} = \frac{40 + 20}{1.47*45} = 0.9 \text{ s}$$
$$ar_B = \frac{96 + 20}{1.47*30} = 2.6 \text{ s}$$

where 20 ft is the assumed average length of a typical vehicle.

Step 5: Determination of Lost Times

As the problem statement specifies the default values of 2.0 s each for start-up lost time and extension of effective green into yellow and all-red intervals, the total lost time in each phase, t_L, is equal to the sum of the yellow and all red intervals, Y. Thus:

$$t_{LA1/A2} = Y_{A1/A2} = 5.0 + 0.9 = 5.9 \text{ s}$$
$$t_{LA3} = Y_{A3} = 5.0 + 0.9 = 5.9 \text{ s}$$
$$t_{LB} = Y_B = 3.9 + 2.6 = 6.5 \text{ s}$$

Note from Figure 18.18 that the first phase transition occurs at the end of Phase A1, but only on Ring 2. A similar transition occurs at the end of Phase A2, but only on Ring 1. The two other transitions, at the end of Phases A3 and B, occur on both rings. Thus, the total lost time per cycle, L is 5.9 + 5.9 + 6.5 = 18.3 s, and the phase plan represents a three-phase signal.

Step 6: Determine the Desirable Cycle Length

The desirable cycle length is found using Equation 18-11:

$$C_{des} = \frac{18.3}{1 - \left(\frac{998}{1{,}615*0.85*0.90}\right)}$$
$$= \frac{18.3}{0.192} = 95.3 \text{ s}$$

Assuming that this is a pretimed controller, a cycle length of 100 s would be selected.

Step 7: Allocate Effective Green to Each Phase

A signal cycle of 100 s with 18.3 s of lost time has 100.0 − 18.3 = 81.7 s of effective green time to allocate in accordance with Equation 18-13. Note that in allocating green to the critical path, Phases A1 and A2 are treated as a single segment. Subsequently, the location of the Ring 2 transition between Phases A1 and A2 will have to be established.

$$g_{A1+A2} = 81.7*\left(\frac{315}{998}\right) = 25.8 \text{ s}$$
$$g_{A3} = 81.7*\left(\frac{334}{998}\right) = 27.3 \text{ s}$$
$$g_B = 81.7*\left(\frac{349}{998}\right) = 28.6 \text{ s}$$

The specific lengths of Phases A1 and A2 are determined by fixing the Ring 2 transition between them. This requires consideration of the noncritical path through combined Phase A, which occurs on Ring 2. The total length of combined Phase A is the sum of g_{A1+A2} and g_{A3}, or 25.8 + 27.3 = 53.1 s. The Ring 2 transition is based upon the relative values of the lane volumes for Phase A1 and the combined Phase A2/A3, or:

$$g_{A1} = 53.1 * \left(\frac{158}{158 + 400}\right) = 15.0 \text{ s}$$

By implication, Phase A2 is the total length of combined Phase A minus the length of Phase A1 and Phase A3, or:

$$g_{A2} = 53.1 - 15.0 - 27.3 = 10.8 \text{ s}$$

Now, the signal has been completely timed for vehicular needs. With the assumption of default values for ℓ_1(2.0 s) and e (2.0 s), actual green times are equal to effective green times (numerically, although they do not occur simultaneously):

$$\begin{aligned} G_{A1} &= 15.0 \text{ s} \\ G_{A2} &= 10.8 \text{ s} \\ Y_{A1/A2} &= 5.9 \text{ s} \\ G_{A3} &= 27.3 \text{ s} \\ Y_{A3} &= 5.9 \text{ s} \\ G_B &= 28.6 \text{ s} \\ Y_B &= 6.5 \text{ s} \\ C &= 100.0 \text{ s} \end{aligned}$$

There is no Step 8 in this case, as there are no pedestrians at this intersection and, therefore, no pedestrian requirements to be checked.

Example 18-4: Signal-Timing Case 4: A T-Intersection

Figure 18.19 illustrates a typical T-intersection, with exclusive lanes for various movements as shown. Note that there is only one opposed left turn in the WB direction.

Step 1: Develop a Phase Plan

In this case, there is only one opposed left turn to check for the need of a protected phase. As the WB left turn > 200 veh/h, it should be provided with a protected left-turn phase. There is no EB or SB left turn, and the NB left turn is unopposed. The standard way of providing for the necessary phasing would be to utilize a leading WB green with no lagging EB green.

