CHAPTER 1. CAPACITY OF ALL-WAY STOP-CONTROLLED INTERSECTIONS

1. Overview

In this chapter we will explore the models on which the HCM capacity analysis method for all-way stop-controlled (AWSC) intersections is based. Table 1 shows a roadmap to the material presented in this chapter. We'll start in section 2 with a discussion of how AWSC intersections operate in the field, particularly the interaction between drivers traveling through the intersection. In section 3, we'll identify the important factors in this interaction that will help us to formulate models to predict the capacity of an intersection approach. The models that we will formulate in sections 4 and 5 are based on "simplified scenarios", scenarios in which only the most important traffic and geometric factors are considered. By focusing only on these factors, you will develop a basic understanding of the operation of an AWSC intersection, one that can later be built upon as the more complex conditions found in the real world are considered.

Table 1. Roadmap to chapter 1

Overview	Simplified Scenarios	Learning in Depth	Closing
1. Overview 2. What do we see in the field 3. Formulating the model	4. Intersection of two one-way streets 5. Four-leg intersection with single lane approaches	6. Building a computational engine to explore the model	7. Summary 8. Glossary 9. References Appendix 1. Visual basic code

You will study two such scenarios. The first scenario is based on the intersection of two one-lane one-way streets, while the second scenario is based on one lane approaches at a standard 4-leg intersection. In both scenarios, we assume through movements only (no turning movements) and a traffic stream consisting only of passenger cars. Finally, we assume that there are no pedestrians to impede the flow of automobile traffic.

You will see that the operation of an AWSC intersection is based primarily on the interactions between drivers, each driver having to make the decision: "when is it my turn to enter the intersection?" The higher the traffic flow rates, the more intense are these interactions, and the longer drivers must wait until it is their turn to enter the intersection.

You will build a computational engine in section 6, based on the second scenario described above. You can use the computational engine (in the form of a spreadsheet) to study the predictions of capacity that the model makes under a range of traffic flow conditions. These predictions will help you to understand when all-way stop control might be an effective control strategy and under what conditions other types of control should be considered. You will also see under what conditions the intersection approach will reach capacity.

A summary of the chapter is presented in Section 7. Section 8 presents a list of all terms and variables used in the chapter and provides a definition or description for each. A list of references is presented in section 9. Appendix 1 includes the Visual Basic code for the computational engine.

2. What Do We Observe in the Field?

An AWSC intersection is an intersection in which all approaches are controlled by stop signs. Each driver must stop when they reach the stop line and determine when it is safe for them to enter the intersection. Some localities are governed by the rule that the "driver on the right" has the right-of-way if several vehicles arrive at the intersection at the same time. But whatever the rule, it is the interaction between the drivers that determines how the intersection operates.

Since we are interested in predicting the capacity of an intersection approach, let's consider what drivers see and do as they arrive at an AWSC intersection. If there are other vehicles on the approach, a driver waits in queue as the other vehicles are served. This time spent waiting in queue is part of the delay experienced by drivers. The other part of the delay is the time spent at the stop line. And, how long a driver waits at the stop line depends largely on whether there are other drivers waiting on the other approaches competing for their turn to enter the intersection.

If there are no other vehicles on any of the other intersection approaches, a driver enters the intersection just as soon as he or she stops and assesses that conditions are safe. If there is one other vehicle on the cross street, the drivers jointly decide who goes next and who must wait. And, if there are vehicles on all of the other approaches, this joint decision making process is even more complex and time consuming. What does this mean for the capacity of the intersection approaches? The more approaches that are occupied by waiting vehicles, the lower the rate of flow of departing vehicles on any of the approaches. Or, said another way, the higher the degree of conflict between drivers on the intersection approaches, the lower the capacity of any given approach.

Other factors also limit the capacity of an intersection approach, such as pedestrians crossing the street, turning vehicles that take extra time to complete their maneuvers, and heavy vehicles that are slower to accelerate than passenger cars. But while these factors are often present in the field, we will only consider simplified scenarios in which there are no pedestrians, only through movements, and only passenger cars in the traffic stream. This will help you to focus on basic principles as you develop an understanding of how an AWSC intersection operates and the factors that affect the capacity of its approaches.

One more point can be made about the flow of traffic at an AWSC intersection, particularly when traffic volumes are high and the intersection operates near capacity. When there is one lane on each approach, a rhythm develops in which vehicles on opposite approaches enter the intersection at the same time: Vehicles on the northbound and southbound approaches enter together, followed by vehicles on the eastbound and westbound approaches. This rhythm may be broken if a driver hesitates or if one vehicle makes a left turn, but it is common to observe this pattern of operation during peak periods.

3. Formulating the Model

We will use a queuing model to represent the traffic flow conditions on one approach of the AWSC intersection based on the conditions that we've observed in the field. This queuing model consists of the following parts:

- Vehicles arrive at the intersection in a random manner, with headways between vehicles following a negative exponential distribution.
- Vehicles are served one at a time at a rate that depends on the degree of conflict that they face.
- The degree of conflict can be represented by a set of distinct cases, each case based on the number of approaches that are occupied by waiting vehicles.
- During conditions of continuous queuing, each degree of conflict case has a defined headway between departing vehicles, called the saturation headway.

To illustrate these concepts, consider a case consisting of the sequence of events shown in Figure 1. The sequence begins with a queue of three vehicles on the approach of interest, called the subject approach. The first vehicle on the subject approach (vehicle 1, event 1) enters the intersection. In event 2, vehicle 2 moves to the stop line. Vehicle 2 enters the intersection in event 3, 3.9 seconds after vehicle 1 enters the intersection. The figure shows these three events in the sequence in which they occur, along with the clock time at which each event occurs.

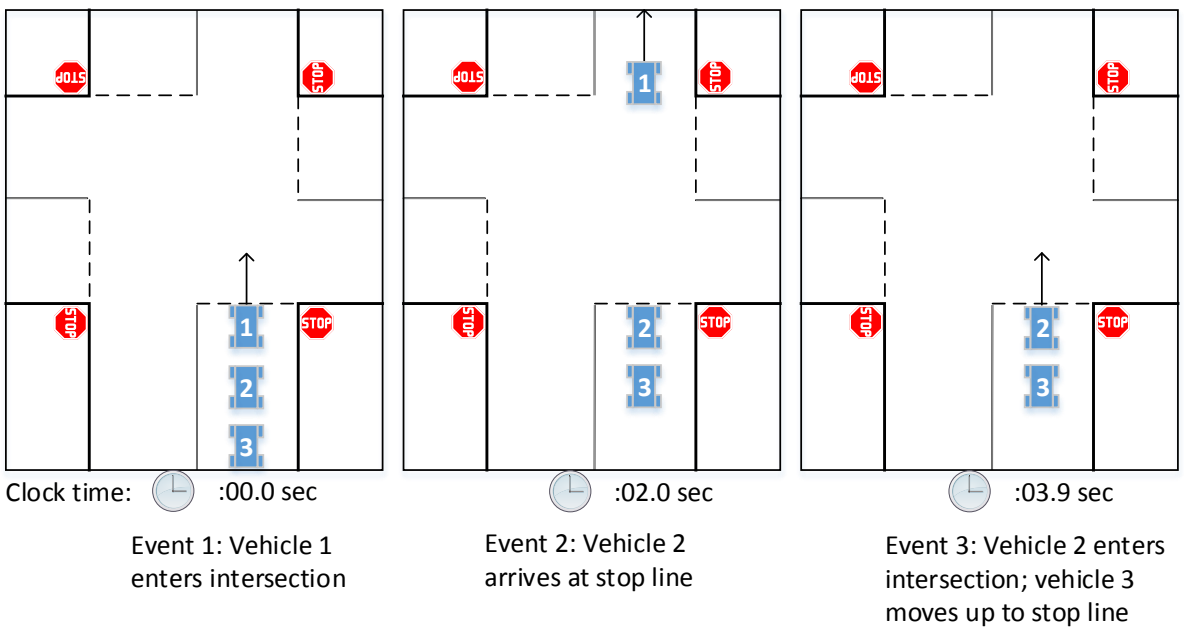


Figure 1. Sequence of events for vehicles entering an AWSC intersection

For this case, the degree of conflict is low since there are no vehicles on the other approaches. The saturation headway for this case is given by:

$$h = clock\ time\ (event\ 3) - clock\ time\ (event\ 1) = 3.9\,\text{sec} - 0.0\,\text{sec} = 3.9\ sec$$

Now consider a case that also starts with a queue of three vehicles on the subject approach but with one vehicle on one of the conflicting approaches of the cross street. The first vehicle on the subject approach enters the intersection (event 1, vehicle 1). In event 2, vehicle A, the vehicle on

the conflicting approach, enters the intersection. In event 3, vehicle 2 enters the intersection. Figure 2 shows these three events in the sequence in which they occur, along with the clock time at which each event occurs.

