# CHAPTER 5. Capacity of TWO-Way Stop-Controlled Intersections

## 1. Introduction

In this chapter we will explore the models on which the HCM capacity analysis method for two-way stop-controlled (TWSC) intersections are based. We’ll start in section 2 with a discussion of how TWSC intersections operate in the field, particularly the interaction between drivers on the major street and those on the stop-controlled approaches. In section 3, we’ll identify the important factors in this interaction that will help us to formulate the models to predict the capacity of a traffic stream. 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 a TWSC intersection, one that can later be built upon as the more complex conditions found in the real world are considered.

You will study two such scenarios. The first scenario is based on the intersection of two one-lane one-way streets. The second scenario is based on a T-intersection with two-way traffic on the major street but only left turning traffic on the stop-controlled approach. In both scenarios, we assume a traffic stream consisting only of passenger cars and no pedestrians to impede the flow of automobile traffic.

You will see that the operation of a TWSC intersection is based on the decisions made by minor stream drivers (those on the stop-controlled approaches) about when it is safe to enter the intersection. Two model parameters represent these decisions in the models, the critical headway and the follow-up headway. You will learn how to calculate these parameters in Section 6.

You will build a computational engine in section 7, based on the two scenarios described above. You can use the computational engine (in the form of a spreadsheet) to study the predictions of capacity that the models make under a range of traffic flow conditions. These predictions will help you to understand when two-way stop control might be an effective control strategy and under what conditions other types of control should be considered.

Section 8 presents a summary of the chapter. Section 9 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 10. A set of problems for you to test your understanding of this material is given in section 11; the solutions to the problems are given in section 12.

## 2. What Do We Observe in the Field?

A TWSC intersection provides priority to vehicles on the major street while requiring vehicles on the minor street to stop before entering the intersection. Minor street drivers look for gaps in the major street traffic stream that are large enough for them to safely enter the intersection and complete their maneuver.

Since we are interested in predicting the capacity of a traffic stream, let’s consider what drivers see and do as they approach a TWSC intersection. Drivers on the major street traveling through or turning right proceed through the intersection without stopping. Drivers turning left from the major street may be delayed if there are oncoming through or right-turning vehicles; these left turning vehicles may need to wait to find a suitable gap in this oncoming traffic stream before completing their maneuver through the intersection.

Drivers on the stop-controlled approaches must stop when they arrive at the stop line and wait for suitable gaps in the major street traffic stream. They must also negotiate “whose turn it is” with drivers on the other stop-controlled approach, jointly deciding who can use the next available gap. The capacity of each minor stream is thus dependent on (1) the traffic flow rates of the higher priority streams as well as (2) on the behavior of the minor stream drivers and the gaps that they require to complete a specific maneuver.

Other factors also limit the capacity of a traffic stream, such as pedestrians crossing the street or 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 and a traffic stream consisting only of passenger cars.

[Add pictures or videos to illustrate basic operations.]

So, why do we study the capacity of a TWSC intersection? Sometimes, we want to determine what type of control is optimal for an intersection given demand and geometric conditions. We might also want to know when it is justified to change from stop sign control to signal control. Or, perhaps there is a driveway from a shopping center or residential development that enters an arterial and we want to know whether stop sign control will be adequate. The models that we will develop in this chapter can help to answer these questions.

## 3. Formulating the Model

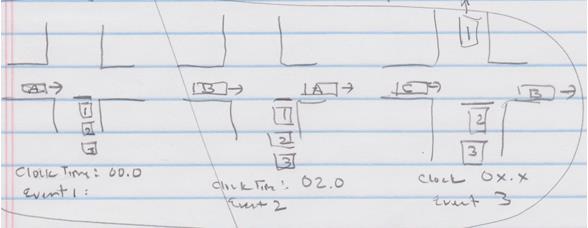
We will use a queuing model to represent the traffic flow conditions on a stop-controlled approach of a TWSC intersection based on the conditions that we’ve observed in the field. This queuing model consists of the following parts:

* Vehicles arrive at the intersection, on both the major and minor streets, in a random manner, with headways between vehicles following a negative exponential distribution.
* Vehicles on the stop-controlled approaches require a minimum headway in the major traffic stream to safely enter the intersection and complete their maneuver. This minimum headway is called the critical headway.
* If there is a continuous queue on a stop-controlled approach, and a large enough gap between vehicles on the major street, the headway between vehicles entering the intersection from this stop-controlled approach using this gap is called the follow-up headway.
* There is a hierarchy among the traffic streams. For example, through and right-turning vehicles on the major street always have priority over vehicles in the other traffic streams. By contrast, left-turning minor stream vehicles must give way to vehicles in all other traffic streams.

The process described above is known as a gap acceptance process. The gap acceptance process can be observed in other traffic flow situations. Examples include vehicles merging from an on-ramp to a freeway mainline, vehicles passing on a two-lane highway, and vehicles making permitted left turns at a signalized intersection.

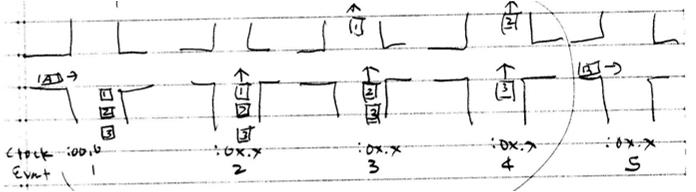
Since we use both terms, gap and headway, to describe what seems like the same thing, it is important to define clearly what each term means. A gap is what drivers see and make judgements about: it is the distance or time between the back bumper of one car and front bumper of following car in the major street traffic stream. The headway that we measure corresponding to this gap is the time between the front bumpers of the first and second cars.

To illustrate the gap acceptance process consider the sequence of events shown in Figure 1. The sequence begins with a queue of three vehicles on the NB (stop-controlled) approach and a vehicle on the major street (EB approach, vehicle A) entering the intersection. The next vehicle to arrive on the major street approach, Vehicle B, enters the intersection (event 2) x.x sec later. The headway between vehicles A and B (2.0 sec) is too small for vehicle 1 on the stop-controlled approach to enter the intersection. The driver of vehicle 1 is said to reject the gap between vehicles A and B. In event 3, we note that vehicle 1 has just cleared the intersection when vehicle C enters the intersection. Vehicle 1 is said to have accepted the gap between vehicle B and vehicle C. While we don’t have enough data in this simple illustration to make a more precise estimate, we do know that the critical headway for vehicle 1 is greater than 2.0 sec but less than x.x sec. The process for estimating the critical headway is described in Section 6 of this chapter.



