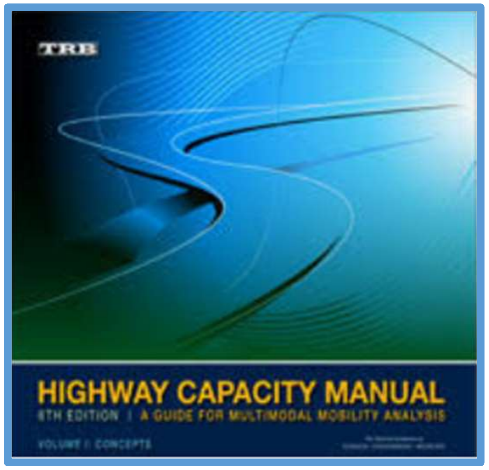
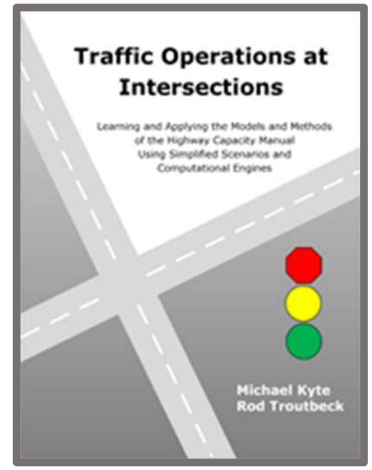


Highway Capacity Manual
6th Edition

Transportation Research Board

Learning and Applying the Methods and Models of the HCM

A Short Course
Day #1



Traffic Operations at Intersections
Learning and Applying
the Models and Methods of the
Highway Capacity Manual
Using Simplified Scenarios and
Computational Engines

Michael Kyte and Rod Troutbeck

Topics for today

- **Welcome and overview**
- Introductions
- Learning the HCM: what this course is … and isn't
- What resources do you have available to you?
- Overview of our book
- Diving in: Exploring three simplified scenarios
- Assignment for next time
- Check-out

Topics for today

- Welcome and overview
- **Introductions**
  - **Who are you?**
  - **What do you do?**
  - **What do you need to and want to learn about the HCM?**
- Learning the HCM: what this course is … and isn't
- What resources do you have available to you?
- Overview of our book
- Diving in: Exploring four simplified scenarios
- Assignment for next time
- Check-out

Topics for today

- Welcome and overview
- Introductions
- **Learning the HCM: what this course is … and isn't**
  - **The basics first: simplified scenarios**
  - **It's not just software**
  - **Be in the field; learn to connect what you see with theory**
  - **HCM scope**
- What resources do you have available to you?
- Overview of our book
- Diving in: Exploring four simplified scenarios
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Topics for today

- Welcome and overview
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- Learning the HCM: what this course is … and isn't
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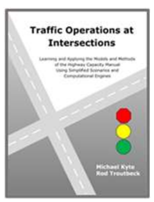
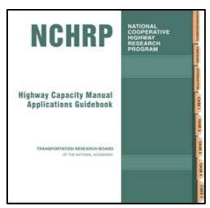
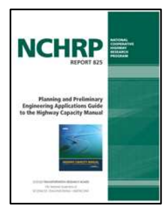
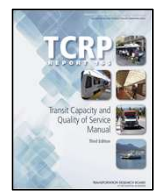
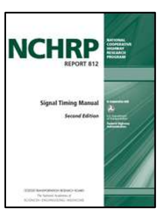
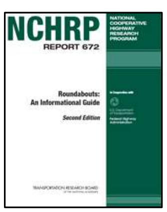


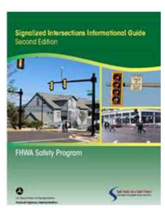




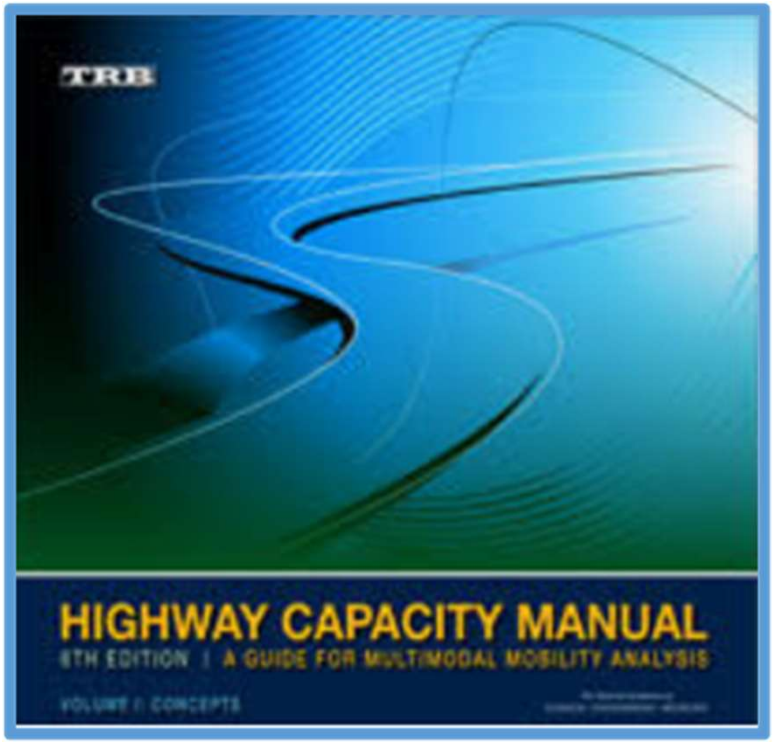








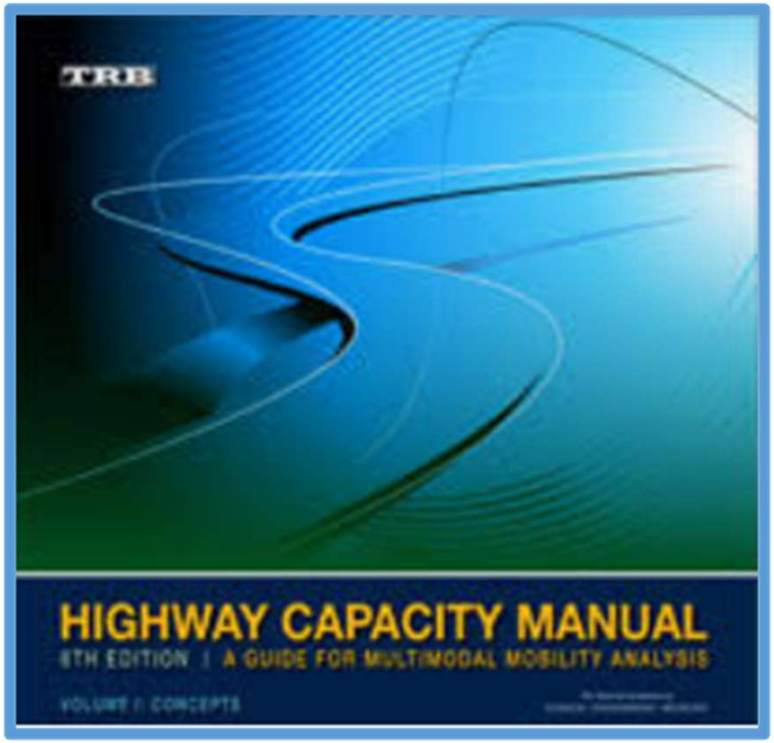
- **What resources do you have available to you?**



Volume 1. Concepts
Volume 2. Uninterrupted Flow
Volume 3. Interrupted Flow
Volume 4. Applications Guide

- Chapter 16. Urban Street Facilities
- Chapter 17. Urban Street Reliability and ATDM
- Chapter 18. Urban Street Segments
- **Chapter 19. Signalized Intersections**
- **Chapter 20. TWSC Intersections**
- **Chapter 21. AWSC Intersections**
- Chapter 22. Roundabouts
- Chapter 23. Ramp Terminals and Alternative Intersections

- **What resources do you have available to you?**

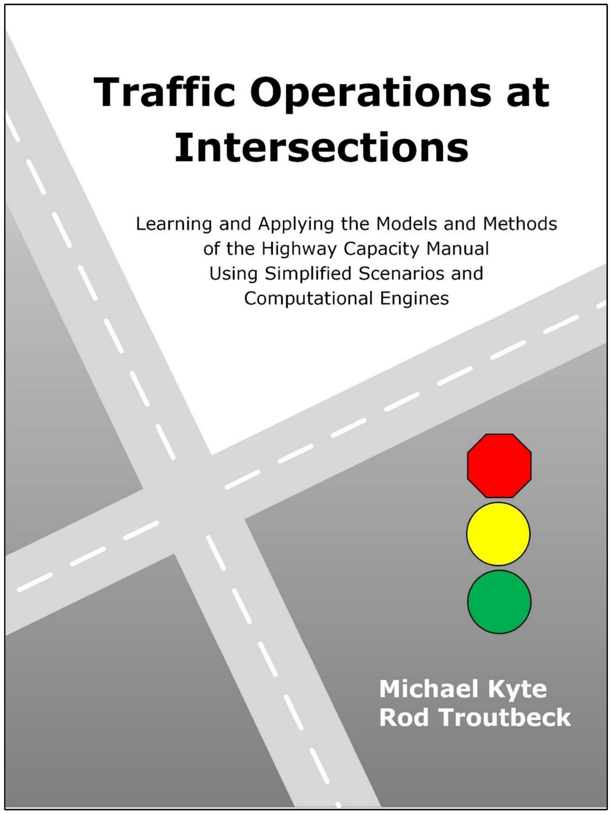


TRB Committee on Highway Capacity and Quality of Service
https://www.hcqstrb.org/

HCM Volume 4
https://hcmvolume4.org/

Current chapter drafts and updates
http://hcm2010update.kaiproject.com/

- **What resources do you have available to you?**

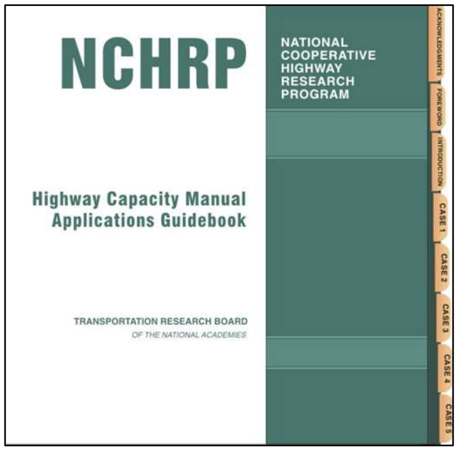


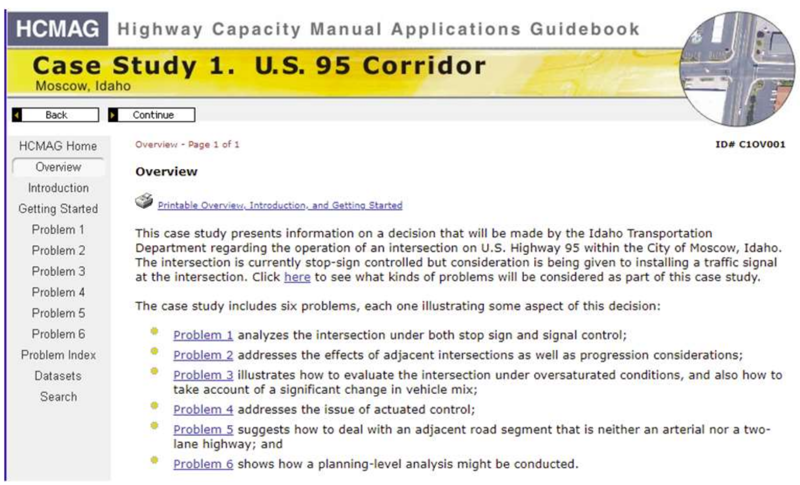
https://hcm-intersection-models-book.weebly.com/

For practicing transportation engineers and university seniors and graduate students:

- Transform the black box of the HCM into a clear box that you can understand and use
- Chapters on AWSC intersections, TWSC intersections, and signalized intersections
- 11 simplified scenarios
- 43 example calculations
- 7 computational engines
- 250 pages
- 138 figures
- Teaching aids including 120 problems to solve ***(new)***

- **What resources do you have available to you?**



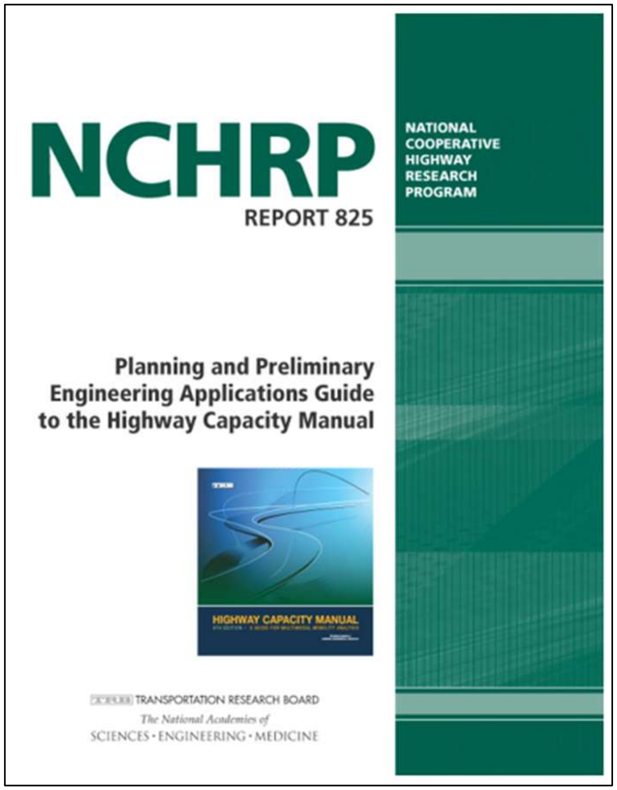


http://www.hcmguide.com/index.htm

This Guidebook is intended to be a supplemental resource document to the HCM that can be used in a variety of ways:

- It can provide guidance on how to approach, execute, and interpret the results of a facility-specific analysis that the user might need to undertake.
- It can offer insights into specific areas of the analysis where special care should be taken to ensure that the analysis results reasonably and appropriately address the issues of concern.
- It can identify and characterize the interactions that one facility type can have on other adjacent or nearby facility types.
- It can provide example data sets and prototypical analysis procedures that can be used as templates for addressing other similar real-world problems that the user might encounter.