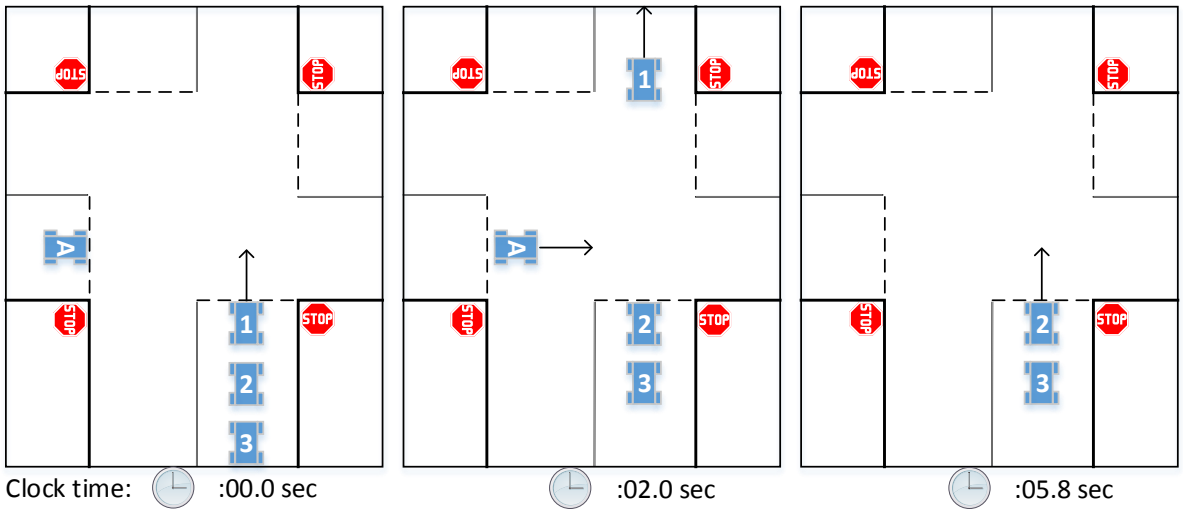
The headway on the subject approach, the clock time between the departure of vehicles 1 and 2, is 5.8 sec. This is the saturation headway for this degree of conflict case.

$$h = clock\ time\ (event\ 3) - clock\ time\ (event\ 1) = 5.8\,\text{sec} - 0.0\,\text{sec} = 5.8\ sec$$

In summary, this model for determining the capacity of one approach of an AWSC intersection is based on the following concepts:

- One approach, called the subject approach, is analyzed at a time.
- The headway between consecutive departing vehicles on the subject approach is called the departure headway; during periods of continuous queuing, the headway is called the saturation headway.
- The saturation headway depends on the degree of conflict experienced by drivers on the subject approach.

In the next section we'll develop a scenario that implements this model formulation for the intersection of two one-way streets.



Event 1: Vehicle 1 enters intersection

Event 2: Vehicle 2 arrives at stop line; vehicle A enters intersection

Event 3: Vehicle 2 enters intersection; vehicle 3 moves up to stop line

Figure 2. Sequence of events for vehicles entering an AWSC intersection

4. Scenario 1: Intersection of Two One-Way Streets

Let's consider an intersection of two one-lane, one-way streets, with through movements only. We'll call this Scenario 1. In this section, we'll study the conditions on both approaches to the intersection and develop a model to predict the capacity of each approach. This capacity depends heavily on the volume of traffic on both approaches.

In this scenario, drivers on each approach face one of two cases. In the first case there are no vehicles on the conflicting approach and in the other case there is one or more vehicles on the conflicting approach. Research has shown that for the first case, the saturation headway between vehicles departing on the subject approach is 3.9 sec, if there is a continuous queue on this approach. For the other case, since the degree of conflict is higher, the saturation headway is also higher: 5.8 sec between departing vehicles. For reasons that we will discuss in section 5, we will call this Case 3.

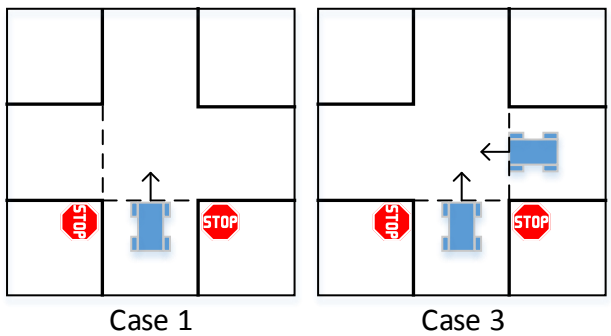


Figure 3. Scenario 1: Two intersecting one-way streets

The mean departure headway between vehicles on the subject approach is thus a function of the saturation headway for each of the two cases, and the probability that each case will occur. From queuing theory, the probability or likelihood of not observing a vehicle on the conflicting approach is equal to one minus the degree of utilization (1-ρ) on that approach. For our analysis of AWSC intersections, the degree of utilization on the conflicting approach is the likelihood that there is a vehicle on that approach and is equal to the arrival flow rate divided by the maximum service rate, or, as more commonly used in traffic engineering, the volume-to-capacity ratio.

Mathematically, we can write the departure headway for vehicles on the subject approach ($h_{d,sub}$) as the expected value of a bimodal distribution, with h_{s1} and h_{s3} as the saturation headways for each of the two modes.

Equation 1

$$h_{d,sub} = h_{s1}(1 - X_{con}) + h_{s3}(X_{con})$$

where X_{con} is the degree of utilization on the conflicting approach. As stated above, we can also think of the degree of utilization as the probability that a vehicle is present on that approach at any given time.

Let's now consider our simplified scenario. For the two intersecting one-way streets (with NB and WB traffic only), the mean departure headway based on Equation 1 for each approach can be written as follows:

Equation 2

$$h_{d,NB} = h_{s1}(1 - X_{WB}) + h_{s3}(X_{WB})$$

Equation 3

$$h_{d,WB} = h_{s1}(1 - X_{NB}) + h_{s3}(X_{NB})$$

We can write Equation 2 and Equation 3 in a form which allows us to more directly calculate the departure headways on each approach. To do this, we must first note that X can be written as the product of the arrival rate λ and the departure headway h_d. Another way of thinking about this formulation of X is as the product of the number of vehicles that arrive in the time period (λ, converted to veh/sec) and the time between departing vehicles (h), as shown in Equation 4 and Equation 5.

Equation 4

$$X_{NB} = \lambda_{NB} h_{d,NB}$$

Equation 5

$$X_{WB} = \lambda_{WB} h_{d,WB}$$

Substituting Equation 4 into Equation 2 and Equation 5 into Equation 3 we get expressions from which we can directly compute the departure headways for the NB and WB approaches.

Equation 6

$$h_{d,NB} = \frac{h_{s1}[1 + \lambda_{WB}(h_{s3} - h_{s1})]}{1 - \lambda_{NB}\lambda_{WB}(h_{s3} - h_{s1})^2}$$

Equation 7

$$h_{d,WB} = \frac{h_{s1}[1 + \lambda_{NB}(h_{s3} - h_{s1})]}{1 - \lambda_{NB}\lambda_{WB}(h_{s3} - h_{s1})^2}$$

More generally, the departure headway for the subject approach can be written:

Equation 8

$$h_{d,sub} = \frac{h_{s1}[1 + \lambda_{con}(h_{s3} - h_{s1})]}{1 - \lambda_{sub}\lambda_{con}(h_{s3} - h_{s1})^2}$$

Since h_{s1} = 3.9 sec and h_{s3} = 5.8 sec, Equation 8 can be simplified to:

Equation 9

$$h_{d,sub} = \frac{(3.9)[1 + \lambda_{con}(5.8 - 3.9)]}{1 - \lambda_{sub}\lambda_{con}(5.8 - 3.9)^2}$$

Equation 10

$$h_{d,sub} = \frac{(3.9)[1 + \lambda_{con}(1.9)]}{1 - \lambda_{sub}\lambda_{con}(1.9)^2}$$

Equation 11

$$h_{d,sub} = \frac{3.9 + 7.41\lambda_{con}}{1 - 3.61\lambda_{sub}\lambda_{con}}$$

And, for this example with NB and WB traffic, the departure headways can be written as:

Equation 12

$$h_{d,NB} = \frac{3.9 + 7.41\lambda_{WB}}{1 - 3.61\lambda_{NB}\lambda_{WB}}$$

Equation 13

$$h_{d,WB} = \frac{3.9 + 7.41\lambda_{NB}}{1 - 3.61\lambda_{NB}\lambda_{WB}}$$

Example Calculation 1

Let's consider an example in which the volumes are 300 veh/hr on the NB approach and 200 veh/hr on the WB approach. We are also given the saturation headways for the two degree of conflict cases:

$$h_{s1} = 3.9\ sec/veh$$

$$h_{s3} = 5.8\ sec/veh$$

What is the mean departure headway for vehicles on each approach and what is the degree of utilization X for each approach? The three steps to solve this problem are shown below.