Figure

Now consider the sequence of events shown in Figure 2. The sequence also begins with a queue of three vehicles on the NB approach, and a vehicle (vehicle A) on the major street entering the intersection. In event 2, vehicle 1 enters the intersection, followed by vehicle 2 (event 3) and vehicle 3 (event 4). Finally, in event 5, the next major street vehicle (Vehicle B) enters the intersection.



Figure

The gap accepted by vehicles 1, 2, and 3 is defined by the headway between vehicles A and B.

We know that this headway is larger than the critical headway since it was used by more than one minor street vehicle. But we can calculate the follow up headway since more than one vehicle from the stop-controlled approach that was part of a continuous queue used the same major street gap.

In summary, the gap acceptance model for determining the capacity of a minor traffic stream at a TWSC intersection is based on the following concepts:

* Drivers in a minor traffic stream require a minimum headway between vehicles in the major traffic stream to safely enter the intersection. This headway is called the critical headway. As we will see later in the chapter, the critical headway is estimated statistically based on the number and size of gaps that are accepted and rejected by minor stream drivers.
* When gaps are large enough, more than one minor stream vehicle may use the same gap. The headway between consecutive minor stream vehicles using the same major stream gap during conditions of continuous queuing in the minor stream is called the follow-up headway.

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

## 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. Vehicles on one of the streets, the major street, always have the right-of-way. Vehicles on the minor street, controlled by a stop sign, must wait for a suitable gap in the major street traffic stream before entering the intersection. We’ll call this Scenario 1. In this section, we’ll study the conditions on the minor street approach and develop a model to predict the capacity of the approach. This capacity depends directly on the major street traffic volume as well as the behavioral characteristics of drivers on the minor street. Said another way, we will consider both the availability of gaps on the major traffic stream and the usefulness of these gaps to minor stream drivers.

[add figure showing the above scenario]

### Availability of Gaps

We start by representing the availability of gaps in the major traffic stream. And, remember, we are assuming that the arrival of major street vehicles can be represented by a random process. Two common statistical distributions are used to represent random processes:

* The Poisson distribution is a discrete distribution, often used to describe how many random events will occur during a specific time interval.
* The negative exponential distribution is a continuous distribution that is used to represent the time between the occurrences of these random events.

Suppose we have a single lane on the major street on which traffic is flowing in one direction. Further assume that the operation of each vehicle is independent of any of the other vehicle in the lane. If the mean flow rate is λ (veh/sec), the probability of observing x vehicles during a specified time period t is given by the Poisson distribution:

Equation

For these conditions, what is the probability that we observe no vehicles during the interval t? The probability that x is zero (no vehicles observed during the interval) is given by Equation 2.

Equation

Another way of looking at the condition described in Equation 2 is: what is the probability that we will see a headway in the traffic stream of at least t seconds? This can be represented by the density function for the negative exponential distribution.

Equation

#### Example Calculation 1

Suppose the mean arrival rate of vehicles on the major street is 400 veh/hr or .111 veh/sec. What is the probability that we will observe a headway greater than or equal to 4 sec? What is the probability that we will see a gap less than 4 sec?

From Equation 3:

The probability that we will observe a headway greater than or equal to 4 sec is:

And the probability that we will observe a headway less than 4 sec is given by:

### Usefulness of Gaps

Next, we’ll look at the usefulness of the available major street gaps to drivers on the minor or stop-controlled approach. The behavior of the minor street drivers is represented by two parameters, the critical headway and the follow-up headway. Headways that are greater than or equal to the critical headway are large enough for the minor street driver to safely enter the intersection and are thus considered useful. Headways that are less than the critical headway are rejected by a minor street driver and are not considered useful.

We will further assume that drivers are both homogeneous (they behave the same way at any location) and consistent (they behave the same way every time). This means that we can use one value for tc and tf for all drivers in a given traffic stream.

### Usefulness of Headway Ranges

The capacity of the minor street approach is calculated by combining these concepts. Consider ranges of major street headways and the number of minor street vehicles that can use each range. We know that if a major street headway is less than the critical headway, no minor street vehicle can use the gap that creates the headway. We also know that if the headway is greater than or equal to tc, then at least one minor street vehicle can use the gap. But we also know if the gap is large enough, more than one minor street vehicle can use the gap. Table 1 shows the number of vehicles can use each headway ranges, covering the cases of no vehicles, one vehicle, and two vehicles, and for the general case of n vehicles.

Table

|  |  |
| --- | --- |
| **Headway range, th** | **Number of vehicles able to use range** |
| th < tc | 0 |
| tc ≤ th < tc + tf | 1 |
| tc +tf ≤ th < tc + 2tf | 2 |
| … |  |
| tc + (n-1)tf ≤ th < tc + ntf | n |

### Likelihood of Headway Range Occurring

The next step is to calculate the likelihood that each headway range will occur. We know that the probability that a headway in the major traffic stream is less than tc, and thus too small to be usable by any vehicle, is given by:

Equation

where λ is the mean arrival rate of the major traffic stream.

The probability that a gap is large enough for only one vehicle is given by the difference between the probability of a headway less than or equal to tc and the probability of a headway less than or equal to tc plus tf:

Equation

In general, the probability that a gap is large enough to be used by n vehicles is given by:

Equation

The probability of a given headway range occurring is given column 3 in Table 2.

Table

|  |  |  |
| --- | --- | --- |
| **Headway range, tg** | **Number of vehicles able to use range** | **Probability of range occurrence** |
| th < tc | 0 |  |
| tc ≤ th ≤ tc +tf | 1 |  |
| tc +tf ≤ th ≤ tc +2tf | 2 |  |
| … |  |  |
| tc + (n-1)tf ≤ th ≤ tc +ntf | n |  |

### Capacity of Minor Stream

We can combine the concepts of gap availability, gap (and headway range) usefulness, and the likelihood of headway range occurrence to estimate the capacity of a stream or movement. We note that capacity is based on the distribution of gaps in the major stream, minor stream driver judgement in selecting gaps, and follow-up headway required by drivers in a queue in the minor stream.