Step 2: Convert Volumes to Through-Vehicle Equivalents

Table 18.7 shows the conversion of volumes to through vehicle equivalents, using the equivalent values given in Tables 18.1 and 18.2 for left and right turns respectively.

Note that the NB left turn is treated as an opposed turn with V_o = 0 veh/h. There are different approaches that have been used to address left turns that are unopposed due to one-way streets and T-intersections, reasons other than the presence of a protected left-turn

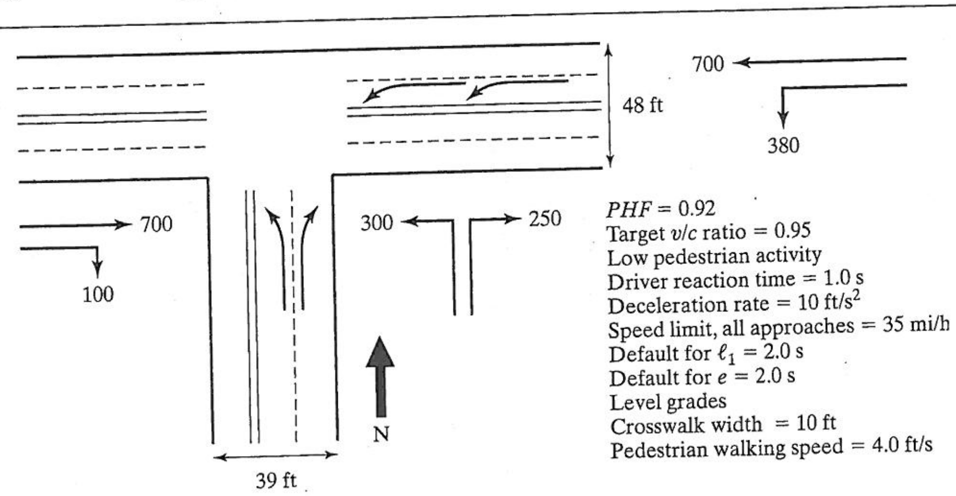

Figure 18.19: Signal-Timing Case 4

Table 18.7: Computation of Through-Vehicle Equivalent Volumes for Signal-Timing Case 3

Approach	Movement	Volume (veh/h)	Equivalent Tables 18.1, 18.2	Volume (tvu/h)	Lane Group Vol. (tvu/h)	Vol./Lane (tvu/h/ln)
EB	T	700	1.00	700	821	411
	R	100	1.21	121		
WB	L	380	1.05	399	399	399
	T	700	1.00	700	700	700
NB	L	300	1.10	330	330	330
	R	250	1.21	303	303	303

phase. Such a movement could also be treated as any protected left turn and an equivalent of 1.05 applied. In some cases, particularly unopposed left turns from a one-way street, the movement is treated as a right turn, using the appropriate factor based on pedestrian interference.

Step 3: Determine Critical-Lane Volumes

Figure 18.20 shows the ring diagram for the phasing described in Step 1 and illustrates the determination of the sum of critical-lane volumes.

In this case, the selection of the critical path through combined Phase A is interesting. Ring 1 goes through two phases, while Ring 2 goes through only one. In this case, the critical path goes through Ring 1 and has a total of three phases. Had the Phase A critical path been through Ring 2, the signal would have only two critical phases. In such cases, the highest critical-lane volume total does not alone determine the critical path. Because one path has an additional phase and, therefore, an additional set of lost times, it could possibly be critical even if it has the lower total critical-lane volume. In such a case, the cycle length would be computed using *either* path, and the one yielding the largest desirable cycle length would be critical. In this case, the path yielding three phases has the highest sum of critical-lane volumes, so only one cycle length will have to be computed.

Step 4: Determine Yellow and All-Red Intervals

Both *yellow* and *all-red* intervals for both streets will be computed using Equations 18-2 and 18-3a (low pedestrian activity) and the speed limit of 35 mi/h for both streets. As a measured average speed was not given, the 85th and 15th percentile speeds cannot be differentiated. For Phases A1 and A2, it will be assumed that both the left-turn and through movements from the E–W street cross the entire 39-ft width of the N–S street. Similarly,