Step 1. Calculate λ, the flow rate in veh/sec, based on the volumes given in veh/hr.

$$\lambda_{NB} = \frac{300\ veh/hr}{3600\ sec/hr} = .083\ veh/sec$$

$$\lambda_{WB} = \frac{200\ veh/hr}{3600\ sec/hr} = .056\ veh/sec$$

Step 2. Calculate the departure headway for each approach, h_d.

For the NB approach, using Equation 12:

$$h_{d,NB} = \frac{3.9 + 7.41\lambda_{WB}}{1 - 3.61\lambda_{NB}\lambda_{WB}}$$

$$h_{d,NB} = \frac{3.9 + 7.41(0.056\ veh/sec)}{1 - 3.61(0.083\ veh/sec)(0.056\ veh/sec)}$$

$$h_{d,NB} = 4.4\ sec$$

For the WB approach, using Equation 13:

$$h_{d,WB} = \frac{3.9 + 7.41\lambda_{NB}}{1 - 3.61\lambda_{NB}\lambda_{WB}}$$

$$h_{d,WB} = \frac{3.9 + 7.41(0.83\ veh/sec)}{1 - 3.61(0.083\ veh/sec)(0.056\ veh/sec)}$$

$$h_{d,WB} = 4.6\ sec$$

For the NB approach, the mean headway for departing vehicles is 4.4 sec while for the WB approach it is 4.6 sec.

Step 3. Calculate X, the degree of utilization for each approach, using Equation 4 and Equation 5.

For the NB approach:

$$X_{NB} = \lambda_{NB} h_{d,NB}$$

$$X_{NB} = (.083\ veh/sec)(4.4\ sec/veh) = .37$$

For the WB approach:

$$X_{WB} = \lambda_{WB} h_{d,WB}$$

$$X_{WB} = (.056\ veh/sec)(4.6\ sec/veh) = .26$$

The degree of utilization is 0.365 for the NB approach and 0.255 for the WB approach, both well below 1.0. There is sufficient capacity to serve the given demand. Note that these values also represent the proportion of time that we are likely to see a vehicle on each of these two approaches.

Example Calculation 2

Let's consider another example in which the volumes are 300 veh/hr on the NB approach and 900 veh/hr on the WB approach. What are the mean departure headway and the degree of utilization for each approach?

Step 1. Calculate λ, the flow rate in veh/sec based on the volumes given in veh/hr.

$$\lambda_{NB} = \frac{300}{3600} = .083\ veh/sec$$

$$\lambda_{WB} = \frac{900}{3600} = .250\ veh/sec$$

Step 2. Calculate departure headway for each approach, h_d.

For the NB approach, using Equation 12:

$$h_{d,NB} = \frac{3.9 + 7.41\lambda_{WB}}{1 - 3.61\lambda_{NB}\lambda_{WB}}$$

$$h_{d,NB} = \frac{3.9 + 7.41(0.250\ veh/sec)}{1 - 3.61(0.083\ veh/sec)(.250\ veh/sec)}$$

$$h_{d,NB} = 6.2\ sec/veh$$

For the WB approach, using Equation 13:

$$h_{d,WB} = \frac{3.9 + 7.41\lambda_{NB}}{1 - 3.61\lambda_{NB}\lambda_{WB}}$$

$$h_{d,WB} = \frac{3.9 + 7.41(0.083\ veh/sec)}{1 - 3.61(0.083\ veh/sec)(0.250\ veh/sec)}$$

$$h_{d,WB} = 4.9\ sec/veh$$

Step 3. Calculate X, the degree of utilization for each approach, using Equation 4 and Equation 5.

For the NB approach:

$$X_{NB} = \lambda_{NB} h_{d,NB}$$

$$X_{NB} = (.083\ veh/sec)(6.2\ sec/veh) = .52$$

For the WB approach:

$$X_{WB} = \lambda_{WB} h_{d,WB}$$

$$X_{WB} = (.250\ veh/sec)(4.9\ sec/veh) = 1.22$$

When we examine these results, a problem arises. The bi-valued distribution for the saturation headways (Cases 1 and 3) has two values: 3.9 sec and 5.8 sec. The departure headway that is computed must be between these two values. For the NB approach it is not. More evidence of the problem arises when we examine the degree of saturation for the WB approach, which we have calculated to be 1.22. While not directly stated, we have implicitly assumed that X is less than 1.0. Clearly this assumption has been violated. We will explore this issue further in Example Calculation 3.

Example Calculation 3

Let's again consider an example in which the volume on the NB approach is 300 veh/hr. But this time we'll investigate a range of flow rates on the WB approach. And we'll ask the following questions:

- What is the capacity of the WB approach?
- How does the degree of utilization on the NB approach vary as the volume on the WB approach increases?
- What is the degree of utilization on the NB approach when the WB approach reaches capacity?

Table 2 shows the results of the calculations for a range of volumes on the WB approach. We note that as the volume on the WB approach increases, the departure headway on the NB approach also increases as NB vehicles are more likely to see one or more vehicles on the WB approach, further increasing the degree of conflict.

Table 2. Variation of X and h with flow rate

v_{WB}	h_{NB}	h_{WB}	X_{NB}	X_{WB}
0	3.9	4.5	0.33	0.00
50	4.0	4.5	0.33	0.06
100	4.1	4.6	0.35	0.13
150	4.3	4.6	0.36	0.19
200	4.4	4.6	0.37	0.26
250	4.5	4.6	0.38	0.32
300	4.6	4.6	0.39	0.39
350	4.8	4.7	0.40	0.45
400	4.9	4.7	0.41	0.52
450	5.0	4.7	0.42	0.59
500	5.1	4.7	0.43	0.65
550	5.3	4.7	0.44	0.72
600	5.4	4.8	0.45	0.79
650	5.5	4.8	0.46	0.86
700	5.7	4.8	0.47	0.93
750	5.8	4.8	0.48	1.00
800	5.9	4.8	0.50	1.08
850	6.1	4.9	0.51	1.15
900	6.2	4.9	0.52	1.22

When X reaches 1.0 on the WB approach, that approach has reached capacity. Even if the demand increases, the volume that is served will never exceed 750 veh/hr. Thus for these conditions (NB approach volume of 300 veh/hr), the capacity of the WB approach is 750 veh/hr.

X_{NB} increases somewhat as the WB volume increases, from 0.33 to 0.52. X_{NB} is 0.48 when the WB approach reaches capacity. Figure 4 shows the change in the departure headway on both the NB and WB approaches as the volume on the WB approach increases. Figure 5 shows the change in the degree of saturation on both approaches as the volume on the WB approach increases.