The number of minor stream vehicles that can enter the intersection during one hour is the capacity of the stop-controlled approach, given the flow rate on the major street. This capacity flow rate can be written as the sum of the products of the probability that a given headway range will occur and the number of vehicles that can use this range. The fourth column in Table 3 shows the probable number of vehicles that can use each headway range. Each row in this column is the product of columns 2 and 3.

[Credit to Baass for Table 3 and following derivation.]

Table

|  |  |  |  |
| --- | --- | --- | --- |
| **Headway range, tg** | **Number of vehicles able to use range** | **Probability of range occurrence** | **Probable number of vehicles using range** |
| th < tc | 0 |  | 0 |
| tc ≤ th ≤ tc +tf | 1 |  | 1 |
| tc +tf ≤ th ≤ tc +2tf | 2 |  | 2 |
| … |  |  |  |
| tc + (n-1)tf ≤ th ≤ tc +ntf | n |  | n |

Equation 7 shows the sum of column 4, an infinite series, to be the probable number of vehicles that can enter the intersection in an hour. This result is the capacity of the approach.

Equation

where vc is the major street flow rate in veh/hr.

This can also be written in a shorter form as shown in Equation 8.

Equation

The sum of the series is given by Equation 9:

Equation

where vc is the flow rate on the major street and is equal to .

[Need to reconcile above calculation: check with Baass article.]

#### Example Calculation 2

Research has shown that for the minor street through movement tc = 6.5 sec and tf = 4.0 sec. What is the capacity of the minor street approach if the major street flow rate is 400 veh/hr or .111 veh/sec?

We can use Equation 9 to determine the capacity flow rate.

We can also illustrate the capacity calculation using the process shown in Table 3. Table 4 shows the probable number of vehicles using ranges up to 62.5 sec. The sum of the probable number of vehicles using the fourteen headway ranges is 540.3 veh/hr, virtually equal to the 541 veh/hr calculated above. As we consider additional headway ranges, the cumulative sum of the probable number of vehicles approaches the calculated value of 541 veh/hr. Figure 3 shows that the greater the number of ranges considered, the closer the cumulative number of vehicles approaches the capacity prediction of 541 veh/hr.

Table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Headway range (sec)** | **Number of vehicles able to use range** | **Probability of range occurrence** | **Probable number of vehicles using range** | **Cumulative number of probable vehicles** |
| < 6.5 | 0 |  | 0 | 0.0 |
| 6.5 - 10.5 | 1 |  | 1 = 1(.174)(400) = 69.6 | 69.6 |
| 10.5 - 14.5 | 2 |  | 2 = 2(.112)(400) = 89.3 | 159.0 |
| 14.5 – 18.5 | 3 |  | = 3(.072)(400) = 86.0 | 244.9 |
| 18.5 – 22.5 | 4 |  | 4 =(4)(.046)(400) = 73.5 | 318.4 |
| 22.5 – 26.5 | 5 |  | = (5)(.030)(400) = 58.9 | 377.4 |
| … |  |  |  |  |
| 26.5 – 30.5 | 6 | 0.019 | 45.4 | 422.8 |
| 30.5 – 34.5 | 7 | 0.012 | 34.0 | 456.7 |
| 34.5 – 38.5 | 8 | 0.008 | 24.9 | 481.6 |
| 38.5 – 42.5 | 9 | 0.005 | 18.0 | 499.6 |
| 42.5 – 46.5 | 10 | 0.003 | 12.8 | 512.4 |
| 46.5 – 50.5 | 11 | 0.002 | 9.0 | 521.4 |
| 50.5 – 54.5 | 12 | 0.001 | 6.3 | 527.7 |
| 54.5 – 58.5 | 13 | 0.001 | 4.4 | 532.1 |
| 58.5 – 62.5 | 14 | 0.001 | 3.0 | 535.2 |
| … |  |  |  |  |
|  | Sum | 0.999 | 535.2 [\*\*check this] |  |



Figure

#### Example Calculation 3

How does the capacity of the minor street approach vary with changes in the major street flow rate? As before, we assume tc = 6.5 sec and tf = 4.0 sec.

When vc = 0:

When vc = 200 veh/hr (or a mean headway in the major street traffic stream of 18 sec):

When vc = 900 veh/hr (or a mean headway in the major street traffic stream of 4 sec):

Figure 4 shows the variation of the minor street capacity with changes in the conflicting flow rate on the major street. When the conflicting flow rate approaches zero, the capacity flow rates approaches 3600/tf, or 900 veh/hr. As the conflicting flow rate increases, the capacity decreases. While the model never predicts a zero capacity, from a practical perspective, the probability of finding a useful gap (one for which the headway exceeds the critical headway) diminishes greatly when the flow rate approaches and then exceeds 1000 veh/hr. At a major street flow of 1000 veh/hr, the probability that a headway exceeds tc is 0.15; at 1500 veh/hr, the probability is .07. This diminishing probability is shown in Figure 5.



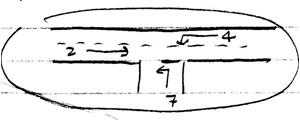
Figure



Figure

## 5. Scenario 2: T-Intersection

Let’s now consider a second simplified scenario, a T-intersection with one lane on each of its three approaches. We will only consider three movements, the EBTH and WBLT movements on the major street and the NBLT movement on the minor street. The movements are numbered according to the scheme used in the HCM, as shown in Figure 6.



Figure

### Potential Capacity

We need to distinguish between two terms, the potential capacity and the movement capacity. The movement capacity will be considered in the next section. The potential capacity for movements 4 and 7 is calculated based on Equation 8 and shown below as Equation 10 and Equation 11, respectively.

Equation

Equation

Let’s now consider how to calculate the conflicting flow rate vc,i for each movement. The conflicting flow for movement 4 is equal to the volume for movement 2, the only movement that conflicts with (or has a higher priority than) movement 4.