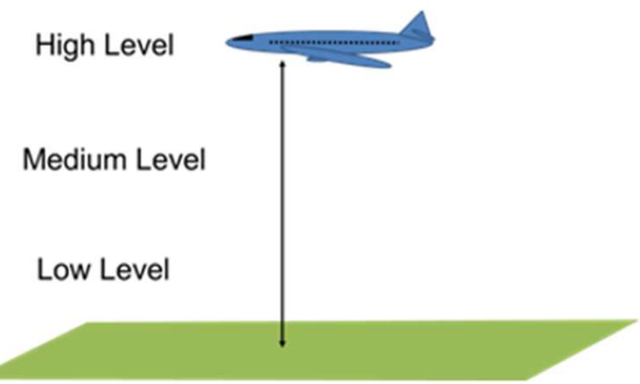
- **What resources do you have available to you?**



https://hcmvolume4.org/pages/6-planning-and-preliminary-engineering-applications-guide-to-the-hcm

Planning and Preliminary Engineering Applications Guide

- High level
  - Large analysis area
  - Low detail
- Medium level
  - Focus on a single roadway facility, segment, or intersection
  - Greater detail
- Low level
  - Highly focused and highly detailed

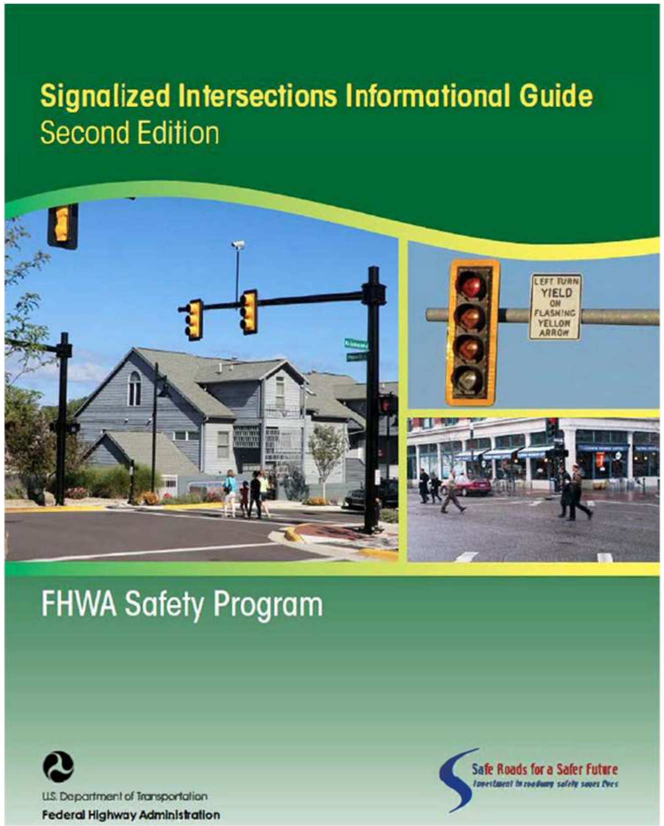


- **What resources do you have available to you?**

https://ops.fhwa.dot.gov/trafficanalysistools/

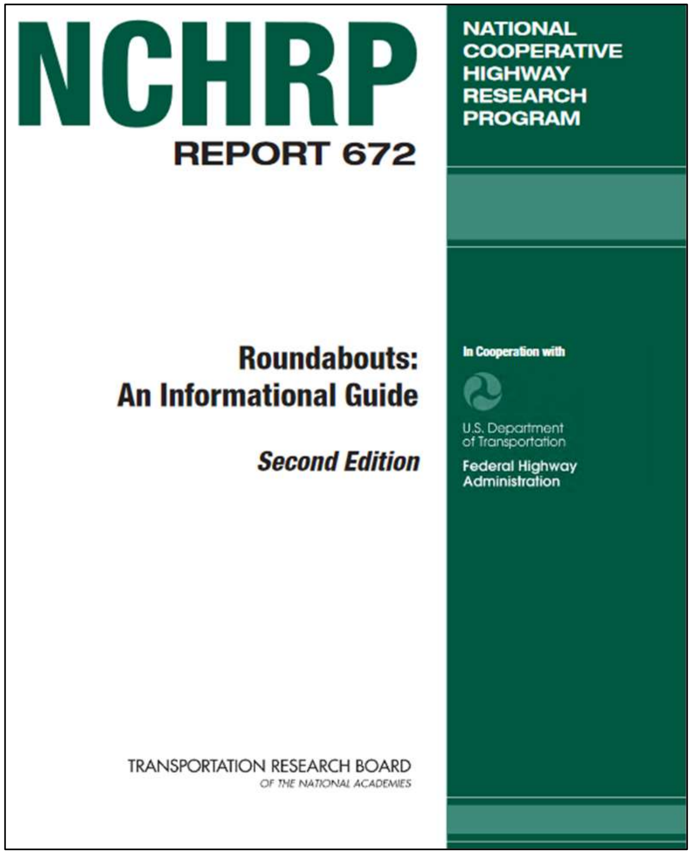
- **Volume I: *Traffic Analysis Tools Primer*** (HTML, PDF 613KB)
  - What's in this Volume?
- **Volume II: *Decision Support Methodology for Selecting Traffic Analysis Tools*** (HTML, PDF 1.3MB)
  - Decision Support Methodology Automated Tool (HTML, XLS 786KB)
  - What's in this Volume?
- **2019 VERSION: Volume III: *Guidelines for Applying Traffic Microsimulation Modeling Software 2019 Update***
  - 5-episode YouTube videos explaining the updated 2019 guidance
  - **2004 VERSION: Volume III: *Guidelines for Applying Traffic Microsimulation Modeling Software*** (HTML,
  - What's in this Volume?
- **Volume IV: *Guidelines for Applying CORSIM Microsimulation Modeling Software*** (HTML, PDF 7.2MB)
  - What's in this Volume?
- **Volume V: *Traffic Analysis Toolbox Case Studies - Benefits and Applications*** (HTML, PDF 3.2MB)
  - What's in this Volume?
- **Volume VI: *Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness*** (
  - What's in this Volume?
- **Volume VII: *Predicting Performance with Traffic Analysis Tools*** (HTML, PDF 1.7MB)
  - What's in this Volume?
- **Volume VIII: *Work Zone Modeling and Simulation - A Guide for Decision-Makers*** (HTML, PDF 1.9MB)
  - What's in this Volume?
- **Volume IX: *Work Zone Modeling and Simulation - A Guide for Analysts*** (HTML, PDF 15MB)
  - What's in this Volume?
- **Volume X: *Localized Bottleneck Congestion Analysis Focusing on What Analysis Tools Are Available, Neces***

- **What resources do you have available to you?**

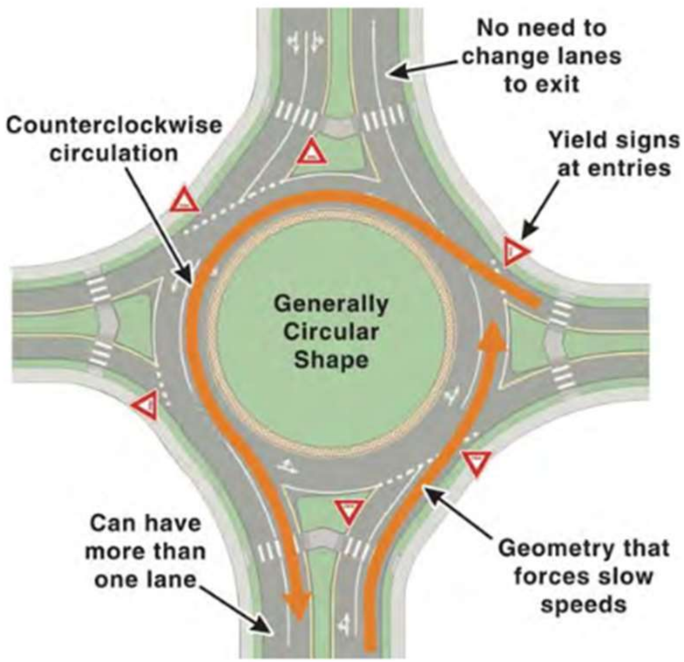


https://safety.fhwa.dot.gov/intersection/signal/fhwasa13027.pdf

- **What resources do you have available to you?**



http://www.trb.org/Publications/Blurbs/164470.aspx



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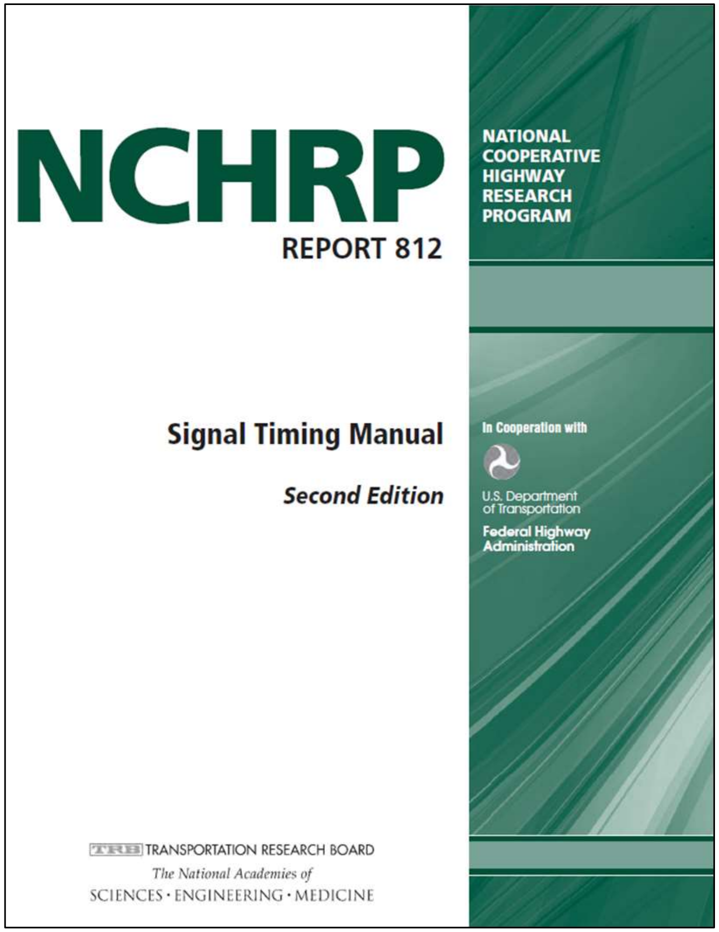
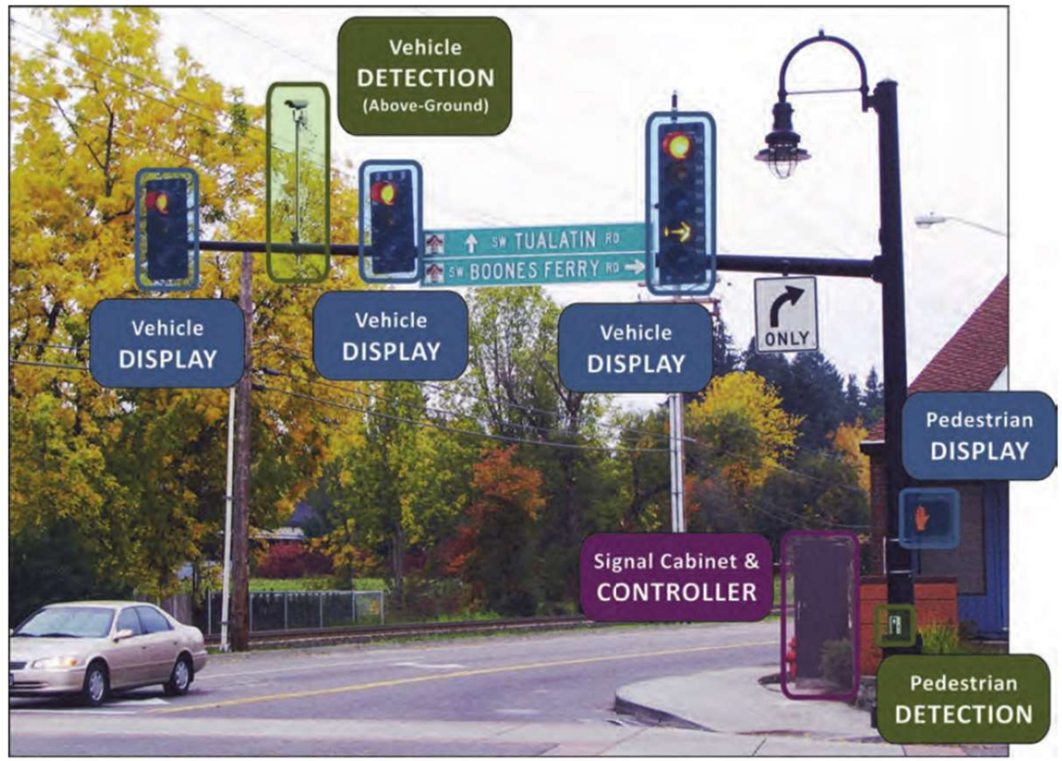
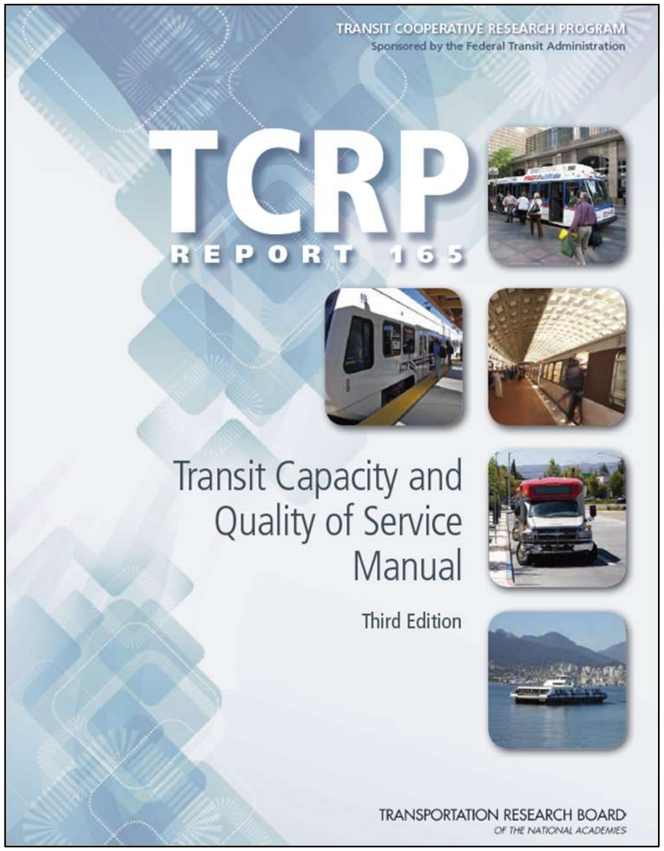