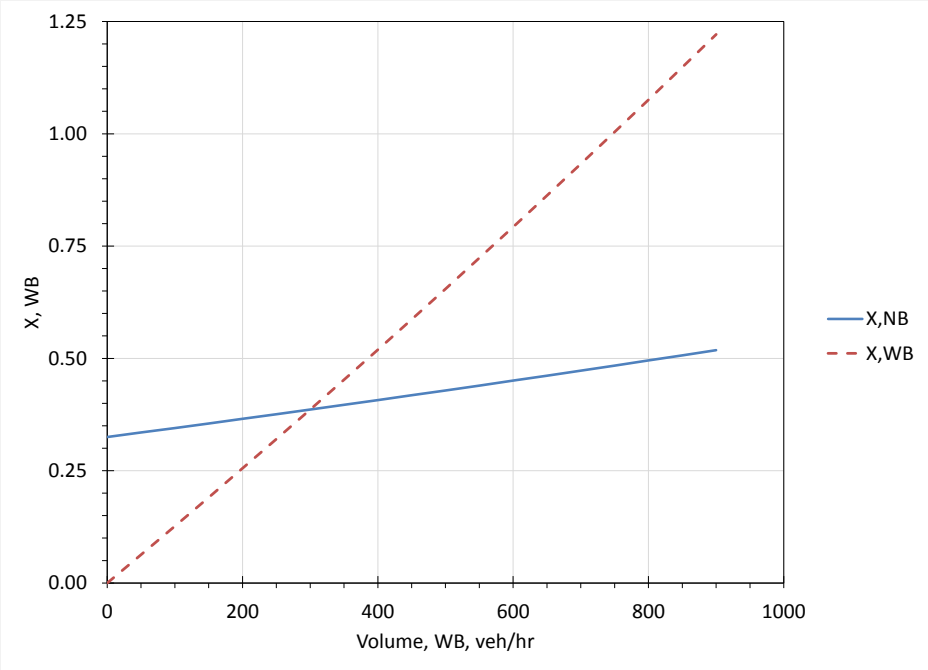


Figure 4. Variation of h with WB approach volume

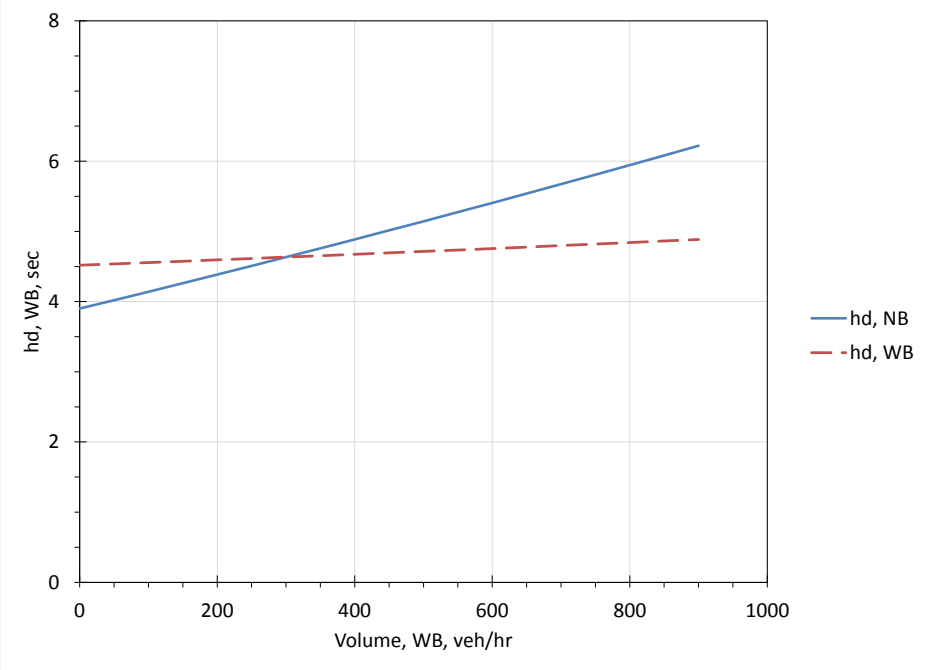


Figure 5. Variation of X with WB approach volume

5. Scenario 2: Four-Leg Intersection with Single Lane Approaches

Let's now consider the second simplified scenario, an intersection with four approaches, and one lane on each approach. Again, we will assume no turning movements; all vehicles proceed straight through the intersection. Here are some questions for you to consider:

- What are the cases that completely describe the degree of conflict experienced by drivers on a given approach?
- What is the saturation headway for each degree of conflict case?
- What is the probability that each degree of conflict case will occur for a given set of traffic flow conditions?

Figure 6 shows the way in which each approach is defined. Note that the NB approach is shown as the subject approach, but that is only for example purposes. As described previously, each approach is analyzed separately and so becomes the subject approach when it is being analyzed.

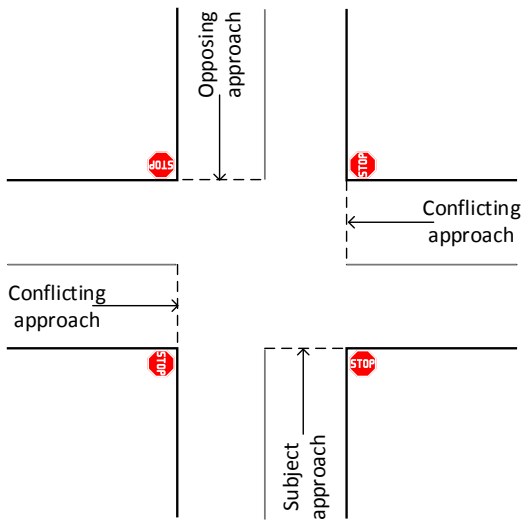


Figure 6. Nomenclature for AWSC intersection approaches

Let's consider the degree of conflict cases. There are five cases as shown in Figure 7, including Case 1 and Case 3 that we considered earlier in the first simplified scenario in section 4. These five cases define the range of conditions that a subject approach vehicle will face:

- Case 1: No vehicles on any of the opposing or conflicting approaches.
- Case 2: A vehicle on the opposing approach, but not on either of the conflicting approaches.
- Case 3: A vehicle on one of the conflicting approaches but not on the opposing approach.
- Case 4: A vehicle on two of the other approaches.
- Case 5: A vehicle on all three approaches.

Each of these cases results in an increasing degree of conflict, from Case 1 the lowest to Case 5 the highest. Similarly, the saturation headway increases as the degree of conflict increases. It simply takes longer to wait your turn and enter the intersection as the number of vehicles on the opposing and conflicting approaches increases.

The probability that each of these cases will occur is given by the products of the degrees of saturation on each of the three approaches faced by the subject approach driver. For case 1, for

example, the case where a subject vehicle does not face any other vehicles, the probability of occurrence is given by Equation 14. Each term in the equation is the probability that a vehicle is not present on one of the three approaches. The product of these terms is the joint probability that no vehicles are present on any of the other approaches.

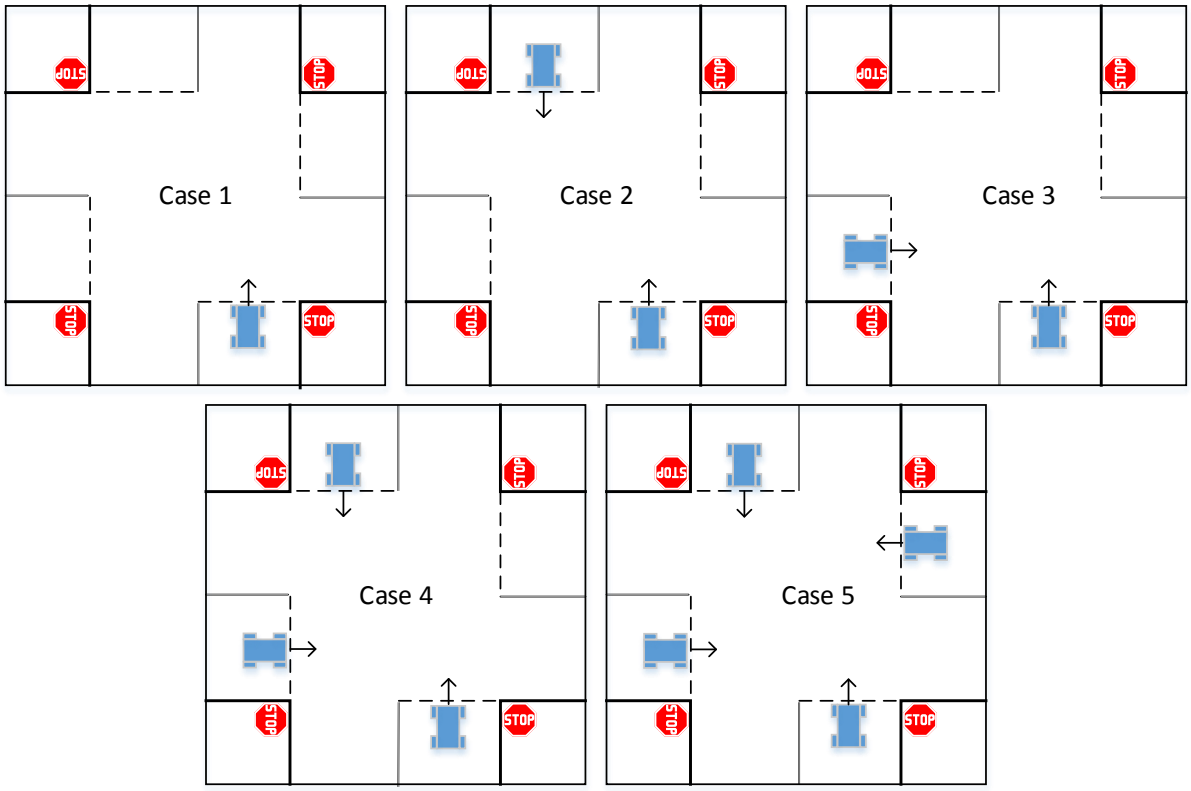


Figure 7. Five degree of conflict cases for Scenario 2

Equation 14

$$P[C_1] = (1 - X_O)(1 - X_{CL})(1 - X_{CR})$$

Based on research, the saturation headway for each degree of conflict case is given in Table 3.

Table 3. Saturation headways for degree of conflict cases

Degree of conflict case	Number of vehicles faced by subject approach vehicle	Saturation headway (sec)
1	0	3.9
2	1	4.7
3	1	5.8
4	2	7.0
5	3	9.6

The expected value of the departure headway h_d on the subject approach is thus the sum of the products of the probability of the occurrence of each degree of conflict case and the saturation headway for that case. This expected value is given by Equation 15.