Equation

However, research has shown that the conflicting flow for movement 7 is equal to the movement 2 volume plus twice the movement 4 volume. Movement 7 drivers apparently react to the movement 4 volume to a degree greater than that represented simply by the volume. Equation 13 gives the conflicting flow for movement 7.

Equation

### Movement Capacity and Impedance

There is an obvious hierarchy among these three traffic movements. One traffic movement, movement 2, doesn’t stop for any other movement. It always has the right-of-way and is called rank 1. At the other extreme, movement 7 must always stop for the other two movements. It is called rank 3. In the middle, movement 4 must stop for or yield to movement 2, but it has priority over movement 7. It is called rank 2.

This hierarchy results in an important concept that we will call impedance. Gaps that could be usable to movement 7 vehicles (rank 3) may not be available because a rank 2 vehicle may use the same gap. For example, let’s say there is a headway of 8 sec between movement 2 vehicles, usually large enough for a waiting movement 7 vehicle to safely enter the intersection. But if a movement 4 vehicle is also waiting for a gap in movement 2 vehicle, the movement 7 vehicle would not be able to use this gap.

To formalize the concept of impedance, note that the probability of a movement 4 vehicle waiting to make a left turn is the traffic intensity (or ratio of the volume to the capacity) of that movement:

Equation

And, the probability that a movement 4 vehicle is not present, what we call a queue-free state for this movement, is given by:

Equation

The impedance of movement 4 on movement 7 drivers reduces the potential capacity for movement 7. This reduced capacity, called the movement capacity, is the product of its potential capacity and the probability that movement 4 is operating in a queue-free state, as given by Equation 16.

Equation

Or,

Equation

### Example Calculation 4

Let’s consider an example calculation to show the effects of movement hierarchy and the concept of impedance. The following conditions are given:

Table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Movement** | **Volume** | **Rank** | **tc** | **tf** |
| 2 | 600 | 1 | - | - |
| 4 | 100 | 2 | 4.1 | 2.2 |
| 7 | 50 | 3 | 7.1 | 3.5 |

The conflicting flow for movement 4 is:

The potential capacity for movement 4 is:

This is also the movement capacity for movement 4:

The conflicting flow for movement 7 is:

The potential capacity for movement 7 is:

We now have to consider the impedance of movement 4 on movement 7. That is, gaps that would have been available to movement 7 vehicles that are actually used by movement 4 vehicles. Impedance is the proportion of time that a minor movement is blocked or impeded by a higher priority minor movement. The movement capacity for movement 7 is the product of the potential capacity for movement 7 and the proportion of time that movement 4 operates in a queue-free state.

The proportion of time that a queue is present for movement 4 is given by:

The probability of a queue-free state is given by:

The movement capacity for movement 7 is:

### Example Calculation 5

Assume the same conditions as given in Example Calculation 4. Determine the effect of changing the WBLT volume on the NBLT capacity by varying the WBLT volumes from 0 to 1200 veh/hr.

Table 6 shows the volume for movement 4 for a range from zero to 600 veh/hr. The resulting conflicting flow for movement 7, the potential capacity for movement 7, the probability of a queue-free state for movement 4, and the movement capacity for movement 7 are also given in the table. As the volume for movement 4 (the WBLT movement) increases, the probability of a queue free-state for that movement decreases. Thus, the movement capacity for movement 7 decreases. Figure 7 illustrates these results for a range of movement 4 volumes from zero to 1200 veh/hr.

Table

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **v4** | **vc,7** | **cp,7** | **p0,4** | **cm,7** |
| 0 | 600 | 416 | 1.000 | 416 |
| 50 | 700 | 357 | 0.949 | 338 |
| 100 | 800 | 306 | 0.899 | 275 |
| 150 | 900 | 262 | 0.848 | 222 |
| 200 | 1000 | 224 | 0.797 | 178 |
| 250 | 1100 | 191 | 0.747 | 143 |
| 300 | 1200 | 163 | 0.696 | 114 |
| 350 | 1300 | 140 | 0.645 | 90 |
| 400 | 1400 | 119 | 0.595 | 71 |
| 450 | 1500 | 101 | 0.544 | 55 |
| 500 | 1600 | 86 | 0.493 | 43 |
| 550 | 1700 | 74 | 0.443 | 33 |
| 600 | 1800 | 63 | 0.392 | 25 |



Figure

Figure 8 shows how the volume-to-capacity ratio for movement 7 increases as the WBLT volume (movement 4) increases.



Figure

## 6. Calculating the Critical Headway and Follow-Up Headway

The critical headway and the follow-up headway define the behavior of drivers at a TWSC intersection when we use a gap acceptance model. The critical headway is the minimum time interval in the major stream traffic stream that allows intersection entry for one minor street vehicle. The follow up headway is the time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same major street headway, under conditions of continuous queuing on the minor street. In this section, we will learn how to use field data to calculate both parameters.

As we noted earlier, a driver actually observes the gap between vehicles when making his or her decision to enter the intersection. This gap is the time between the passage of the rear of one vehicle by a specific point and the arrival of the front of the next vehicle at that same point. However, gaps are difficult to measure consistently. It is standard practice to measure the headway, which is the time between the fronts of two consecutive vehicles in the traffic stream passing the same point. So while we often talk about the gap that a driver sees we refer to the headway as the relevant parameter that we use.

### Accepted and Rejected Gaps

Let’s look at an example of a T-intersection as shown in Figure 13 to illustrate how we estimate the critical headway. There are four movements, or traffic streams, at this intersection, including movements 2, 3, and 5 on the major street and movement 7 on the minor street, as shown in Figure 13.



Figure

We will look at the time that three types of events occur: (1) vehicles on the major street entering and passing through the intersection, and vehicles on the minor street (2) arriving at the end of a queue and then (3) arriving at the stop line. In this example, we will consider event data collected at an intersection over a period of three minutes to illustrate some of the issues in determining the critical headway and the follow-up headway. From the standpoint of drivers at the minor street stop line, some gaps will be too small to be usable, while other gaps will be large enough to be usable by one or more minor stream drivers.