https://ops.fhwa.dot.gov/publications/fhwahop08024/index.htm



- **What resources do you have available to you?**



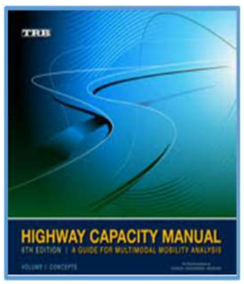
http://www.trb.org/Main/Blurbs/169437.aspx

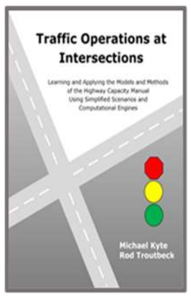
- **What resources do you have available to you?**

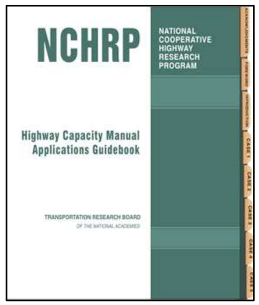
TRANSPORTATION SYSTEM SIMULATION MANUAL (TSSM)

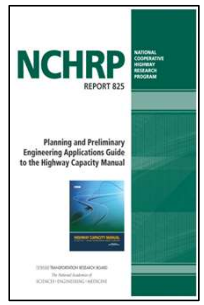
http://sites.kittelson.com/TSSM

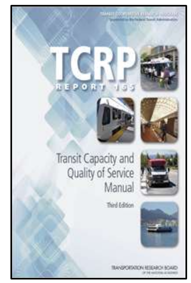
- **What resources do you have available to you?**
  - Which of these have you used?
  - Which of these didn't you know about before?

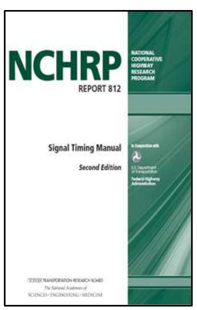


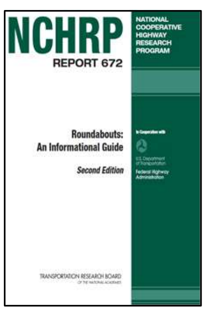


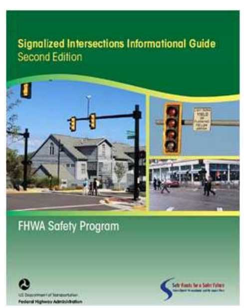












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CHAPTER 1 INTRODUCTION

"In my first professional engineering job after I finished graduate school, I worked
a team studying the environmental impact of a proposed freeway in Portland, Ore
task was to analyze the performance of signalized intersections to be constructed
parallel arterials as part of the freeway project. Our intersection analyses were co
based on the 1965 Highway Capacity Manual (yes, the 1965 HCM!) using nomogra
worksheets. A typical analysis took about 10 to 15 minutes for each intersection.
were simpler back then!"
One of the authors

What's a nomograph? Look it up!

Intersections are where it all comes together. People in cars, buses, trains. People on bicy
People on foot. All wanting to get through a point, the intersection, to get somewhere.

Traffic engineers spend a lot of time thinking about this flow of people through intersectio
develop new and innovative designs, hoping to minimize the delay experienced by traveler
maximize the flow of people.

But with each new design comes the need to understand how the intersection will operate
experience the traveler will have at the intersection. To answer these questions, the traffi
often turns to a model to help predict the operational performance of the design. And, he
has a choice from a selection of models available today.

The models of the Highway Capacity Manual (HCM) are often the engineer's choice to ana
intersection performance. These models are complex, and nearly all transportation engin
software implementations of these models to conduct their analyses. Software applicatio
powerful tools that help engineers solve problems. But these applications also serve as ba
the understanding of the complex models embedded in the software.

Our major objective in writing this book was to transform the "black box" of the HCM inte
models, and their software implementations, into a "clear box" that allows the engineer to
understand how these models actually work. When you have completed reading and study
book, you will better understand the fundamentals of the HCM intersection models and yo
able to apply these models to the kinds of complex intersections that you find in the field v
confidence, and insight.

1. Intersection Types and Their Characteristics

The HCM includes methods to analyze the operation of intersections with four different ty
control: all-way stop-controlled intersections, two-way stop-controlled intersections, roun
and signalized intersections.

CHAPTER 2 CAPACITY OF ALL-WAY STOP-CONTROLLED INTERSECTIONS

1. What's in this Chapter?

In this chapter we explore the models on which the Highway Capacity Manual
analysis method for all-way stop-controlled (AWSC) intersections is based [4].
grouped into four categories:

- Fundamentals
- Simplified scenarios
- Learning in depth
- Closing

Table 2-1 shows a roadmap to the material presented in Chapter 2.

Table 2-1. Roadmap to Chapter 2

Section	Topic
Fundamentals	
1	What's in this chapter?
2	What do we observe in the field?
3	Formulating the model
Simplified Scenarios	
4	Scenario 2-1. Calculating the capacity of each lane for an int lane one-way streets
5	Scenario 2-2. Calculating the capacity of each lane for a star Four-leg intersection with single lane approaches
Learning in Depth	
6	Building a computational engine and exploring the model
Closing	
7	Summary
8	Glossary
9	References

We start with the fundamentals. In Section 2, we discuss how AWSC intersecti
field, particularly the interaction between drivers traveling through the interse
we identify the important factors in this interaction that will help us to formul
the capacity of an intersection approach.

The models in Sections 4 and 5 are based on simplified scenarios, scenarios in
important traffic and geometric factors are considered. By focusing only on th
develop an understanding of the operation of an AWSC intersection, one that
as the more complex conditions found in the real world are considered.

You will study two such simplified scenarios.

- Scenario 2-1. Calculating the capacity of each lane for an intersection of tw streets.
- Scenario 2-2. Calculating the capacity of each lane for a standard 4-leg int

CHAPTER 3 CAPACITY OF TWO-WAY STOP-CONTROLLED INTERSECTIONS

1. What's in this Chapter?

In this chapter we will explore the models on which the Highway Capacity Man
analysis method for two-way stop-controlled (TWSC) intersections are based [
grouped into four categories:

- Fundamentals
- Simplified scenarios
- Learning in depth
- Closing

Table 2-1 shows a roadmap to the material presented in Chapter 3.

Table 3-1. Roadmap to Chapter 3

Section	Topic
Fundamentals	
1	What's in this chapter?
2	What do we observe in the field?
3	Formulating the model
Simplified Scenarios	
4	Scenario 3-1. Calculating the capacity of each movement fo two one-lane one-way streets
5	Scenario 3-2. Calculating the capacity of each movement fo with two-way traffic on the major street but only left turni stop-controlled approach
Learning in Depth	
6	Calculating the critical headway and follow-up headway
7	Building a computational engine and exploring the model
Closing	
8	Summary
9	Glossary
10	References

We start with the fundamentals. In Section 2, we discuss how TWSC intersectio
field, particularly the interaction between drivers on the major street and thos
controlled approaches. In Section 3, we identify the important factors in this in
help us to formulate the models to predict the capacity of a traffic stream.

The models in Sections 4 and 5 are based on simplified scenarios, scenarios in
important traffic and geometric factors are considered. By focusing only on th
develop a basic understanding of the operation of a TWSC intersection, one th
upon as the more complex conditions found in the real world are considered.

CHAPTER 4 CAPACITY OF SIGNALIZED INTERSECTIONS

1. What's in this Chapter

In this chapter we explore the models on which the Highway Capacity Manual (HCM) capacity analysis method for signalized intersections are based [9]. This material is grouped into four categories:

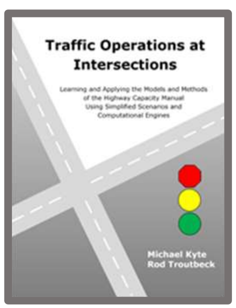
- Fundamentals
- Simplified scenarios
- Learning in depth
- Closing

Table 2-1 shows a roadmap to the material presented in Chapter 4.

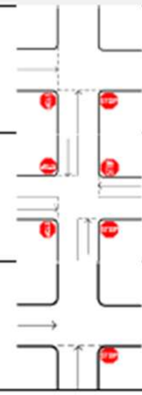
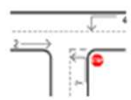
Table 4-1. Roadmap to Chapter 4

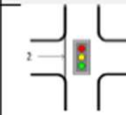
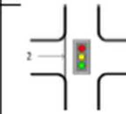
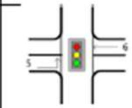
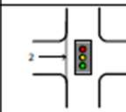
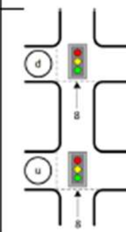
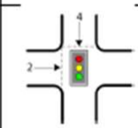
Section	Topic
Fundamentals	
1	What's in this chapter?
2	What do we observe in the field?
3	Movements and phases
4	Actuated control processes
5	Formulating the model
Simplified Scenarios	
6	Scenario 4-1. Calculating the capacity of a lane based on one signal cycle
7	Scenario 4-2. Calculating the delay on a lane when demand is less than capacity
8	Scenario 4-3. Calculating the capacity of an exclusive left turn lane for permitted LT phasing
9	Scenario 4-4. Calculating the capacity utilization for an intersection using critical movement analysis
10	Scenario 4-5. Calculating the delay on a lane when demand exceeds capacity
11	Scenario 4-6. Calculating delay on a lane when the arrival pattern is non-uniform
12	Scenario 4-7. Predicting average green time for a phase under actuated control
Learning in Depth	
13	Calculating saturation headways
14	Building the computational engines and exploring the model
Closing	
15	Summary
16	Glossary
17	References

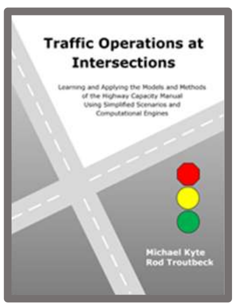
We start with the fundamentals. In Section 2, we discuss how signalized intersections operate in the field, focusing on the operation of one approach. In Section 3, we define traffic movements and signal phases, both important in describing the operation of signalized intersections. Signal control, both pretimed and actuated, is described in Section 4. In Section 5, we identify the important factors in the interaction of traffic flow and signal control that will help us to formulate the models to predict the capacity of a lane. While the method has increased in complexity since the publication of the first version in the 1950 HCM, the basic concept remains the same: the capacity of a lane is