Equation 15

$$h_d = \sum_{i=1}^{5} P[C_i]h_{si}$$

where $P[C_i]$ is the probability that case i will occur and h_{si} is the saturation headway for case i. But in contrast to Scenario 1, we can't solve directly for h_d for each approach. The interdependencies of the traffic flow on the approaches are just too great. So we must use an iterative process, calculating the departure headway for each approach, and recalculating it until the values from one iteration do not change substantially from the values calculated in the previous iteration. This process is too complex to be done manually; a computational engine is required.

To begin this process, let's lay out the six computational steps involved. These steps are completed concurrently for each approach.

Step 1. Convert the volume v in veh/hr to the flow rate λ in veh/sec.

Equation 16

$$\lambda = \frac{v}{3600}$$

Step 2. Calculate the degree of utilization.

Equation 17

$$X = \lambda h_d$$

Step 3. Compute the probability of each degree of conflict case.

Equation 18

$$P[C_1] = (1 - X_O)(1 - X_{CL})(1 - X_{CR})$$

Equation 19

$$P[C_2] = (X_O)(1 - X_{CL})(1 - X_{CR})$$

Equation 20

$$P[C_3] = (1 - X_O)(X_{CL})(1 - X_{CR}) + (1 - X_O)(1 - X_{CL})(X_{CR})$$

Equation 21

$$P[C_4] = (X_O)(1 - X_{CL})(X_{CR}) + (X_O)(X_{CL})(1 - X_{CR}) + (1 - X_O)(X_{CL})(X_{CR})$$

Equation 22

$$P[C_5] = (X_O)(X_{CL})(X_{CR})$$

Step 4. Compute the departure headway.

Equation 23

$$h_d = \sum_{i=1}^{5} P[C_i] h_{si}$$

Step 5. Check if the value of h_d in the current iteration has not changed by more than the convergence criterion (.001) from its value in the previous iteration. If the convergence criterion is met, as described in Equation 24, then proceed to step 6. If not, return to step 2 and recalculate X for each approach based on the current value of h_d for that approach.

Equation 24

$$h_{d,iteration\ i} - h_{d,iteration\ i-1} < 0.0001$$

Step 6. Compute the capacity. The capacity on the subject approach is computed under the assumption that the flows on the other approaches remain constant, while the flow on the subject approach is increased until X_{sub} reaches 1.0. When this occurs, the volume on the subject approach is said to be its capacity. This process is summarized in Figure 8.

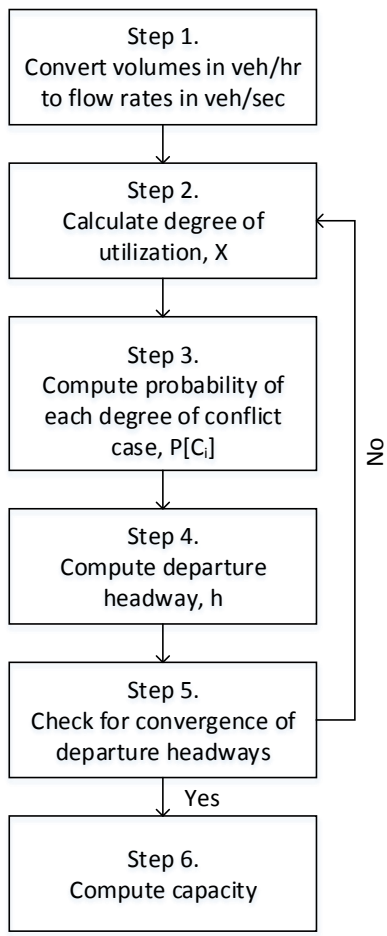


Figure 8. Calculation steps for Scenario 2

To learn more about this model and to see the results that it produces under various conditions, we need to build a computational engine. We will build this engine in the next section of this chapter.

6. Building a Computational Engine and Exploring the Model

Let's now set up the computational engine and explore what the model predicts under a variety of traffic flow conditions. The computational engine, to be built using an Excel spreadsheet, should satisfy the following requirements:

- Accepts the volumes (v, veh/hr) on each approach as inputs.
- Computes flow rates (λ, veh/sec) for each approach.
- Computes X_S, X_O, X_{CL}, and X_{CR} for each approach iteratively.
- Computes $P[C_i]$ for each of the five degree of conflict cases for each approach iteratively.
- Computes the departure headway h_d for each approach iteratively until convergence is reached.

Figure 9 shows the computational engine template. The input volumes are entered in row 4 for each approach. The flow rates in veh/sec are calculated in row 7. The degree of utilization for each subject approach is calculated in row 10. The degrees of utilization for the other approaches are calculated in rows 11 through 13. The probability of occurrence for each degree of conflict case is calculated in rows 16 through 20. As a check, the sum of these probabilities is shown in row 21 and must equal one. The resulting departure headway and degree of utilization are calculated in rows 24 and 25, respectively. Note that the value of X shown in row 10 is constrained to be equal to or less than one, while the value shown in row 25 is not. This is because the value in row 10 is also considered to be the probability that a vehicle is present on the approach and this value must always be less than or equal to one.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**				
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)				
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)				
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S				
11	x_O				
12	x_{CL}				
13	x_{CR}				
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$				
17	$P[C_2]$				
18	$P[C_3]$				
19	$P[C_4]$				
20	$P[C_5]$				
21	$\Sigma P[C_i]$				
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)				
25	Degree of utilization (X)				

Figure 9. AWSC intersection computational engine template

To assist you in constructing the computational engine, Table 4 shows the formulas that are used for column B in the template shown in Figure 9.

Table 4. Example formulas for NB approach (column B)

Row	Formula
7	=B4/3600
10	=IF(B25>1,1,B25)
11	=IF(C25>1,1,C25)
12	=IF(D25>1,1,D25)
13	=IF(E25>1,1,E25)
16	=(1-B11)*(1-B12)*(1-B13)
17	=B11*(1-B12)*(1-B13)
18	=(1-B11)*B12*(1-B13)+(1-B11)*(1-B12)*B13
19	=B11*(1-B12)*B13+B11*B12*(1-B13)+(1-B11)*B12*B13
20	=B11*B12*B13
21	=SUM(B16:B20)
24	=B24
25	=B24*B7

An alternative method to automate the process is to use Visual Basic code to calculate the elements of the computational engine. Enter the volumes in row 4 and then press the "Run AWSC" button as shown in Figure 10. The Visual Basic code accomplishes the same goal as the computational code shown in Table 4.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)				
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)				
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S				
11	x_O				
12	x_{CL}				
13	x_{CR}				
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$				
17	$P[C_2]$				
18	$P[C_3]$				
19	$P[C_4]$				
20	$P[C_5]$				
21	$\Sigma P[C_i]$				
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)				
25	Degree of utilization (X)				
26	Iterations	1			

Figure 10. AWSC intersection computational engine template, with VB run button

The Visual Basic code is given in Appendix 1 at the end of this chapter. Comments are provided throughout this code for a clearer explanation of the steps involved. These steps are listed below:

- Saturation headways for each degree of conflict case are set.
- All values in the spreadsheet are reset to blank.
- Input volumes are read.
- Input volumes are converted to flow rates (λ) in vehicles per second. [Step 1 in code]
- λ values are printed in row 7.

- Initial degrees of utilization are calculated. [step 2 in code]
- Convergence Do Loop
    - Reset x to maximum value of 1.
    - Departure headway last set to current value of departure headway.
    - Probability of each degree of conflict case is calculated. [Step 3 in code]
    - Departure headway calculated. [Step 4 in code]
    - X calculated.
    - Reset x to maximum value of 1.
    - Convergence check. [Step 5 in code]
- Print final results in cells.
- Print iteration number.

Example Calculation 4.
Consider an AWSC intersection at which the volumes on each approach are 300 veh/hr. Let's run several tests to validate that our computational engine is working correctly.