Table 9 shows the time that each event occurred during this three-minute period. The first six columns show the event number and the time that vehicles on the major street (movements 5, 2, and 3) pass through the central point of the intersection, what we might call the conflict point. The last four columns show the event number and the times that the minor street vehicles (movement 7) arrive at the stop line (the server) and enter the intersection (depart from the server). The time format shown in the table is minutes, seconds, and tenths of seconds.

Table

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Vehicles arrive at conflict point on major street** | | | | | | **Minor street vehicles, Movement 7** | | | |
| **Movement 5** | | **Movement 2** | | **Movement 3** | | **Arrive server** | | **Depart server** | |
| **Event** | **Time** | **Event** | **Time** | **Event** | **Time** | **Event** | **Time** | **Event** | **Time** |
| 1  2  3  4  5  6  7  8  9  10  11  12  13  14 | 00:15.4  00:20.2  00.22.6  00:25.4  00:26.2  00:28.3  00:45.0  00:48.7  00:58.6  01:32.6  01:34.8  01:39.1  01:44.9  02:40.9 | 1  2  3  4  5  6  7  8  9  10 | 00:24.5  00:37.3  00:46.6  00:50.4  01.02.8  01:26.8  01:45.6  01:52.6  01:57.8  02:02:2 | 1  2  3  4  5  6  7  8  9 | 00:26.7  00:44.3  00:55.3  01:12.0  01:15.0  01:19.4  01:24.6  01:30.9  02:13.5 | 1  3  5  7  9  11  13  15  17  19 | 00:05.4  00:11.9  00:32.9  01:09.1  01:17.6  01:42.4  01:50.8  01:57.4  02:08.4  02:18.8 | 2  4  6  8  10  12  14  16  18  20 | 00:09.3  00:28.6  01:04.0  01:11.1  01:39.9  01.47.3  01:54.2  02:04.3  02:10.9  02:19.8 |

Let’s first illustrate a rejected gap. Figure 14 shows two events, Event 2 and Event 3 for movement 5. These events define the beginning and ending of a headway between two vehicles in the major street traffic stream. We note that the same two vehicles are waiting at the stop line during both events. This implies that the first vehicle in line on the stop-controlled approach rejects this gap. The duration of the headway represented by this gap is 22.6 sec – 20.2 sec, or 2.4 sec.



Figure

Figure 15 shows a time line for these events. For the first 30 sec of the observation period, the figure shows the times that the major street vehicles pass the conflict point (the center of the intersection), and when each minor street vehicle arrives at the stop line and then enters the intersection. The minor street vehicle that arrives at the stop line at t = 11.9 sec waits at the stop line until t = 28.6 sec before it enters the intersection. It rejects seven gaps until finally accepting one. As represented in the figure, one of the gaps is rejected by the vehicles, shown as the headway between events 2 and 3.



Figure

Let’s next consider a series of events that illustrate an accepted gap. Figure 16 shows the four events of interest: (a) the arrival of a minor street vehicle, (b) the passage of a major street vehicle past the conflict point, (c) the entry of the minor street vehicle into the intersection, and (d) the passage of the next major street vehicle past the conflict point. The gap that the minor street vehicle accepts is shown as the headway between events 8 and 9, or 5.2 sec.

|  |  |
| --- | --- |
| a. minor street vehicle arrives at stop line | b. major street vehicle passes conflict point |
| c. minor street vehicle enters intersection | d. major street vehicle passes conflict point |

Figure

Figure 17 shows a time line for these events, covering the 30-sec period from t = 1:45 to t = 2:15. The minor street vehicle arrives at the stop line (Event 13 for movement 7) at t = 1:50.8 and departs (Event 14) at t = 1:54.2. Events 8 and 9 for movement 2 define the gap that is accepted by this vehicle. The headway corresponding to this gap is 5.2 sec.



Figure

We can further analyze these data by showing the number and size of gaps that are accepted and rejected. Figure 18 shows the frequency plot for gaps that are rejected, as represented by the headways for these gaps. We can note that with one exception, all drivers accept gaps with headways that are 5.5 sec or longer. Again, with one exception, all drivers reject gaps with headway that are 5.5 sec or shorter. While this is not a statistically sound method, we could assume that the critical headway in this case is about 5.5 sec.



Figure

### Calculating the Critical Headway

[Example calculation of tc example data, and Rod Troutbeck MLE process and spreadsheet.]

### Example Calculation 6

[add]

### Calculating the Follow Up Headway

[Example and calculation of follow up headway.]

### Example Calculation 7

[add]

### Example Calculation 8

[add]

## 7. Building a Computational Engine and Exploring the Model

Let’s now set up a computational engine for each of the two simplified scenarios and explore what the models predict under a variety of traffic flow conditions.

### Scenario 1

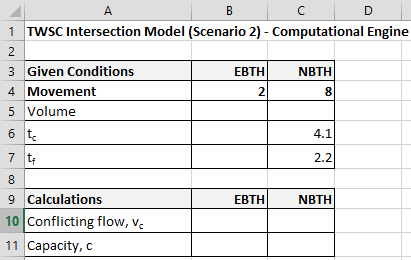
For Scenario 1, we assume an intersection that consists of two-one lane one-way streets. The capacity of the minor street approach is given by:

Equation

The computational engine should satisfy the following requirements:

* Accepts volumes (v, veh/hr) for the two approaches as inputs.
* Assumes the critical headway (tc, sec) and follow up headway (tf, sec) for the minor street movement.
* Computes the conflicting flow for the minor street movement.
* Computes the capacity for the minor street movement.

Figure 19 shows the computational engine template. The input volumes are entered in row 5. The critical headway and follow up headway for movement 8 are given in rows 6 and 7. The conflicting flow for movement 8 (NBTH movement) is calculated in row 10. The capacity for movement 8 is calculated in row 11.



Figure

To assist you in constructing the computational engine, Table 10 shows the formulas for several of the cells.

Table

|  |  |
| --- | --- |
| **Cell** | **Formula** |
| C10 | =B5 |
| C11 | =PotCap(C10,C6,C7) |

The code for the VBA function PotCap is shown in Table 11. The function requires the conflicting flow (vc), the critical headway (tc), and the follow-up headway (tf) as inputs. The capacity calculation is performed in three steps. The numerator (term1) and denominator (term2) are calculated first and the capacity is then computed as term1 divided by term2.