- Simplified scenarios

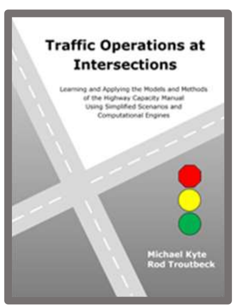
Intersection Control	Scenario	Conditions	Illustration
AWSC intersections	2-1. Calculating the capacity of each lane for an intersection of two one-lane one-way streets	• Two one-way streets • TH movements	
	2-2. Calculating the capacity of each lane for a standard 4-leg intersection	• Four approaches • TH movements	
TWSC intersections	3-1. Calculating the capacity of each movement for an intersection of two one-lane one-way streets	• Two one-way streets • TH movements	
	3-2. Calculating the capacity of each movement for a T-intersection with two-way traffic on the major street but only left turning traffic on the stop-controlled approach	• T-intersection • Three movements	

Intersection Control	Scenario	Conditions	Illustration
Signalized intersections	4-1. Calculating the capacity of a lane based on one signal cycle	• Pretimed control • Demand < capacity • TH movements only • Uniform arrivals • Isolated	
	4-2. Calculating the delay on a lane when demand is less than capacity	• Pretimed control • Demand < capacity • TH movements only • Uniform arrivals • Isolated	
	4-3. Calculating the capacity of an exclusive left turn lane for permitted LT phasing	• Pretimed control • Demand < capacity • Permitted LTs • Uniform arrivals • Isolated	
	4-4. Calculating the capacity utilization for an intersection using critical movement analysis	• Pretimed control • Demand < capacity • Protected or permitted LTs • Uniform arrivals • Isolated	
	4-5. Calculating the delay on a lane when demand exceeds capacity	• Pretimed control • Demand > capacity • TH movements only • Uniform arrivals • Isolated	
	4-6. Calculating delay on a lane when the arrival pattern is non-uniform	• Pretimed control • Demand < capacity • TH movements only • Non-uniform arrivals • Interconnected	
	4-7. Predicting average green time for a phase under actuated control	• Actuated control • Demand < capacity • TH movements only • Two phases • Random arrivals • Isolated	



- Computational engines

	A	B	C	D	E	F	G	H	I	J
1	**CMA computational engine - scenario 2**									
2										
3	**Input data**		**East-West Concurrency Group**				**North-South Concurrency Group**			
4	Volume data (veh/hr)	Ring 1	v_1		v_2		v_3		v_4	
5		Ring 2	v_5		v_6		v_7		v_8	
6										
7	LT phasing, EW concurrency group									
8	LT phasing, NS concurrency group									
9	Cycle length, sec									
10	Lost time per phase, sec									
11	Saturation flow rate, TH, veh/hr									
12	Saturation flow rate, protected LT, veh/hr									
13										
14	**Step 1: Compute the flow ratio Y for each movement present at the intersection**									
15			**East-West Concurrency Group**				**North-South Concurrency Group**			
16			v_1		v_2		v_3		v_4	
17		Ring 1	s_1		s_2		s_3		s_4	
18			Y_1		Y_2		Y_3		Y_4	
19			v_5		v_6		v_7		v_8	
20		Ring 2	s_5		s_6		s_7		s_8	
21			Y_5		Y_6		Y_7		Y_8	
22										
23	**Step 2: Determine the flow ratio sums for the phase sequences in each ring for each concurrency group (for the case of protected LTs only).**									
24			**East-West Concurrency Group**				**North-South Concurrency Group**			
25			v_1		v_2		v_3		v_4	
26		Ring 1	s_1		s_2		s_3		s_4	
27			Y_1		Y_2		Y_3		Y_4	
28			Y_{EW1}				Y_{NS1}			
29			v_5		v_6		v_7		v_8	
30		Ring 2	s_5		s_6		s_7		s_8	
31			Y_5		Y_6		Y_7		Y_8	
32			Y_{EW2}				Y_{NS2}			



- Derivations

Availability of Headways

We start by representing the availability of headways in the major traffic stream. 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 vehicles in the lane. If the mean flow rate is λ (veh/sec), the probability of observing x vehicles during a specified time interval t is given by the Poisson distribution:

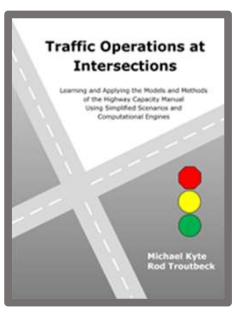
Equation 3-1

$$P[x] = \frac{(\lambda t)^x}{x!} e^{-\lambda t}$$

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 3-2.

Equation 3-2

$$P[x = 0] = \frac{(\lambda t)^0}{0!} e^{-\lambda t} = e^{-\lambda t}$$



- Example calculations

Example Calculation 4-10. Calculation of Average Delay When Volume Is Less than Capacity

A lane has an arrival rate of 630 veh/hr and a saturation flow rate of 1900 veh/hr. The cycle length is 100 sec, the effective red time is 60 sec, and the effective green time is 40 sec. Determine the queue service time and the average delay for this lane.

Step 1. Using Equation 4-6, calculate the lane capacity and compare it to the arrival flow rate.

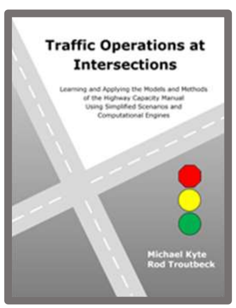
$$c = s(g/C) = (1900\ veh/hr)\left(\frac{40\ sec}{100\ sec}\right) = 760\ veh/hr$$

The arrival volume (630 veh/hr) is thus less than the lane capa
method can be used to calculate the average uniform delay.

Step 2. Calculate the queue service time using Equation 4-8.

$$g_s = \frac{vr}{s-v} = \frac{(630\ veh/hr)(60\ se}{1900\ veh/hr - 630\ ve}$$

Step 3. Construct the cumulative vehicle diagram and the que
step is not necessary to solve this problem, the preparation of
for better understanding these concepts).



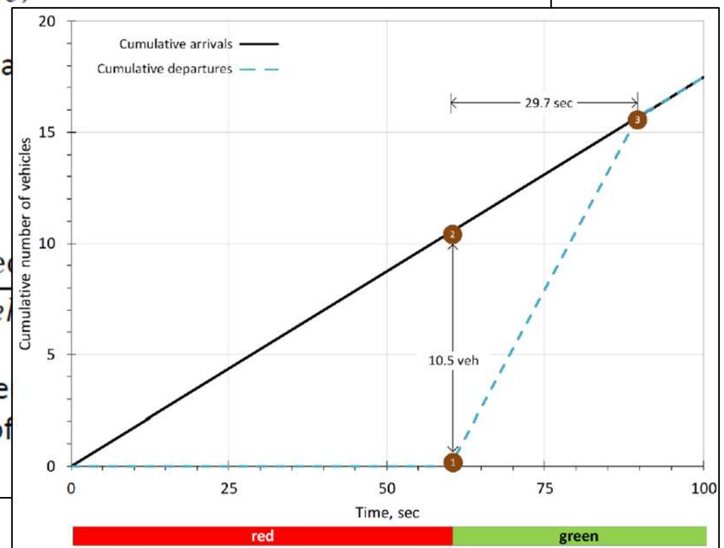
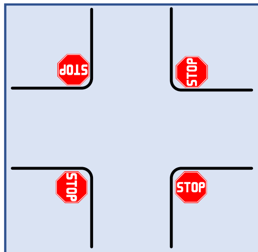


Figure 4-42. Cumulative vehicle diagram for Example Calculation 4-10

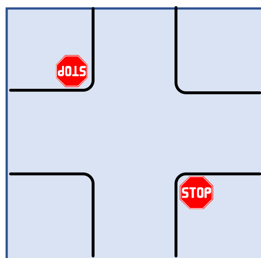
- What determines capacity?

AWSC intersections



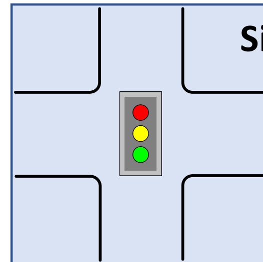
- What is the traffic intensity or degree of conflict?
- How many competitors do you face?
- How does this degree of conflict translate to a saturation headway?

TWSC intersections

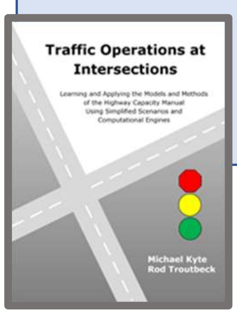


- What are the size, availability, and usefulness of gaps/headways?
- How does this translate to capacity?
- How do we represent driver behavior?
    - critical headway
    - follow-up headway

Signalized intersections



- What is the saturation flow rate?
- How much green time is available?
- How do we predict green time and cycle length?



Topics for today

- Welcome and overview
- Introductions
- Learning the HCM: what this course is … and isn’t
- What resources do you have available to you?
- Overview of our book
- **Diving in: Exploring three simplified scenarios**
  - **Scenario 3.1**
- Assignment for next time
- Check-out

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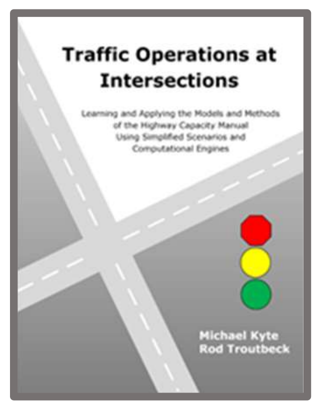
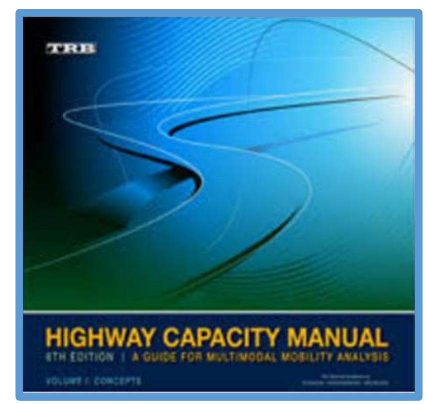


Simplified



Complex

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

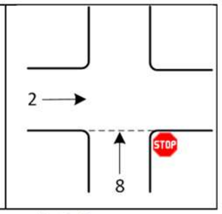


Figure 3-4. Scenario 3-1

The Big Picture

- How large are the headways in the major traffic stream?
- What size headways do minor stream drivers need?

Model Assumptions (M/M/1 queuing model)

- Random process (vehicle arrivals)
- Two behavioral parameters for minor stream drivers
  - Critical headway
  - Follow-up headway
- Traffic stream hierarchy

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

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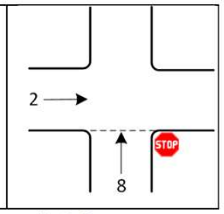


Figure 3-4. Scenario 3-1

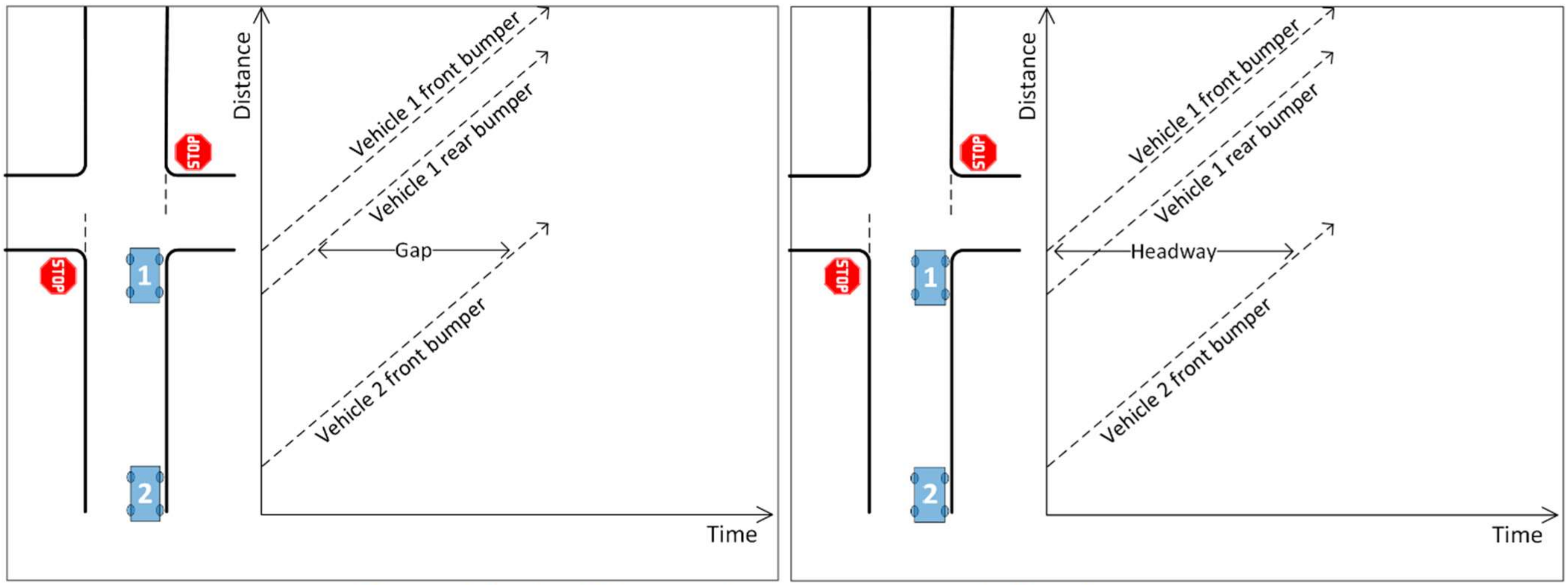


Figure 3-1. The difference between a gap and a headway

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

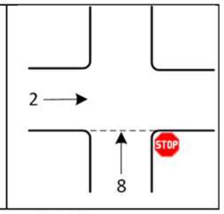
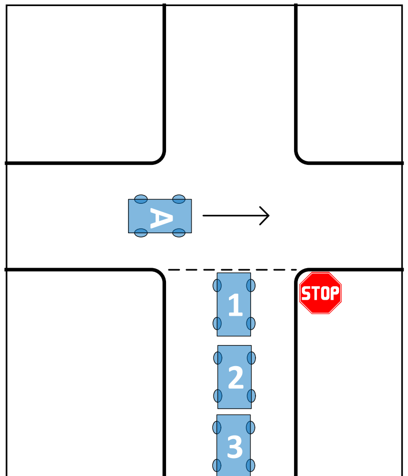