Test 1. The first test is to make sure that the sum of the probabilities for the degree of conflict cases equals one. Examining the results shown in row 21 in Figure 11, we see that this is true.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	300	300	300	300
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.083	0.083	0.083	0.083
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	0.55	0.55	0.55	0.55
11	x_O	0.55	0.55	0.55	0.55
12	x_{CL}	0.55	0.55	0.55	0.55
13	x_{CR}	0.55	0.55	0.55	0.55
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.089	0.089	0.089	0.089
17	$P[C_2]$	0.110	0.110	0.110	0.110
18	$P[C_3]$	0.220	0.220	0.220	0.220
19	$P[C_4]$	0.411	0.411	0.411	0.411
20	$P[C_5]$	0.170	0.170	0.170	0.170
21	$\Sigma P[C_i]$	1.000	1.000	1.000	1.000
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	6.7	6.7	6.7	6.7
25	Degree of utilization (X)	0.55	0.55	0.55	0.55
26	Iterations	14			

Figure 11. Example Calculation 4, Test 1

Test 2. The second test is to make sure that the boundary condition represented by each of the five degree of conflict cases is accurately represented. With traffic present only on one approach, the departure headway for the subject approach should be equal to the saturation headway for Case 1, or 3.9 sec. When we set the volume on the northbound approach to 923 veh/hr, and zero on the other approaches, the resulting departing headway on that approach should be 3.9 sec. Examining the result in row 24, Figure 12, we confirm that this is true.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	923	0	0	0
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.256			
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00			
11	x_O	0.00			
12	x_{CL}	0.00			
13	x_{CR}	0.00			
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	1.000			
17	$P[C_2]$	0.000			
18	$P[C_3]$	0.000			
19	$P[C_4]$	0.000			
20	$P[C_5]$	0.000			
21	$\Sigma P[C_i]$	1.000			
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	3.9			
25	Degree of utilization (X)	1.00			
26	Iterations	2			

Figure 12. Example Calculation 4, Test 2, Case 1

With traffic on the NB and SB approaches only, the departure headway for the two approaches should equal the saturation headway for Case 2, or 4.7 sec. When we set the volume on the northbound and southbound approaches to 765 veh/hr (and zero on the other two approaches), we expect the resulting departure headway to be 4.7 sec. We confirm that this is true by examining the results in row 24, Figure 13.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	765	765	0	0
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.213	0.213		
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00	1.00		
11	x_O	1.00	1.00		
12	x_{CL}	0.00	0.00		
13	x_{CR}	0.00	0.00		
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.002	0.002		
17	$P[C_2]$	0.998	0.998		
18	$P[C_3]$	0.000	0.000		
19	$P[C_4]$	0.000	0.000		
20	$P[C_5]$	0.000	0.000		
21	$\Sigma P[C_i]$	1.000	1.000		
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	4.7	4.7		
25	Degree of utilization (X)	1.00	1.00		
26	Iterations	7			

Figure 13. Example Calculation 4, Test 2, Case 2

With traffic on the NB and EB approaches only, the departure headway for the two approaches should equal the saturation headway for Case 3, or 5.8 sec. We confirm that this is true by examining the results in row 24, Figure 14.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	621	0	621	0
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.173		0.173	
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00		1.00	
11	x_O	0.00		0.00	
12	x_{CL}	1.00		1.00	
13	x_{CR}	0.00		0.00	
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.000		0.000	
17	$P[C_2]$	0.000		0.000	
18	$P[C_3]$	1.000		1.000	
19	$P[C_4]$	0.000		0.000	
20	$P[C_5]$	0.000		0.000	
21	$\Sigma P[C_i]$	1.000		1.000	
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	5.8		5.8	
25	Degree of utilization (X)	1.00		1.00	
26	Iterations	8			

Figure 14. Example Calculation 4, Test 2, Case 3

With traffic on three approaches, the departure headway for each approach should equal the saturation headway for Case 4, or 7.0 sec, as shown in row 24, Figure 15.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	514	514	514	0
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.143	0.143	0.143	
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00	1.00	1.00	
11	x_O	1.00	1.00	0.00	
12	x_{CL}	1.00	0.00	1.00	
13	x_{CR}	0.00	1.00	1.00	
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.000	0.000	0.000	
17	$P[C_2]$	0.001	0.001	0.000	
18	$P[C_3]$	0.001	0.001	0.002	
19	$P[C_4]$	0.998	0.998	0.998	
20	$P[C_5]$	0.000	0.000	0.000	
21	$\Sigma P[C_i]$	1.000	1.000	1.000	
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	7.0	7.0	7.0	
25	Degree of utilization (X)	1.00	1.00	1.00	
26	Iterations	14			

Figure 15. Example Calculation 4, Test 2, Case 4

For Case 5, with traffic on all four approaches, the departure headway for each approach should equal the saturation headway for this case, or 9.6 sec, as shown in row 24, Figure 16.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	375	375	375	375
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.104	0.104	0.104	0.104
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00	1.00	1.00	1.00
11	x_O	1.00	1.00	1.00	1.00
12	x_{CL}	1.00	1.00	1.00	1.00
13	x_{CR}	1.00	1.00	1.00	1.00
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.000	0.000	0.000	0.000
17	$P[C_2]$	0.000	0.000	0.000	0.000
18	$P[C_3]$	0.000	0.000	0.000	0.000
19	$P[C_4]$	0.000	0.000	0.000	0.000
20	$P[C_5]$	1.000	1.000	1.000	1.000
21	$\Sigma P[C_i]$	1.000	1.000	1.000	1.000
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	9.6	9.6	9.6	9.6
25	Degree of utilization (X)	1.00	1.00	1.00	1.00
26	Iterations	42			

Figure 16. Example Calculation 4, Test 2, Case 5

Example Calculation 5

Assume an intersection with 300 veh/hr on each approach. Use the spreadsheet to determine the capacity of the NB approach.

Figure 17 shows the results when the volume on each approach is 300 veh/hr.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	300	300	300	300
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.083	0.083	0.083	0.083
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	0.55	0.55	0.55	0.55
11	x_O	0.55	0.55	0.55	0.55
12	x_{CL}	0.55	0.55	0.55	0.55
13	x_{CR}	0.55	0.55	0.55	0.55
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.089	0.089	0.089	0.089
17	$P[C_2]$	0.110	0.110	0.110	0.110
18	$P[C_3]$	0.220	0.220	0.220	0.220
19	$P[C_4]$	0.411	0.411	0.411	0.411
20	$P[C_5]$	0.170	0.170	0.170	0.170
21	$\Sigma P[C_i]$	1.000	1.000	1.000	1.000
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	6.7	6.7	6.7	6.7
25	Degree of utilization (X)	0.55	0.55	0.55	0.55
26	Iterations	14			

Figure 17. Initial results for Example Calculation 5

To determine the capacity of the NB approach, the volume on that approach is increased until X_{NB} reaches 1.0. This condition occurs when the volume on the NB approach is 494 veh/hr. Thus the capacity for this approach, under these traffic flow conditions, is 494 veh/hr. Figure 18 shows this result.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	494	300	300	300
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.137	0.083	0.083	0.083
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00	0.66	0.67	0.67
11	x_O	0.66	1.00	0.67	0.67
12	x_{CL}	0.67	0.67	1.00	0.66
13	x_{CR}	0.67	0.67	0.66	1.00
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.038	0.000	0.000	0.000
17	$P[C_2]$	0.073	0.111	0.000	0.000
18	$P[C_3]$	0.152	0.000	0.114	0.114
19	$P[C_4]$	0.444	0.444	0.447	0.447
20	$P[C_5]$	0.293	0.445	0.439	0.439
21	$\Sigma P[C_i]$	1.000	1.000	1.000	1.000
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	7.3	7.9	8.0	8.0
25	Degree of utilization (X)	1.00	0.66	0.67	0.67
26	Iterations	17			

Figure 18. Final results for Example Calculation 5 showing capacity for NB approach

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Example Calculation 6

Consider the second part of Example Calculation 5, in which the NB volume was 494 veh/hr and the volume on the other three approaches was 300 veh/hr. We determined that the capacity of the NB approach is 494 veh/hr since the degree of utilization was determined to be 1.0, as shown in Figure 19.

But what happens if the NB volume is increased to 600 veh/hr, as shown in Figure 20? The value of the degree of utilization in row 10 for the NB approach is 1.00. This is the maximum value for X in rows 10 through 13, since here X is viewed as the probability that a given degree of conflict case will occur. And, this value can't exceed 1.0. However, X in row 25 is equal to 1.22. This is the true degree of utilization and the value implies that the demand exceeds the capacity of the approach. Even though the demand on the NB approach is 600 veh/hr, only 494 vehicles will be served during the hour. A more complete analysis of these conditions would consider a second time period in which the demand that wasn't served during the first time period would be analyzed.