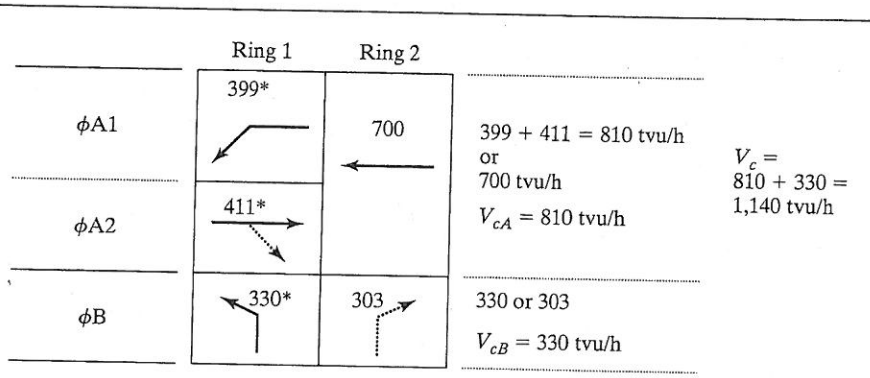

Figure 18.20: Determination of Critical Lane Volumes—Signal-Timing Case 4

in Phase B, it will be assumed that both movements cross the entire 48-ft width of the E–W street. Then:

$$y_{A1,A2,B} = 1.0 + \frac{1.47*35}{(2*10)+(0)} = 3.6 \text{ s}$$

$$ar_{A1,A2} = \frac{39+20}{1.47*35} = 1.1 \text{ s}$$

$$ar_B = \frac{48+20}{1.47*35} = 1.3 \text{ s}$$

Step 5: Determination of Lost Times

Once again, 2.0-s default values are used for start-up lost time (ℓ_1) and extension of effective green into yellow and all-red (e), so that the total lost time for each phase is equal to the sum of the yellow plus all-red intervals:

$$Y_{A1} = t_{LA1} = 3.6 + 1.1 = 4.7 \text{ s}$$
$$Y_{A2} = t_{LA2} = 3.6 + 1.1 = 4.7 \text{ s}$$
$$Y_B = t_{LB} = 3.6 + 1.3 = 4.9 \text{ s}$$

The total lost time per cycle is, therefore, $4.7 + 4.7 + 4.9 = 14.3$ s.

Step 6: Determine the Desirable Cycle Length

Equation 18-11 is once again used to determine the desirable cycle length, using the sum of critical-lane volumes, 1,140 tvu/h:

$$C_{des} = \frac{14.3}{1 - \left(\frac{1{,}140}{1{,}615*0.92*0.95}\right)} = \frac{14.3}{0.192} = 74.5 \text{ s}$$

For a pretimed controller, a cycle length of 75 s would be implemented.

Step 7: Allocate Effective Green to Each Phase

The available effective green time for this signal is $75.0 - 14.3 = 60.7$ s. It is allocated in proportion to the critical-lane volumes for each phase:

$$g_{A1} = 60.7*\left(\frac{399}{1140}\right) = 21.2 \text{ s}$$

$$g_{A2} = 60.7*\left(\frac{411}{1140}\right) = 21.9 \text{ s}$$

$$g_B = 60.7*\left(\frac{330}{1140}\right) = 17.6 \text{ s}$$

As the usual defaults for ℓ_1 and e are used, actual green times are numerically equal to effective green times.

Step 8: Check Pedestrian Requirements

While there is low pedestrian activity at this intersection, pedestrians must still be safely accommodated by the signal phasing. It will be assumed that pedestrians cross the N–S street only during Phase A2 and that pedestrians crossing the E–W street will use Phase B. The number of pedestrians per cycle in each crosswalk is based on the default volume for "low" activity—50 peds/h (Table 18.2)—and the number of cycles per hour—3,600/75 = 48. Then, N_{ped} in each crosswalk would be 50/48 = 1.0 ped/cycle. Equation 18-15 is used to compute minimum pedestrian requirements:

$$G_{pA2} = 3.2 + \left(\frac{39}{4.0}\right) + (0.27*1.0) = 13.2 \text{ s}$$

$$G_{pB} = 3.2 + \left(\frac{48}{4.0}\right) + (0.27*1.0) = 15.5 \text{ s}$$

These requirements must be checked against the vehicular green, yellow, and all-red intervals:

$$G_{pA2} = 13.2 \text{ s} < G_{A2} + Y_{A2} = 21.9 + 4.7 = 26.6 \text{ s OK}$$

$$G_{pB} = 15.5 \text{ s} < G_B + Y_B = 17.6 + 4.9 = 22.5 \text{ s OK}$$

Pedestrians are safely accommodated by the vehicular signalization, and no changes are required.

References

1. Pusey, R. and Butzer, G., "Traffic Control Signals," *Traffic Engineering Handbook*, 5th Edition