Figure 3-4. Scenario 3-1

- Accepting and rejecting a headway…



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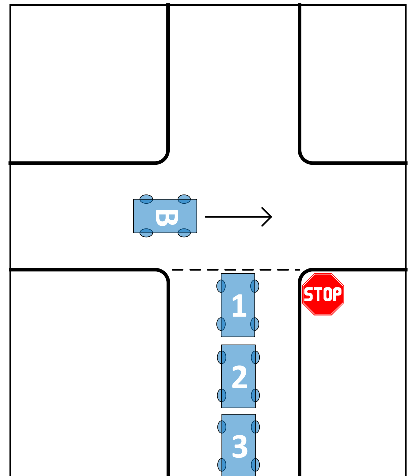
Event 1: Vehicle A enters intersection



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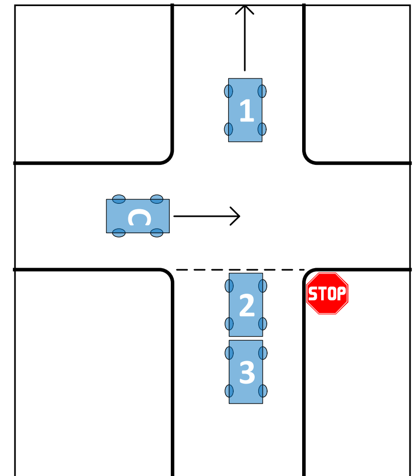
Event 2: Vehicle B enters intersection



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Event 3: Vehicle 1 uses gap between vehicles B and C

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

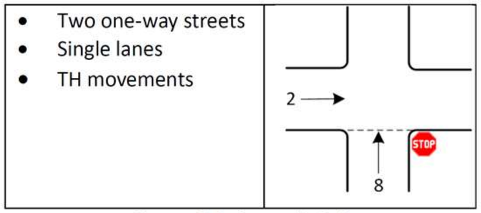
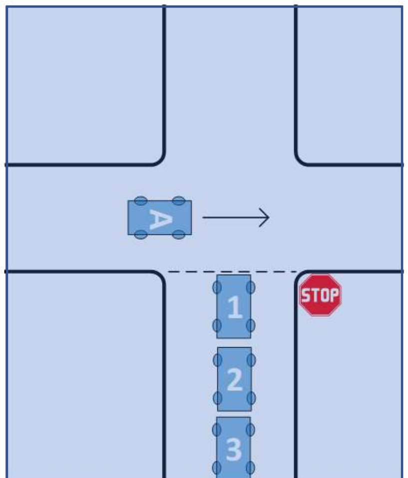


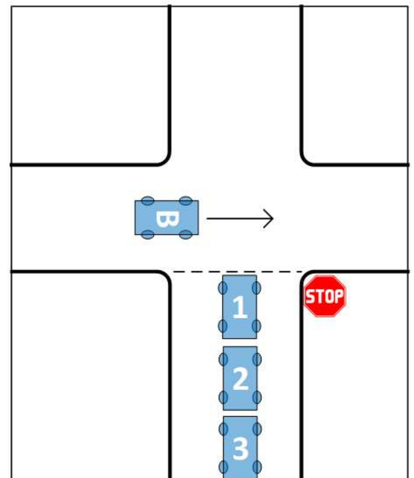
Figure 3-4. Scenario 3-1

- Accepting and rejecting a headway…



Clock time: :00.0 sec

Event 1: Vehicle A enters intersection



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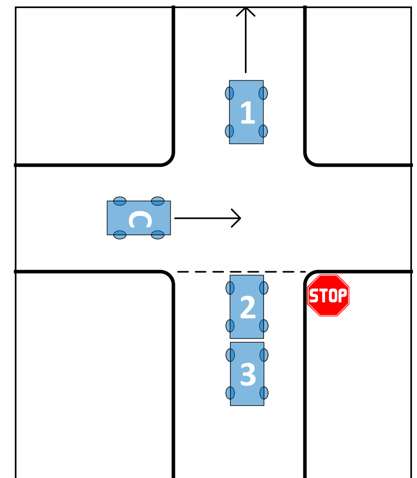
Event 2: Vehicle B enters intersection



:10.0 sec

Event 3: Vehicle 1 uses gap between vehicles B and C

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

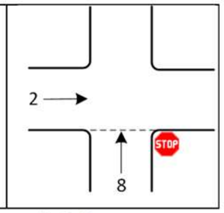
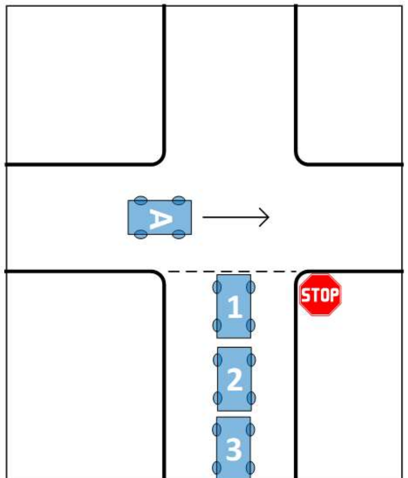


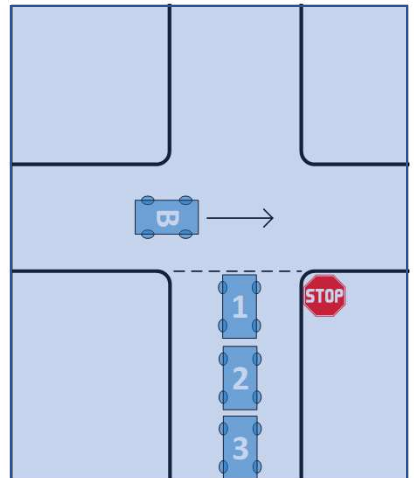
Figure 3-4. Scenario 3-1

- Accepting and rejecting a headway…



Clock time: :00.0 sec

Event 1: Vehicle A enters intersection



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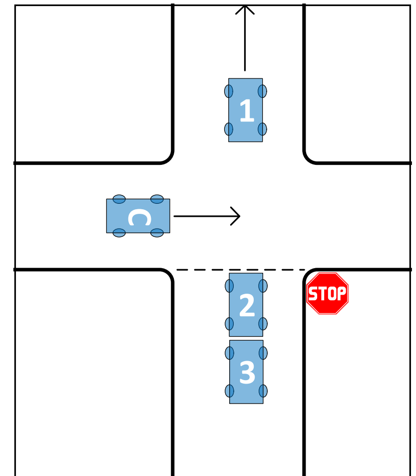
Event 2: Vehicle B enters intersection



:10.0 sec

Event 3: Vehicle 1 uses gap between vehicles B and C

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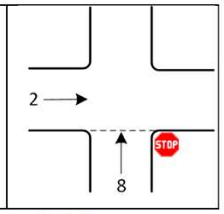
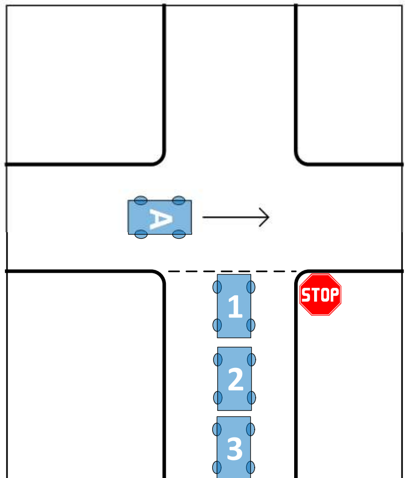


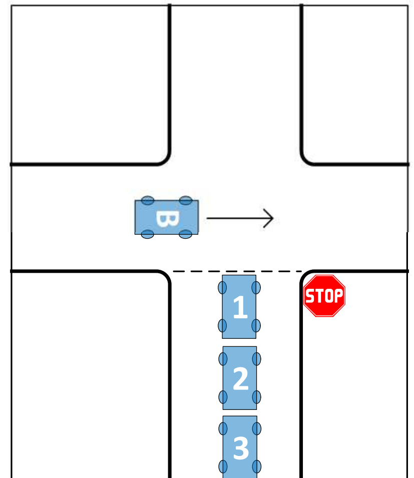
Figure 3-4. Scenario 3-1

- Accepting and rejecting a headway…



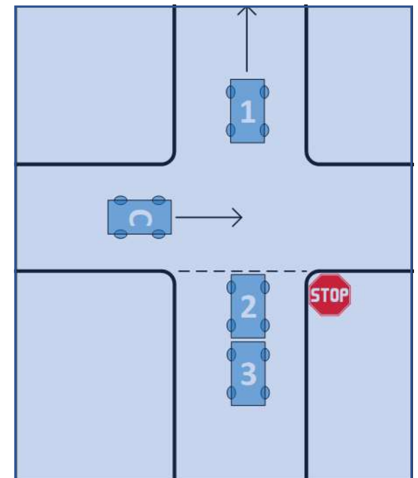
Clock time: :00.0 sec

Event 1: Vehicle A enters intersection



:02.0 sec

Event 2: Vehicle B enters intersection



:10.0 sec

Event 3: Vehicle 1 uses gap between vehicles B and C

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

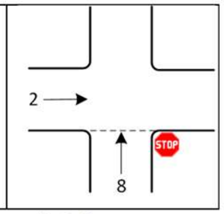
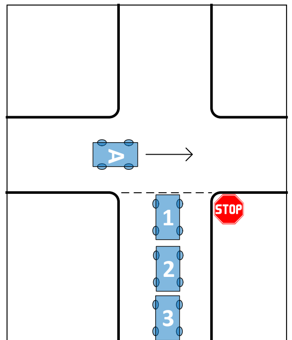


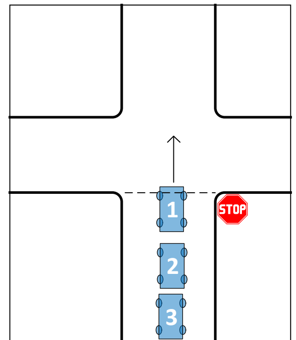
Figure 3-4. Scenario 3-1

- Follow up headway: more than one minor street vehicle using one major street headway



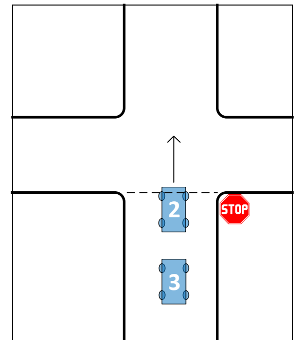
Clock time: :00.0 sec

Event 1: Vehicle A enters intersection on major street



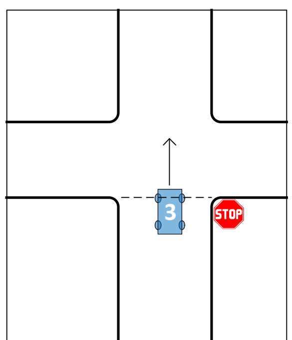
:03.0 sec

Event 2: Vehicle 1 enters intersection on minor street



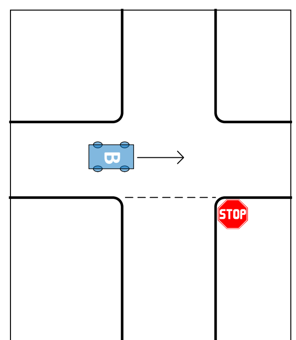
:06.8 sec

Event 3: Vehicle 2 enters intersection on minor street



Clock time: :11.0 sec

Event 4: Vehicle 3 enters intersection on minor street



:14.5 sec

Event 5: Vehicle B enters intersection on major street

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

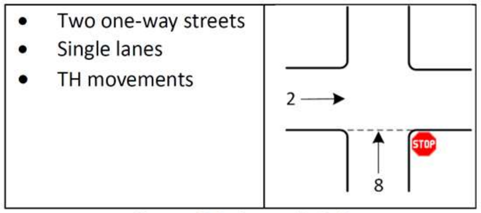
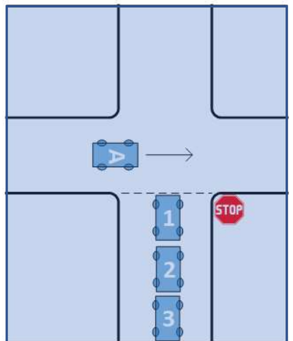