Table

|  |
| --- |
| Public Function PotCap(vc, tc, tf)  'This function computes the potential capacity for a movement based on vc, tc, and tf  term1 = Exp(-vc \* tc / 3600)  term2 = 1 - Exp(-vc \* tf / 3600)  PotCap = vc \* (term1 / term2)  End Function |

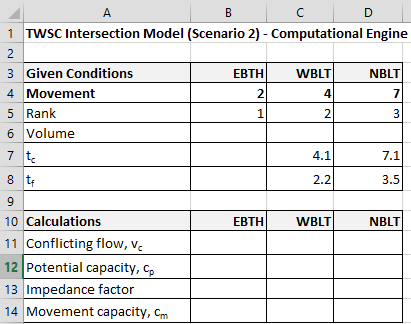
### Scenario 2

For Scenario 2, we assume a T-intersection that consists of a major street with two-way traffic and a minor street with one movement.

The computational engine should satisfy the following requirements:

* Accepts volumes (v, veh/hr) for the three approaches as inputs.
* Assumes critical headway (tc, sec) and follow up headway (tf, sec) for movements 4 and 7.
* Computes the conflicting flow for movements 4 and 7.
* Computes the potential capacity for movements 4 and 7.
* Computes the impedance factor for movement 7
* Computes the movement capacity for movements 4 and 7.

Figure 20 shows the computational engine template. The input volumes are entered in row 6. The critical headway and follow-up headway for movements 4 and 7 are given in rows 7 and 8. The conflicting flow for movements 4 and 7 is calculated in row 11. The potential capacity for movements 4 and 7 are calculated in row 12. The impedance factor for movement 7 is calculated in row 13. The movement capacity for movements 4 and 7 is calculated in row 14.



Figure

To assist you in constructing the computational engine, Table 10 shows the formulas that are used for the NBLT movement.

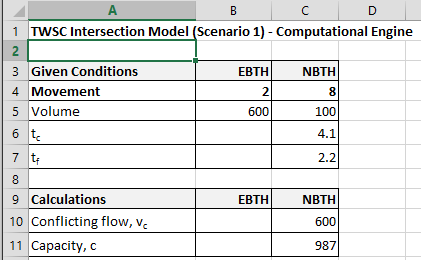
Table

|  |  |
| --- | --- |
| **Cell** | **Formula** |
| D11 | =B6 + 2\*C6 |
| D12 | =PotCap(D11,D7,D8) |
| D13 | =1-C6/C12 |
| D14 | =D12\*D13 |

The code for the VBA function PotCap is shown, as before, in Table 11.

### Example Calculation 9

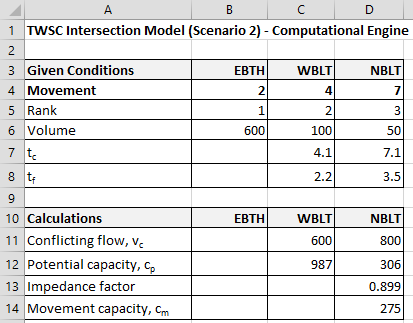
Consider a TWSC intersection that includes two one-way streets, the configuration described earlier in this chapter as Scenario 1. Movement 2 has a volume of 600 veh/hr while movement 8 has a volume of 100 veh/hr. Figure 21 shows the resulting capacity for movement 8 using the computational engine.



Figure

### Example Calculation 10

Let’s now consider a TWSC T-intersection, the configuration described earlier as Scenario 2. The given data and results are given in Figure 22.



Figure

### Example Calculation 11

Case study calibration examples

|  |  |
| --- | --- |
|  |  |
|  |  |

## 8. Summary

In this chapter we explored the models on which the HCM capacity analysis method for TWSC intersections is based. xx

## 9. Glossary

Table . Terms used in this chapter

|  |  |
| --- | --- |
| **Term** | **Definition** |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |

Table . Variables used in this chapter

|  |  |  |
| --- | --- | --- |
| **Variable** | **Description** | **Units** |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |
|  |  |  |

## 10. References

Brilon articles, especially in 1989 symposium (from my notes)

Baass article in ITE Journal that lays out the calculation process for the capacity of a stream.

NCHRP 3-46 project in which field data calibrates US model for HCM.

Robertson and Bonneson work on platoon dispersion model.

Troutbeck model for calculation of critical headway.

## 11. Problems

Problem 1. Field observations at TWSC intersection. Spend 15 minutes observing the operation of a TWSC intersection. Prepare a set of bullet points that summarize what you observed. Be particularly aware of the driver behavior on the minor street and how it is affected by traffic flow on the major street. What are the major things that you observed in the field?

Problem 2. Define the following variables: critical gap, follow up time, conflicting flow rate, and potential capacity.

Problem 3. Write the expression that describes the probability of a gap being larger than t.

Problem 4. Write the expression for the potential capacity of a traffic stream.

Problem 5. What statistical distributions are used to represent the occurrence of random phenomena? What kinds of traffic phenomena can be represented by these distributions?

Problem 6. What are the basic elements of a single server FIFO queuing system?

Problem 7. What are the basic elements of a gap acceptance model that is used to represent traffic flow at a TWSC intersection?

Problem 8. Describe the concept of impedance as it is used in the capacity analysis for a TWSC intersection. Give an example (including the calculations involved and the results) of an impedance calculation and show how the impedance affects the capacity of a movement or approach.

Problem 9. How is the follow up time measured?

Problem 10. Why can’t the critical headway be measured or observed directly in the field?

Problem 11. What is the difference between the potential capacity and the movement capacity?

Problem 12. How many vehicles can use gap, given tc and tf.

tc,4 = 4.1 sec

tf,4 = 2.2 sec

|  |
| --- |
| **Arrival times of 2** |
| 00:03.0 |
|  |
| 00:07.0 |
|  |
| 00.14.0 |
|  |
| 00:23.0 |
|  |
| 00:29.0 |

Problem 13: Which statement correctly describes the capacity of movement 4?