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	494	300	300	300
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.137	0.083	0.083	0.083
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00	0.66	0.67	0.67
11	x_O	0.66	1.00	0.67	0.67
12	x_{CL}	0.67	0.67	1.00	0.66
13	x_{CR}	0.67	0.67	0.66	1.00
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.038	0.000	0.000	0.000
17	$P[C_2]$	0.073	0.111	0.000	0.000
18	$P[C_3]$	0.152	0.000	0.114	0.114
19	$P[C_4]$	0.444	0.444	0.447	0.447
20	$P[C_5]$	0.293	0.445	0.439	0.439
21	$\Sigma P[C_i]$	1.000	1.000	1.000	1.000
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	7.3	7.9	8.0	8.0
25	Degree of utilization (X)	1.00	0.66	0.67	0.67
26	Iterations	17			

Figure 19. Initial results for Example Calculation 6

	A	B	C	D	E
1	**AWSC Intersection Model - 4 Legs (Scenario 2)**			Run AWSC	
2					
3	**Given Conditions**	**NB**	**SB**	**EB**	**WB**
4	Volume (v, veh/hr)	600	300	300	300
5					
6	**Calculations**	**NB**	**SB**	**EB**	**WB**
7	Lambda (λ, veh/sec)	0.167	0.083	0.083	0.083
8					
9	Degree of utilization	**NB**	**SB**	**EB**	**WB**
10	x_S	1.00	0.66	0.67	0.67
11	x_O	0.66	1.00	0.67	0.67
12	x_{CL}	0.67	0.67	1.00	0.66
13	x_{CR}	0.67	0.67	0.66	1.00
14					
15	Probability of DOC cases	**NB**	**SB**	**EB**	**WB**
16	$P[C_1]$	0.038	0.000	0.000	0.000
17	$P[C_2]$	0.073	0.111	0.000	0.000
18	$P[C_3]$	0.152	0.000	0.114	0.114
19	$P[C_4]$	0.444	0.444	0.447	0.447
20	$P[C_5]$	0.293	0.445	0.439	0.439
21	$\Sigma P[C_i]$	1.000	1.000	1.000	1.000
22					
23	**Results**	**NB**	**SB**	**EB**	**WB**
24	Departure headway (h_d, sec/veh)	7.3	7.9	8.0	8.0
25	Degree of utilization (X)	1.22	0.66	0.67	0.67
26	Iterations	13			

Figure 20. Final results for Example Calculation 6

7. Summary

In this chapter we explored the models on which the HCM capacity analysis method for AWSC intersections is based. We reviewed how an AWSC intersection operates in the field, and the factors on which models to predict the capacity of an intersection approach could be based. In developing the models we used the concept of the simplified scenario, in which only the most important traffic and geometric factors are considered. By focusing only on these factors, you developed a basic understanding of the operation of an AWSC intersection, one that can be later built upon as the more complex conditions found in the real world are considered.

You studied two such scenarios. The first scenario was based on the intersection of two one-lane one-way streets, while the second scenario was based on one lane approaches at a standard 4-leg intersection. In both scenarios, we assumed through movements only (no turning movements), a traffic stream consisting only of passenger cars, and no pedestrians to impede the flow of automobile traffic. You learned that the operation of an AWSC intersection is based primarily on the interactions between drivers, each driver having to make the decision: "when is it my turn to enter the intersection?" The higher the traffic flow rates, the more intense are these interactions, and the longer drivers must wait until it is their turn.

8. Glossary

Table 5. Terms used in this chapter

Term	Definition
Capacity	"Maximum number of vehicles that can pass a given point during a specified period under prevailing roadway, traffic, and control conditions." [From the HCM]
Conflicting approach	The approach or approaches on the cross street from the perspective of the subject approach.
Degree of utilization	"The probability of finding at least one vehicle on [an] approach." [From the HCM]
Departure headway	The time between the departures of two consecutive vehicles on one approach of an AWSC intersection.
Opposing approach	The approach opposite the subject approach.
Saturation headway	The time between the departures of two consecutive vehicles on one approach of an AWSC intersection during a period of continuous queuing on that approach.
Subject approach	The approach currently being analyzed.

Table 6. Variables used in this chapter

Variable	Description	Units
h_d	Departure headway	sec/veh
h_{is}	Saturation headway for degree of conflict case i	sec/veh
$P[C_i]$	Probability of degree of conflict case i	-
v	Arrival volume	veh/hr
X	Degree of utilization	-
λ	Arrival flow rate	veh/sec

9. References

Hebert studied the headways between vehicles for two conditions at several AWSC intersections in Chicago in 1963. His work formed the basis for Richardson, who developed the initial formulations for what are described here as Scenarios 1 and 2. Kyte and others extended Richardson's model for 4-leg intersections and, through a national study of AWSC intersections, delineated five degree of conflict cases and measured the saturation headway for each case. The work of Kyte and others is the basis for the HCM AWSC intersection methodology.

Hebert, J. A Study of Four-Way Stop-Controlled Intersection Capacities. In Highway Research Record 27, Highway Research Board, Washington, D.C., 1963.

Richardson, A.J. A Delay Model for Multiway Stop-Sign Intersections. In Transportation Research Record 1112, Transportation Research Board, National Research Council, Washington, D.C., 1987, pp 107-114.

Kyte, M., Z. Tian, Z. Mir, Z. Hameedmansoor, W. Kittelson, M. Vandehey, B. Robinson, W. Brilon, L. Bondzio, N. Wu, and R. Troutbeck. NCHRP Web Document 6: Capacity and Level of Service at Unsignalized Intersections: Final Report, Vol 2--All-Way Stop-Controlled Intersections. Transportation Research Board, National Research Council, Washington, D.C., April 1996.

Kyte, M., Z. Tian, J. Kuhn, H. Poffenroth, M. Butorac, and B. Robertson. Saturation Headways at Stop-Controlled Intersections. In Transportation Research Record 1457, Transportation Research Board, National Research Council, Washington, D.C., 1994, pp 111-117.