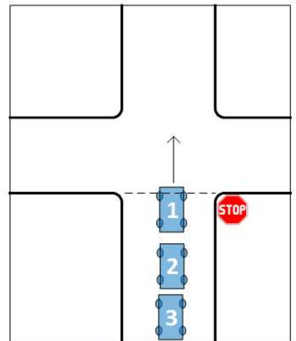
Figure 3-4. Scenario 3-1

- Follow up time: more than one minor street vehicle using one major street headway



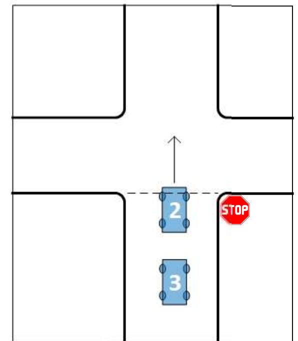
Clock time: :00.0 sec

Event 1: Vehicle A enters intersection on major street



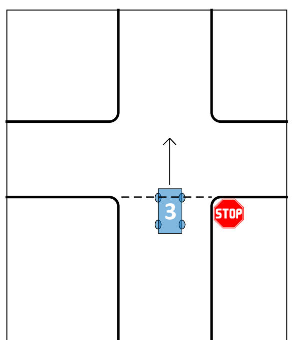
:03.0 sec

Event 2: Vehicle 1 enters intersection on minor street



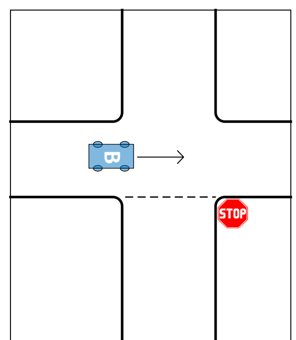
:06.8 sec

Event 3: Vehicle 2 enters intersection on minor street



Clock time: :11.0 sec

Event 4: Vehicle 3 enters intersection on minor street



:14.5 sec

Event 5: Vehicle B enters intersection on major street

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

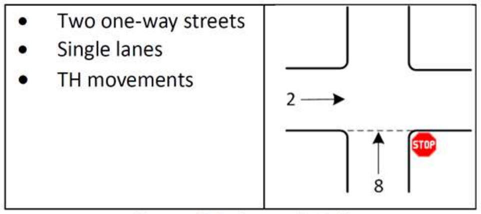
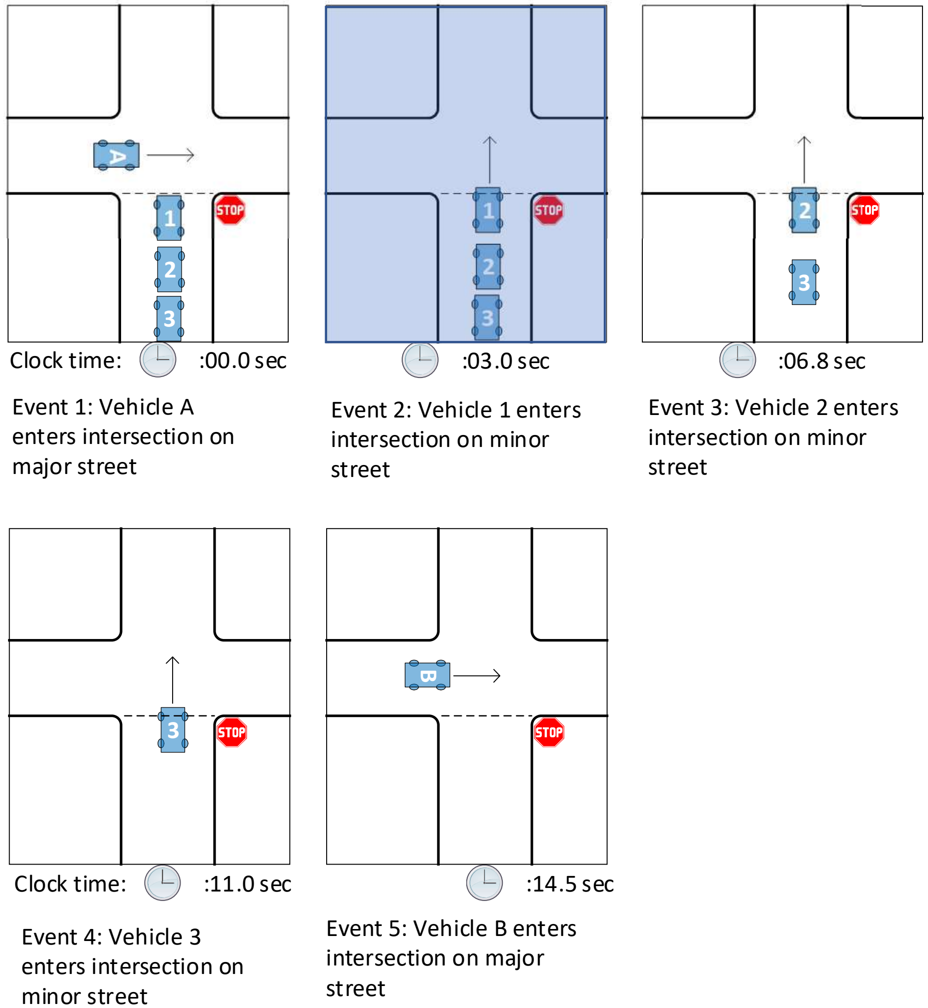


Figure 3-4. Scenario 3-1

- Follow up time: more than one minor street vehicle using one major street headway



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

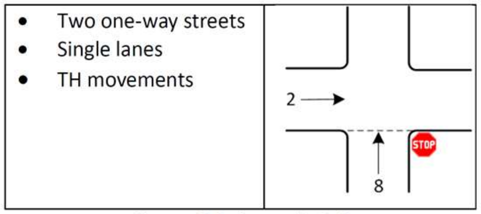
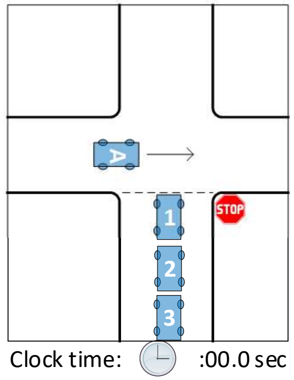
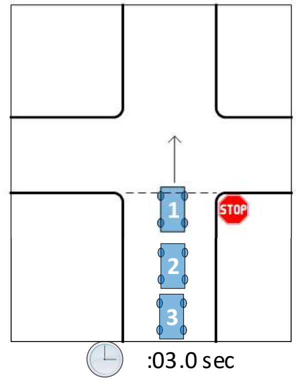


Figure 3-4. Scenario 3-1

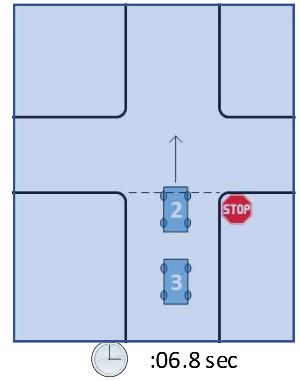
- Follow up time: more than one minor street vehicle using one major street headway



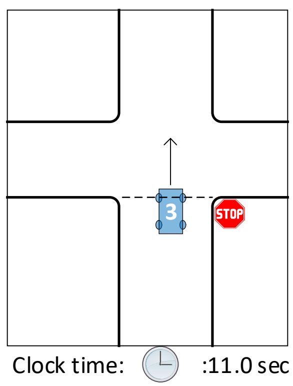
Event 1: Vehicle A enters intersection on major street



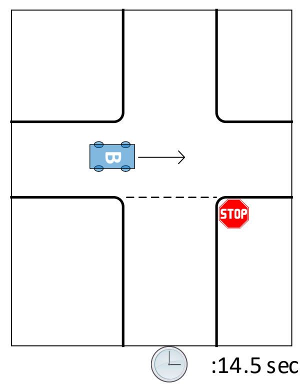
Event 2: Vehicle 1 enters intersection on minor street



Event 3: Vehicle 2 enters intersection on minor street



Event 4: Vehicle 3 enters intersection on minor street



Event 5: Vehicle B enters intersection on major street

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

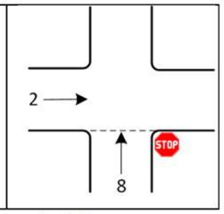
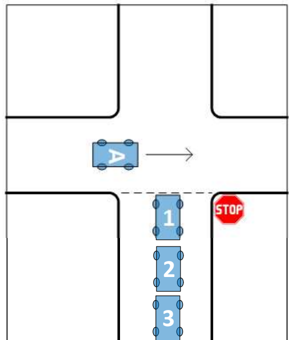


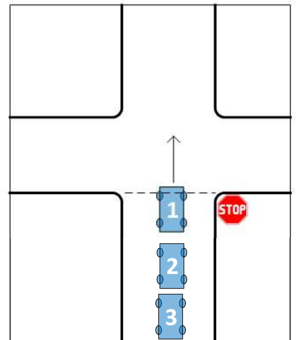
Figure 3-4. Scenario 3-1

- Follow up time: more than one minor street vehicle using one major street headway



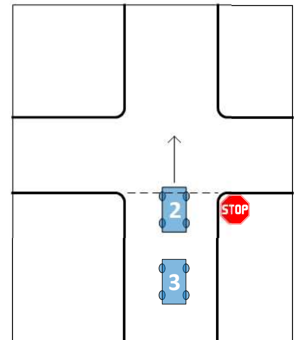
Clock time: :00.0 sec

Event 1: Vehicle A enters intersection on major street



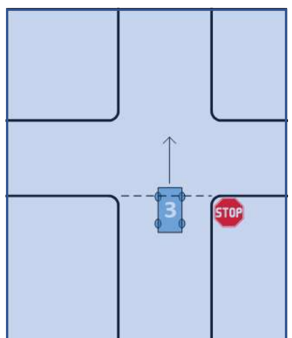
:03.0 sec

Event 2: Vehicle 1 enters intersection on minor street



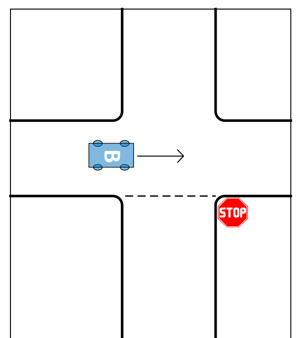
:06.8 sec

Event 3: Vehicle 2 enters intersection on minor street



Clock time: :11.0 sec

Event 4: Vehicle 3 enters intersection on minor street



:14.5 sec

Event 5: Vehicle B enters intersection on major street

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

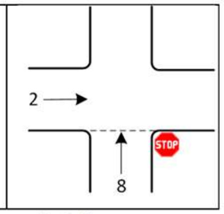
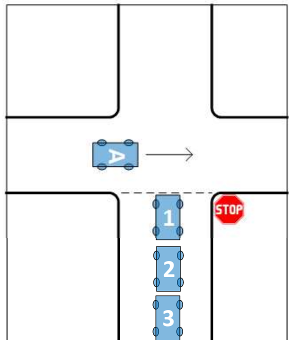


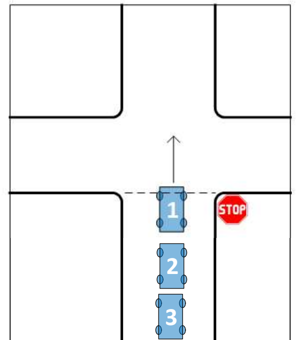
Figure 3-4. Scenario 3-1

- Follow up time: more than one minor street vehicle using one major street headway



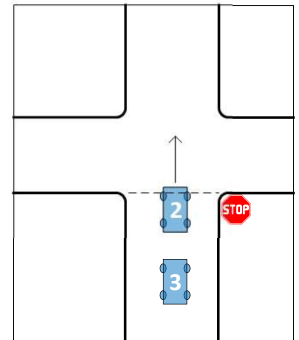
Clock time: :00.0 sec

Event 1: Vehicle A enters intersection on major street



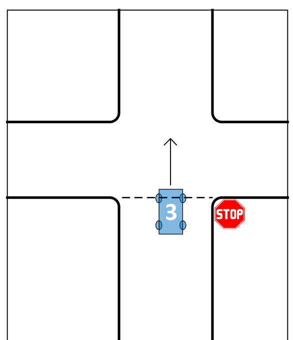
:03.0 sec

Event 2: Vehicle 1 enters intersection on minor street



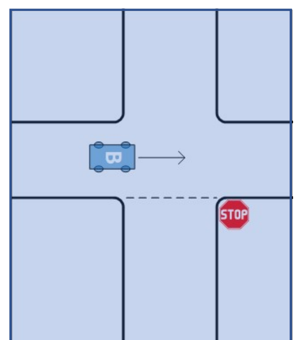
:06.8 sec

Event 3: Vehicle 2 enters intersection on minor street



Clock time: :11.0 sec

Event 4: Vehicle 3 enters intersection on minor street



:14.5 sec

Event 5: Vehicle B enters intersection on major street

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

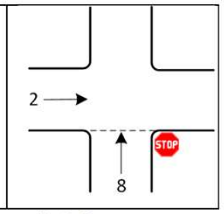
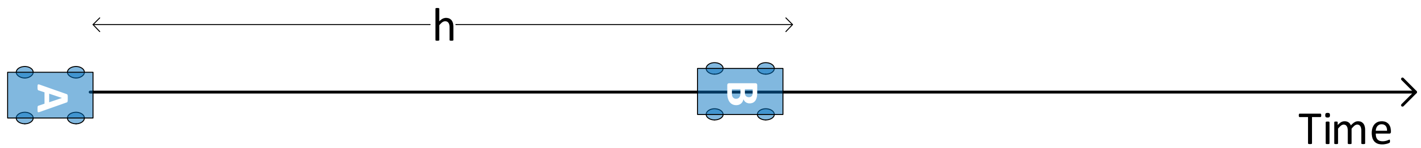