(1)

(2)

(3)

Problem 14. Consider a TWSC t-intersection, with three movements: eastbound through, westbound left turn, and northbound left turn. The data for each approach is given in the table below:

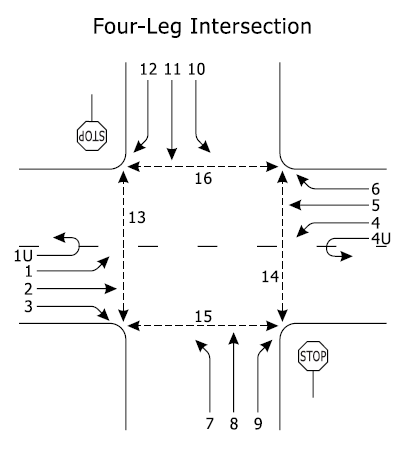
|  |  |  |  |
| --- | --- | --- | --- |
| **Movement** | **Volume** | **Critical gap** | **Follow up time** |
| EB TH (2) | 1000 |  |  |
| WB LT (4) | 800 | 4.1 sec | 2.2 sec |
| NB LT (7) | 300 | 7.1 sec | 3.5 sec |

a. Which of the data listed above are used to compute the movement capacity of stream 4?

b. Which of the data listed above are used to compute the movement capacity of stream 7?

c. Define (but don’t calculate) the impedance that is used to compute the capacity for stream 4.

Problem 15. Circle each of the following statements relating to TWSC intersections that are true. (More than one response could be true.)



1. The movement capacity for rank 2 streams is equal to the potential capacity.
2. The follow up time is a measurement taken for the minor traffic stream.
3. The critical gap is a measurement taken for the minor traffic stream.
4. The impedance factor for movement 7 relates to the proportion of time that movement 2 vehicles are waiting at the intersection.

Problem 16: Which statement correctly describes the proportion of time that a movement 4 vehicle is present and waiting to turn left?

(1)

(2)

(3)

Problem 17: Which traffic streams are included in the conflicting flow for movement 7 (vc,7)?

1. v2 only
2. v4 only
3. v2 and v4
4. Neither v2 nor v4

Problem 18: Consider the potential capacity for movement 7, cp,7. Which factors are included explicitly in the computation of this potential capacity?

1. tc,7
2. tc,4
3. tf,7
4. tf,4
5. vc,7
6. v4/c4
7. 1-v4/c4

Problem 19: Consider the movement capacity for movement 7, cm,7. Which factors are explicitly included in the computation of this movement capacity?

1. cp,7
2. 1-v4/c4
3. 1-v2/c2

Problem 20: What is the conflicting flow for movement 7, vc,7?

Problem 21. The following data have been collected for movements 2 and 8 at a TWSC intersection (see figure below). Assume that there is no traffic for any of the other traffic streams.



|  |  |
| --- | --- |
| **Clock times movement 2 entered intersection** | **Clock times movement 8 entered intersection** |
| 10.8 | 11.3 |
| 19.8 | 13.5 |
| 35.0 | 15.6 |
| 40.5 | 20.5 |
| 47.9 | 22.6 |
| 51.3 | 24.9 |
| 53.3 | 27.2 |
|  | 36.3 |
|  | 48.3 |

a. Describe how you would use these data to compute the follow up time for movement 8.

b. Using these data and the method that you suggested above, what is your estimate of the follow up time for movement 8?

Problem 22 (S2011). Consider a TWSC T-intersection. The demand volumes are:

* Movement 2 (EBTH) = 600 veh/hr
* Movement 4 (WBLT) = 100 veh/hr
* Movement 7 (NBLT) = 50 veh/hr

What is the effect of changing the WBLT volume on the NBLT capacity? Consider a range of WBLT flows from 0 to 1200 veh/hr.

|  |  |  |
| --- | --- | --- |
| Movement | tc | Tf |
| 4 | 4.1 | 2.2 |
| 7 | 7.1 | 3.5 |

## 11. Problem Solutions

Problem 1. Field observations at TWSC intersection. Spend 15 minutes observing the operation of a TWSC intersection. Prepare a set of bullet points that summarize what you observed. Be particularly aware of the driver behavior on the minor street and how it is affected by traffic flow on the major street. What are the major things that you observed in the field?

Problem 2. Define the following variables: critical gap, follow up time, conflicting flow rate, and potential capacity.

Problem 3. Write the expression that describes the probability of a gap being larger than t.

Problem 4. Write the expression for the potential capacity of a traffic stream.

Problem 5. What statistical distributions are used to represent the occurrence of random phenomena? What kinds of traffic phenomena can be represented by these distributions?

Problem 6. What are the basic elements of a single server FIFO queuing system?

Problem 7. What are the basic elements of a gap acceptance model that is used to represent traffic flow at a TWSC intersection?

Problem 8. Describe the concept of impedance as it is used in the capacity analysis for a TWSC intersection. Give an example (including the calculations involved and the results) of an impedance calculation and show how the impedance affects the capacity of a movement or approach.

Solution: Impedance is the proportion of time that the server is occupied for a non-rank 1 movement of a TWSC intersection It means that gaps or headways that would be otherwise available to a lesser ranked stream would not be available. [Example calc from spreadsheet.]

Problem 9. How is the follow up time measured?

Solution: For a continuous queue for a minor stream, it is the headway between the 2nd and all following vehicle pairs using a single gap in the major street traffic stream.

Problem 10. Why can’t the critical headway be measured or observed directly in the field?

Solution: Because all we can measure in the field are the gaps that are rejected or accepted. The critical headway is a statistical measure that uses these data as a basis to estimate it.

Problem 11. What is the difference between the potential capacity and the movement capacity?

Solution: Movement capacity is the potential capacity reduced by the impedance factor.