Appendix 1

```
Public Sub AWSCcap()
'This Sub computes the degree of utilization and delay for an AWSC
intersection approach
'
'Written by Michael Kyte, 9 May 2017
'Revisions:
'Error checking/corrections, 16 May 2017
'
'Variables:
'v is the input volume (veh/hr) for each approach: vNB, vSB, vEB, vWB
'lambda is the flow rate (veh/sec) for each approach: lambdaNB, lambdaSB,
lambdaEB, lambdaWB

'hd_initial is the initial value of the departure headway (hd_initial=3.9
sec)
'hd is the departure headway for each approach: hdNB, hdSB, hdEB, hdWB
'hsi is the saturation headway for each of five cases:
hs1 = 3.9
hs2 = 4.7
hs3 = 5.8
hs4 = 7#
hs5 = 9.6

'x is the degree of utilization for each approach: xNB, xSB, xEB, xWB

'P[Ci] is the probability that each of the five cases will occur for each
approach:
'P[C1], P[C2] P[C3], P[C4], P[C5]

'Reset values on spreadsheet to zero
Range("b7").Value = ""
Range("c7").Value = ""
Range("d7").Value = ""
Range("e7").Value = ""

Range("b10").Value = ""
Range("c10").Value = ""
Range("d10").Value = ""
Range("e10").Value = ""

Range("b11").Value = ""
Range("c11").Value = ""
Range("d11").Value = ""
Range("e11").Value = ""

Range("b12").Value = ""
Range("c12").Value = ""
Range("d12").Value = ""
Range("e12").Value = ""

Range("b13").Value = ""
Range("c13").Value = ""
Range("d13").Value = ""
Range("e13").Value = ""
```

```
Range("b16").Value = ""
Range("c16").Value = ""
Range("d16").Value = ""
Range("e16").Value = ""

Range("b17").Value = ""
Range("c17").Value = ""
Range("d17").Value = ""
Range("e17").Value = ""

Range("b18").Value = ""
Range("c18").Value = ""
Range("d18").Value = ""
Range("e18").Value = ""

Range("b19").Value = ""
Range("c19").Value = ""
Range("d19").Value = ""
Range("e19").Value = ""

Range("b20").Value = ""
Range("c20").Value = ""
Range("d20").Value = ""
Range("e20").Value = ""

Range("b21").Value = ""
Range("c21").Value = ""
Range("d21").Value = ""
Range("e21").Value = ""

Range("b24").Value = ""
Range("c24").Value = ""
Range("d24").Value = ""
Range("e24").Value = ""

Range("b25").Value = ""
Range("c25").Value = ""
Range("d25").Value = ""
Range("e25").Value = ""

Range("b26").Value = ""

'Set initial value of iteration number
IterationNum = 0

'Read given approach volumes
vNB = Range("b4").Value
vSB = Range("c4").Value
vEB = Range("d4").Value
vWB = Range("e4").Value

'Step 1. Convert the volume v in veh/hr to the flow rate lambda in veh/sec
lambdaNB = vNB / 3600
lambdaSB = vSB / 3600
lambdaEB = vEB / 3600
lambdaWB = vWB / 3600
```

```
'Print lambda values in row 7
Range("b7").Value = lambdaNB
Range("c7").Value = lambdaSB
Range("d7").Value = lambdaEB
Range("e7").Value = lambdaWB

'Step 2. Calculate the initial degree of utilization
hdNB = 3.9
hdSB = 3.9
hdEB = 3.9
hdWB = 3.9

xNB = lambdaNB * hdNB
xSB = lambdaSB * hdSB
xEB = lambdaEB * hdEB
xWB = lambdaWB * hdWB

'This loop continues until hd changes less than 0.0001 on each approach
Do

'Reset x to maximum value of 1
If xNB > 1 Then xNB = 1
If xSB > 1 Then xSB = 1
If xEB > 1 Then xEB = 1
If xWB > 1 Then xWB = 1

'Set hdlast to current value of hd for each approach
hdNBlast = hdNB
hdSBlast = hdSB
hdEBlast = hdEB
hdWBlast = hdWB

'Iteration number: increase
IterationNum = IterationNum + 1

'Step 3. Compute the probability of each degree of conflict case for each
approach

'NB approach
PC1NB = (1 - xSB) * (1 - xEB) * (1 - xWB)
PC2NB = (xSB) * (1 - xEB) * (1 - xWB)
PC3NB = (1 - xSB) * (xEB) * (1 - xWB) + (1 - xSB) * (1 - xEB) * (xWB)
PC4NB = (xSB) * (1 - xEB) * (xWB) + (xSB) * (xEB) * (1 - xWB) + (1 - xSB)
* (xEB) * (xWB)
PC5NB = (xSB) * (xEB) * (xWB)

'SB approach
PC1SB = (1 - xNB) * (1 - xWB) * (1 - xEB)
PC2SB = (xNB) * (1 - xWB) * (1 - xEB)
PC3SB = (1 - xNB) * (xWB) * (1 - xEB) + (1 - xNB) * (1 - xWB) * (xEB)
PC4SB = (xNB) * (1 - xWB) * (xEB) + (xNB) * (xWB) * (1 - xEB) + (1 - xNB)
* (xWB) * (xEB)
PC5SB = (xNB) * (xWB) * (xEB)

'EB approach
PC1EB = (1 - xWB) * (1 - xSB) * (1 - xNB)
```

```
PC2EB = (xWB) * (1 - xSB) * (1 - xNB)
PC3EB = (1 - xWB) * (xSB) * (1 - xNB) + (1 - xWB) * (1 - xSB) * (xNB)
PC4EB = (xWB) * (1 - xSB) * (xNB) + (xWB) * (xSB) * (1 - xNB) + (1 - xWB)
* (xSB) * (xNB)
PC5EB = (xWB) * (xSB) * (xNB)

'WB approach
PC1WB = (1 - xEB) * (1 - xNB) * (1 - xSB)
PC2WB = (xEB) * (1 - xNB) * (1 - xSB)
PC3WB = (1 - xEB) * (xNB) * (1 - xSB) + (1 - xEB) * (1 - xNB) * (xSB)
PC4WB = (xEB) * (1 - xNB) * (xSB) + (xEB) * (xNB) * (1 - xSB) + (1 - xEB)
* (xNB) * (xSB)
PC5WB = (xEB) * (xNB) * (xSB)

'Step 4. Compute the departure headway
hdNB = PC1NB * hs1 + PC2NB * hs2 + PC3NB * hs3 + PC4NB * hs4 + PC5NB * hs5
hdSB = PC1SB * hs1 + PC2SB * hs2 + PC3SB * hs3 + PC4SB * hs4 + PC5SB * hs5
hdEB = PC1EB * hs1 + PC2EB * hs2 + PC3EB * hs3 + PC4EB * hs4 + PC5EB * hs5
hdWB = PC1WB * hs1 + PC2WB * hs2 + PC3WB * hs3 + PC4WB * hs4 + PC5WB * hs5

'Compute x for each approach
xNB = lambdaNB * hdNB
xSB = lambdaSB * hdSB
xEB = lambdaEB * hdEB
xWB = lambdaWB * hdWB

'Reset x to maximum value of 1
If xNB > 1 Then xNB = 1
If xSB > 1 Then xSB = 1
If xEB > 1 Then xEB = 1
If xWB > 1 Then xWB = 1

'Step 5. Convergence check
If Abs(hdNBlast - hdNB) < 0.0001 Then
    hdNBcheck = 0
Else
    hdNBcheck = 2
End If

If Abs(hdSBlast - hdSB) < 0.0001 Then
    hdSBcheck = 0
Else
    hdSBcheck = 2
End If

If Abs(hdEBlast - hdEB) < 0.0001 Then
    hdEBcheck = 0
Else
    hdEBcheck = 2
End If

If Abs(hdWBlast - hdWB) < 0.0001 Then
    hdWBcheck = 0
Else
    hdWBcheck = 2
End If
```

```
Loop Until hdNBcheck + hdSBcheck + hdEBcheck + hdWBcheck = 0

'Print final results in cells

If vNB = 0 Then
    Range("b7").Value = ""
    Range("b10").Value = ""
    Range("b11").Value = ""
    Range("b12").Value = ""
    Range("b13").Value = ""
    Range("b16").Value = ""
    Range("b17").Value = ""
    Range("b18").Value = ""
    Range("b19").Value = ""
    Range("b20").Value = ""
    Range("b21").Value = ""
    Range("b24").Value = ""
    Range("b25").Value = ""
ElseIf vNB <> 0 Then
    Range("b10").Value = xNB
    Range("b11").Value = xSB
    Range("b12").Value = xEB
    Range("b13").Value = xWB
    Range("b16").Value = PC1NB
    Range("b17").Value = PC2NB
    Range("b18").Value = PC3NB
    Range("b19").Value = PC4NB
    Range("b20").Value = PC5NB
    Range("b21").Value = PC1NB + PC2NB + PC3NB + PC4NB + PC5NB
    Range("b24").Value = hdNB
    Range("b25").Value = hdNB * lambdaNB
End If

If vSB = 0 Then
    Range("c7").Value = ""
    Range("c10").Value = ""
    Range("c11").Value = ""
    Range("c12").Value = ""
    Range("c13").Value = ""
    Range("c16").Value = ""
    Range("c17").Value = ""
    Range("c18").Value = ""
    Range("c19").Value = ""
    Range("c20").Value = ""
    Range("c21").Value = ""
    Range("c24").Value = ""
    Range("c25").Value = ""
ElseIf vSB <> 0 Then
    Range("c10").Value = xSB
    Range("c11").Value = xNB
    Range("c12").Value = xWB
    Range("c13").Value = xEB
    Range("c16").Value = PC1SB
    Range("c17").Value = PC2SB
    Range("c18").Value = PC3SB
    Range("c19").Value = PC4SB
    Range("c20").Value = PC5SB
```

```
    Range("c21").Value = PC1SB + PC2SB + PC3SB + PC4SB + PC5SB
    Range("c24").Value = hdSB
    Range("c25").Value = hdSB * lambdaSB
End If

If vEB = 0 Then
    Range("d7").Value = ""
    Range("d10").Value = ""
    Range("d11").Value = ""
    Range("d12").Value = ""
    Range("d13").Value = ""
    Range("d16").Value = ""
    Range("d17").Value = ""
    Range("d18").Value = ""
    Range("d19").Value = ""
    Range("d20").Value = ""
    Range("d21").Value = ""
    Range("d24").Value = ""
    Range("d25").Value = ""
ElseIf vEB <> 0 Then
    Range("d10").Value = xEB
    Range("d11").Value = xWB
    Range("d12").Value = xNB
    Range("d13").Value = xSB
    Range("d16").Value = PC1EB
    Range("d17").Value = PC2EB
    Range("d18").Value = PC3EB
    Range("d19").Value = PC4EB
    Range("d20").Value = PC5EB
    Range("d21").Value = PC1EB + PC2EB + PC3EB + PC4EB + PC5EB
    Range("d24").Value = hdEB
    Range("d25").Value = hdEB * lambdaEB
End If

If vWB = 0 Then
Range("e10").Value = ""
    Range("e7").Value = ""
    Range("e11").Value = ""
    Range("e12").Value = ""
    Range("e13").Value = ""
    Range("e16").Value = ""
    Range("e17").Value = ""
    Range("e18").Value = ""
    Range("e19").Value = ""
    Range("e20").Value = ""
    Range("e21").Value = ""
    Range("e24").Value = ""
    Range("e25").Value = ""
ElseIf vWB <> 0 Then
    Range("e10").Value = xWB
    Range("e11").Value = xWB
    Range("e12").Value = xSB
    Range("e13").Value = xNB
    Range("e16").Value = PC1WB
    Range("e17").Value = PC2WB
    Range("e18").Value = PC3WB
    Range("e19").Value = PC4WB
```

```
    Range("e20").Value = PC5WB
    Range("e21").Value = PC1WB + PC2WB + PC3WB + PC4WB + PC5WB
    Range("e24").Value = hdWB
    Range("e25").Value = hdWB * lambdaWB
End If

'Print iteration number in cell b26
Range("b26").Value = IterationNum

End Sub
```