Figure 3-4. Scenario 3-1



Question: How do we model a random process?

$$P[h \geq t] = e^{-\lambda t}$$

$$P[h \geq t_c] = e^{-\lambda t_c}$$

$$P[h < t_c] = 1 - e^{-\lambda t_c}$$

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

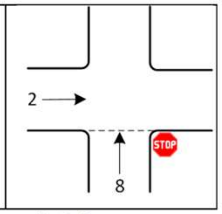
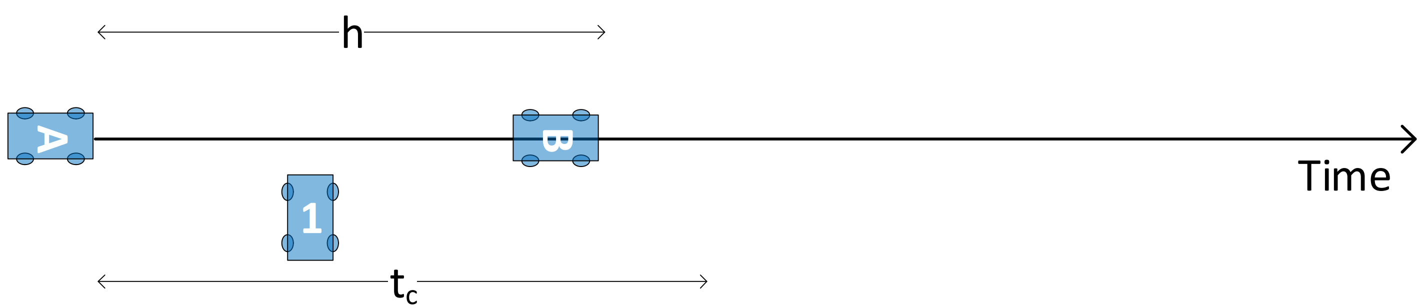


Figure 3-4. Scenario 3-1

Headway range (sec)	Number of vehicles able to use headway
$h < t_c$	0

Question: How useful is a headway of a given size?



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

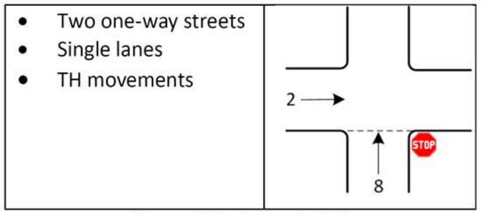
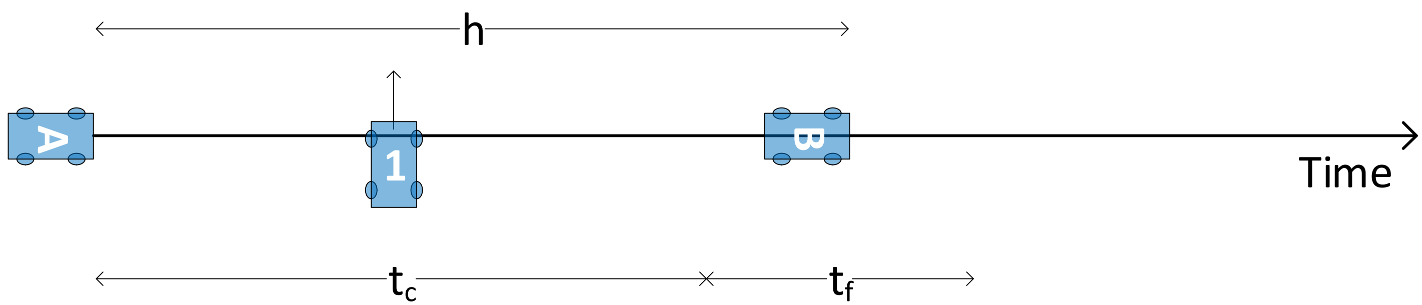


Figure 3-4. Scenario 3-1

Headway range (sec)	Number of vehicles able to use headway
$h < t_c$	0
$t_c \leq h < t_c + t_f$	1

Question: What is the capacity of a major street headway?



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

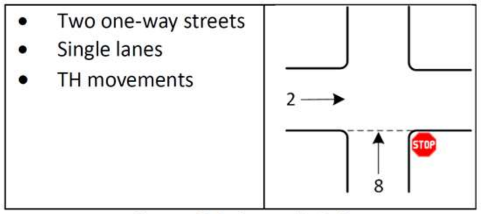
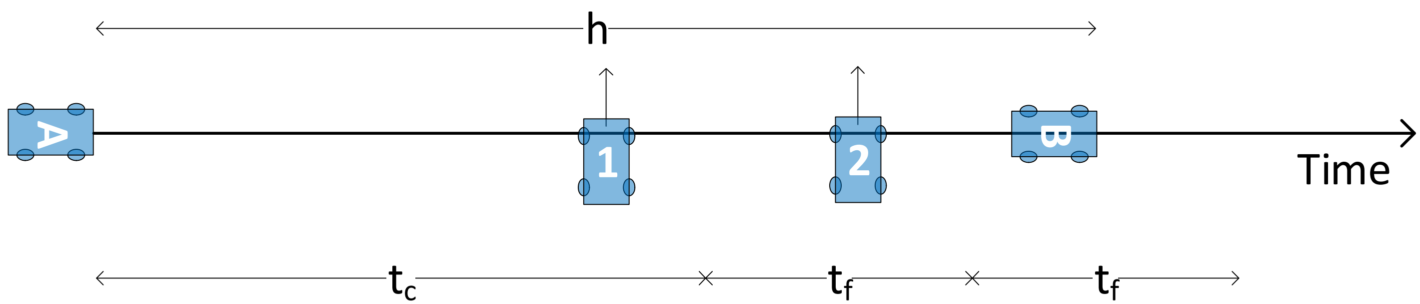


Figure 3-4. Scenario 3-1

Headway range (sec)	Number of vehicles able to use headway
$h < t_c$	0
$t_c \leq h < t_c + t_f$	1
$t_c + t_f \leq h < t_c + 2t_f$	2

Question: What is the capacity of a major street headway?



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

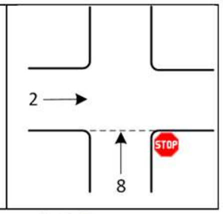


Figure 3-4. Scenario 3-1

Question: How likely is a given headway range to occur?

Table 3-3. Probability of occurrence of given headway range

Headway range (sec)	Number of vehicles able to use headway	Probability that headway is in range
$h < t_c$	0	$1 - e^{-\lambda t_c}$
$t_c \le h < t_c + t_f$	1	$e^{-\lambda t_c} - e^{-\lambda(t_c+t_f)}$
$t_c + t_f \le h < t_c + 2t_f$	2	$e^{-\lambda(t_c+t_f)} - e^{-\lambda(t_c+2t_f)}$
...		
$t_c + (n-1)t_f \le h < t_c + nt_f$	n	$e^{-\lambda(t_c+(n-1)t_f)} - e^{-\lambda(t_c+nt_f)}$

$$P[h < t_c] = 1 - e^{-\lambda t_c}$$

$$P\left[h < t_c + t_f\right] = 1 - e^{-\lambda(t_c+t_f)}$$

$$P\left[t_c \le h < t_c + t_f\right] = \left(1 - e^{-\lambda\left(t_c+t_f\right)}\right) - \left(1 - e^{-\lambda t_c}\right)$$

$$P\left[t_c \le h < t_c + t_f\right] = e^{-\lambda t_c} - e^{-\lambda\left(t_c+t_f\right)}$$

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

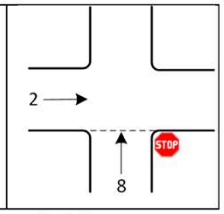


Figure 3-4. Scenario 3-1

Question: What is the capacity of a given headway or headway range?

How many gaps or headway occur in one hour?

$3600\lambda \quad or \quad v$

What is capacity of headway range?

$(n)\ P[range\ occuring]\ (3600\lambda)$ or $(n)\ P[range\ occuring]\ (v)$

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

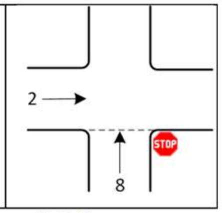


Figure 3-4. Scenario 3-1

Question: What is the capacity of the minor stream?

Table 3-4. Probable number of vehicles using headway range

Headway range (sec)	Number of vehicles able to use each headway	Number of headways in range in one hour	Expected number of vehicles using all headways in the range (in one hour)
$h < t_c$	0	$(1 - e^{-\lambda t_c})(3600\lambda)$	0
$t_c \leq h < t_c + t_f$	1	$\left(e^{-\lambda t_c} - e^{-\lambda(t_c+t_f)}\right)(3600\lambda)$	$1\left(e^{-\lambda t_c} - e^{-\lambda(t_c+t_f)}\right)(3600\lambda)$
$t_c + t_f \leq h < t_c + 2t_f$	2	$\left(e^{-\lambda(t_c+t_f)} - e^{-\lambda(t_c+2t_f)}\right)(3600\lambda)$	$2\left(e^{-\lambda(t_c+t_f)} - e^{-\lambda(t_c+2t_f)}\right)(3600\lambda)$
…	…	…	…
$t_c + (n-1)t_f \leq h < t_c + nt_f$	n	$\left(e^{-\lambda(t_c+(n-1)t_f)} - e^{-\lambda(t_c+nt_f)}\right)(3600\lambda)$	$n\left(e^{-\lambda(t_c+(n-1)t_f)} - e^{-\lambda(t_c+nt_f)}\right)(3600\lambda)$

$$c = \frac{v_c e^{-v_c t_c/3600}}{1 - e^{-v_c t_f/3600}}$$

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

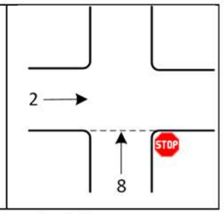


Figure 3-4. Scenario 3-1

Example Calculation 3-2. Calculating the Capacity of a Lane

The HCM gives the critical headway and the follow-up headway for minor street TH movements as t_c = 6.5 sec/veh and t_f = 4.0 sec/veh, respectively. What is the capacity of the minor street lane if the major street volume is 400 veh/hr or .111 veh/sec?

$$c = \frac{v_c e^{-v_c t_c/3600}}{1 - e^{-v_c t_f/3600}}$$

$$c = \frac{400 e^{-(400)(6.5)/3600}}{1 - e^{-(400)(4.0)/3600}}$$

$$c = 541 \text{ veh/hr}$$

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

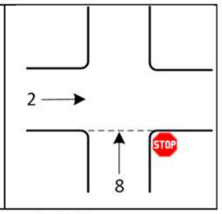


Figure 3-4. Scenario 3-1

Example Calculation 3-2. Calculating the Capacity of a Lane

The HCM gives the critical headway and the follow-up headway for minor street TH movements as t_c = 6.5 sec/veh and t_f = 4.0 sec/veh, respectively. What is the capacity of the minor street lane if the major street volume is 400 veh/hr or .111 veh/sec?