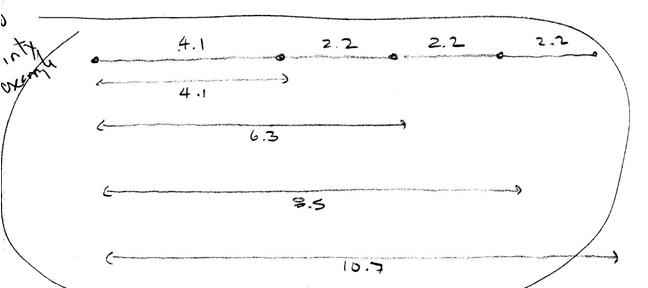
Problem 12. How many vehicles can use gap, given tc and tf.

tc,4 = 4.1 sec

tf,4 = 2.2 sec

Solution:

|  |  |  |
| --- | --- | --- |
| **Arrival times of 2** | **Headway/gap** | **Number of vehicles using gap** |
| 00:03.0 |  |  |
|  | 4.0 | 0 |
| 00:07.0 |  |  |
|  | 7.0 | 2 |
| 00.14.0 |  |  |
|  | 9.0 | 3 |
| 00:23.0 |  |  |
|  | 6.0 | 1 |
| 00:29.0 |  |  |



Problem 13: Which statement correctly describes the capacity of movement 4?

(1)

(2)

(3)

Solution: (1); (2) is possible.

Problem 14. Consider a TWSC t-intersection, with three movements: eastbound through, westbound left turn, and northbound left turn. The data for each approach is given in the table below:

|  |  |  |  |
| --- | --- | --- | --- |
| **Movement** | **Volume** | **Critical gap** | **Follow up time** |
| EB TH (2) | 1000 |  |  |
| WB LT (4) | 800 | 4.1 sec | 2.2 sec |
| NB LT (7) | 300 | 7.1 sec | 3.5 sec |

a. Which of the data listed above are used to compute the movement capacity of stream 4?

Solution:Stream 4 required data:

1. Data for potential capacity (vc4 = v2)
2. Critical gap and follow up time

b. Which of the data listed above are used to compute the movement capacity of stream 7?

Solution: vc,7 = function of v2 and v4

tc,7

tc,4

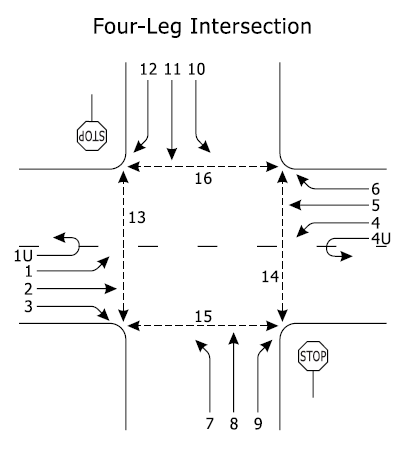
c. Define (but don’t calculate) the impedance that is used to compute the capacity for stream 4.

Solution: HCM p 9.9: “The reduction in the capacity of lower-rank movements caused by congestion of higher-ranked movements at a TWSC intersection.”

Or: Reduction of capacity due to higher-ranked vehicles using gaps that could have been available to lower-ranked vehicles.

[Add part c to problem 17]

Problem 15. Circle each of the following statements relating to TWSC intersections that are true. (More than one response could be true.)



1. The movement capacity for rank 2 streams is equal to the potential capacity.
2. The follow up time is a measurement taken for the minor traffic stream.
3. The critical gap is a measurement taken for the minor traffic stream.
4. The impedance factor for movement 7 relates to the proportion of time that movement 2 vehicles are waiting at the intersection.

Solution:

True

True

True or False (?)

False

Problem 16: Which statement correctly describes the proportion of time that a movement 4 vehicle is present and waiting to turn left?

(1)

(2)

(3)

Solution: (2)

Problem 17: Which traffic streams are included in the conflicting flow for movement 7 (vc,7)?

1. v2 only
2. v4 only
3. v2 and v4
4. Neither v2 nor v4

Solution: (3)

Problem 18: Consider the potential capacity for movement 7, cp,7. Which factors are included explicitly in the computation of this potential capacity?

1. tc,7
2. tc,4
3. tf,7
4. tf,4
5. vc,7
6. v4/c4
7. 1-v4/c4

Solution: (1), (3), (5)

Problem 19: Consider the movement capacity for movement 7, cm,7. Which factors are explicitly included in the computation of this movement capacity?

1. cp,7
2. 1-v4/c4
3. 1-v2/c2

Solution: (1), (2)

Problem 20: What is the conflicting flow for movement 7, vc,7?

Solution: ?? [4? Check this.]

Problem 21. The following data have been collected for movements 2 and 8 at a TWSC intersection (see figure below). Assume that there is no traffic for any of the other traffic streams.



|  |  |
| --- | --- |
| **Clock times movement 2 entered intersection** | **Clock times movement 8 entered intersection** |
| 10.8 | 11.3 |
| 19.8 | 13.5 |
| 35.0 | 15.6 |
| 40.5 | 20.5 |
| 47.9 | 22.6 |
| 51.3 | 24.9 |
| 53.3 | 27.2 |
|  | 36.3 |
|  | 48.3 |

a. Describe how you would use these data to compute the follow up time for movement 8.

Solution: Identify minor vehicles (movement 8) that used one major gap. Compute headways for these vehicles.

b. Using these data and the method that you suggested above, what is your estimate of the follow up time for movement 8?

Solution: Gap 1: 10.8 to 19.8

11.3-13.5 = 2.2 sec

13.5-15.6 = 2.1 sec

19.8 to 35.0

20.5-22.6 = 2.1 sec

22.6-24.9=2.3 sec

24.9-27.2=2.3 sec

Mean = 2.2 sec

Problem 22 (S2011). Consider a TWSC T-intersection. The demand volumes are:

* Movement 2 (EBTH) = 600 veh/hr
* Movement 4 (WBLT) = 100 veh/hr
* Movement 7 (NBLT) = 50 veh/hr

What is the effect of changing the WBLT volume on the NBLT capacity? Consider a range of WBLT flows from 0 to 1200 veh/hr.

Solution: (31 Jan 2005)

|  |  |  |
| --- | --- | --- |
| Movement | tc | Tf |
| 4 | 4.1 | 2.2 |
| 7 | 7.1 | 3.5 |

Equation

Conflicting flows

where

Solution steps:

1. Compute potential capacity for movement 4

2. Compute movement capacity for movement 4

3. Compute potential capacity for movement 7

4. Compute impedance for movement 7

5. Compute movement capacity for movement 7

6. Vary WB LT demand volumes from 0 to 1200 veh/hr

Final result:

The capacity of movement 7 decreases as the volume of movement 4 increases.