Headway range (sec)	Number of vehicles able to use the headway	Probability that headways is in range	Expected average number of vehicles using range (in an hour)
< 6.5	0	0.514	0
6.5 - 10.5	1	0.174	69.7
10.5 - 14.5	2	0.112	89.4
14.5 – 18.5	3	0.072	86.0
18.5 – 22.5	4	0.046	73.5
22.5 – 26.5	5	0.030	58.9
26.5 – 30.5	6	0.019	45.3
30.5 – 34.5	7	0.012	33.9
34.5 – 38.5	8	0.008	24.8
38.5 – 42.5	9	0.005	17.9
42.5 – 46.5	10	0.003	12.8
46.5 – 50.5	11	0.002	9.0
50.5 – 54.5	12	0.0013	6.3
54.5 – 58.5	13	0.0008	4.4
58.5 – 62.5	14	0.0005	3.0
…			
	Sum	1.000	541

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

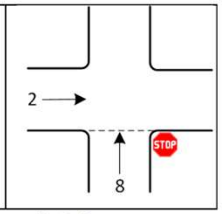


Figure 3-4. Scenario 3-1

Example Calculation 3-2. Calculating the Capacity of a Lane

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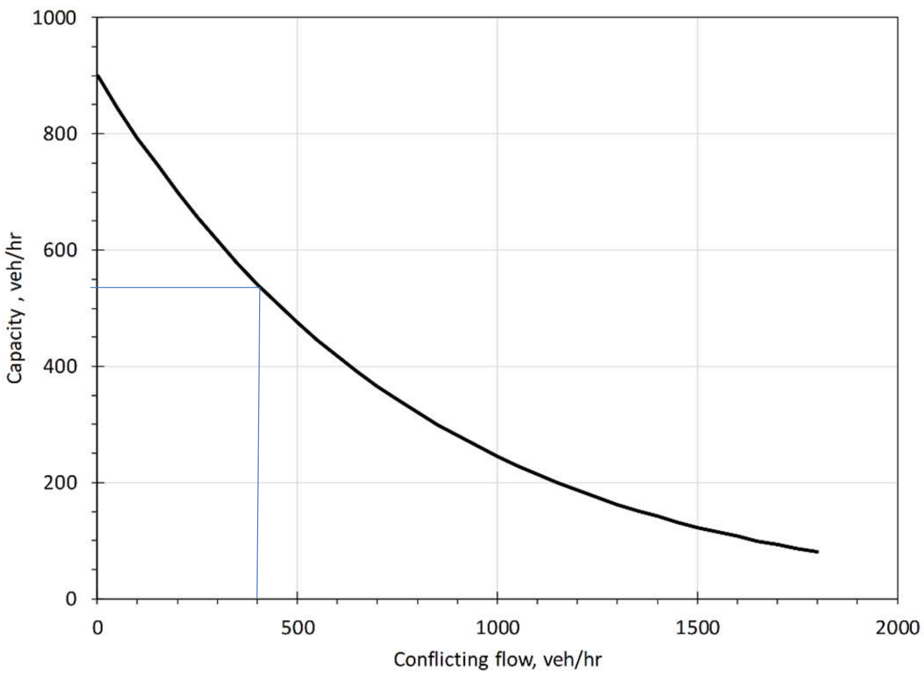


Figure 3-6. Capacity as function of conflicting flow

4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

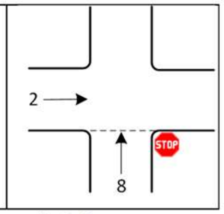
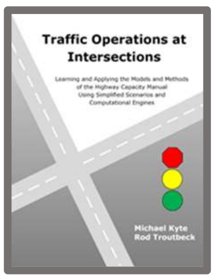
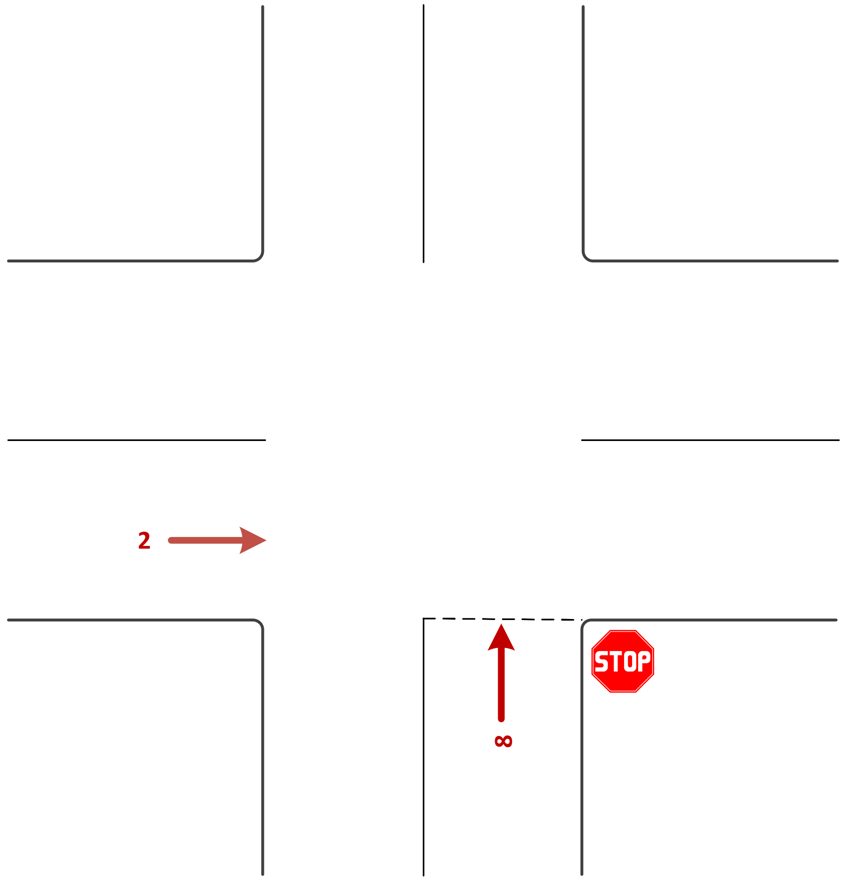


Figure 3-4. Scenario 3-1





4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
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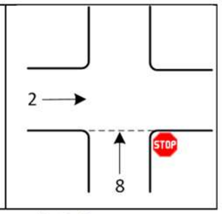
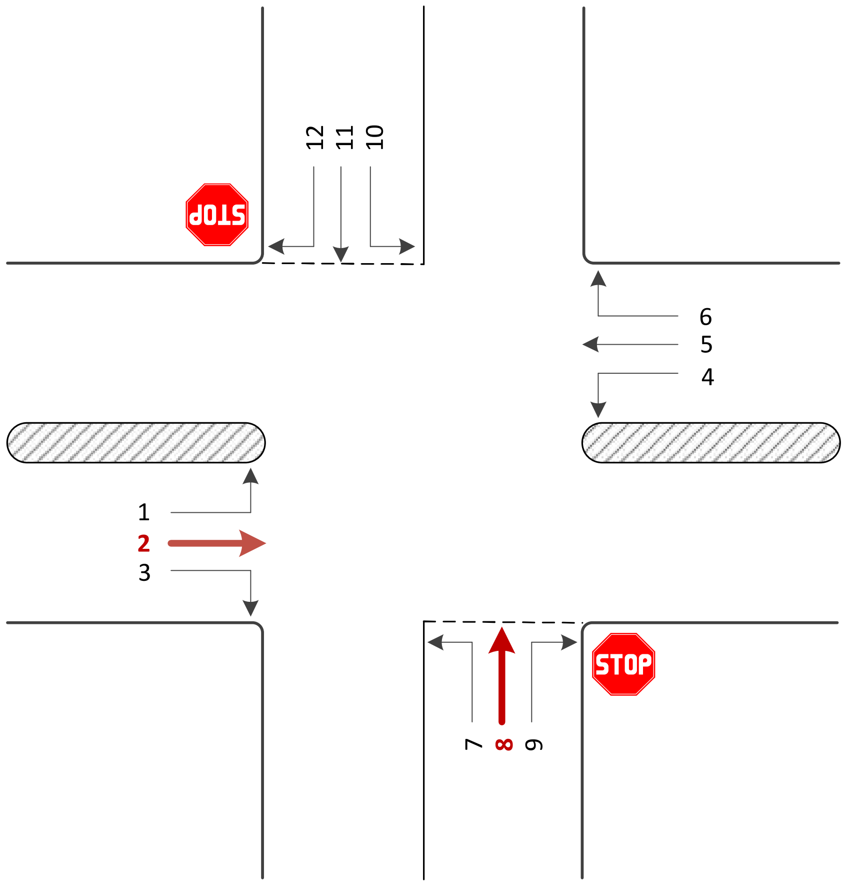


Figure 3-4. Scenario 3-1



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
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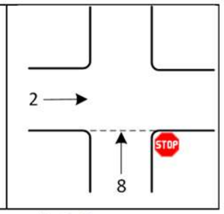
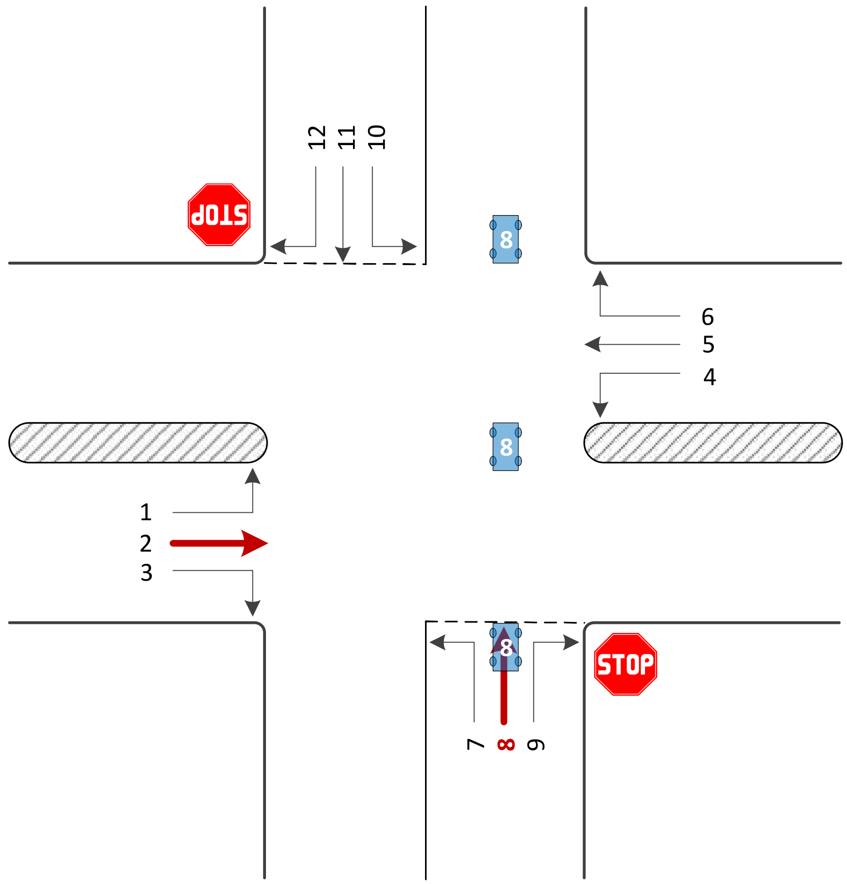


Figure 3-4. Scenario 3-1



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
- Single lanes
- TH movements

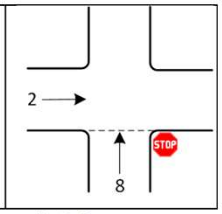
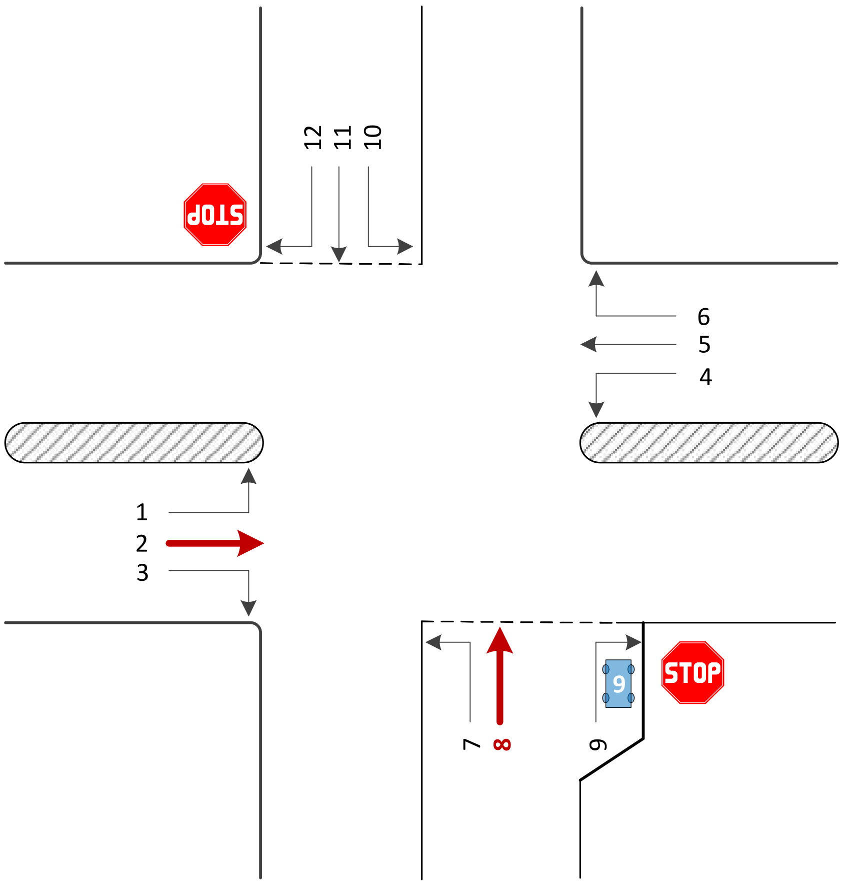


Figure 3-4. Scenario 3-1



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

- Two one-way streets
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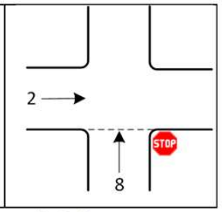
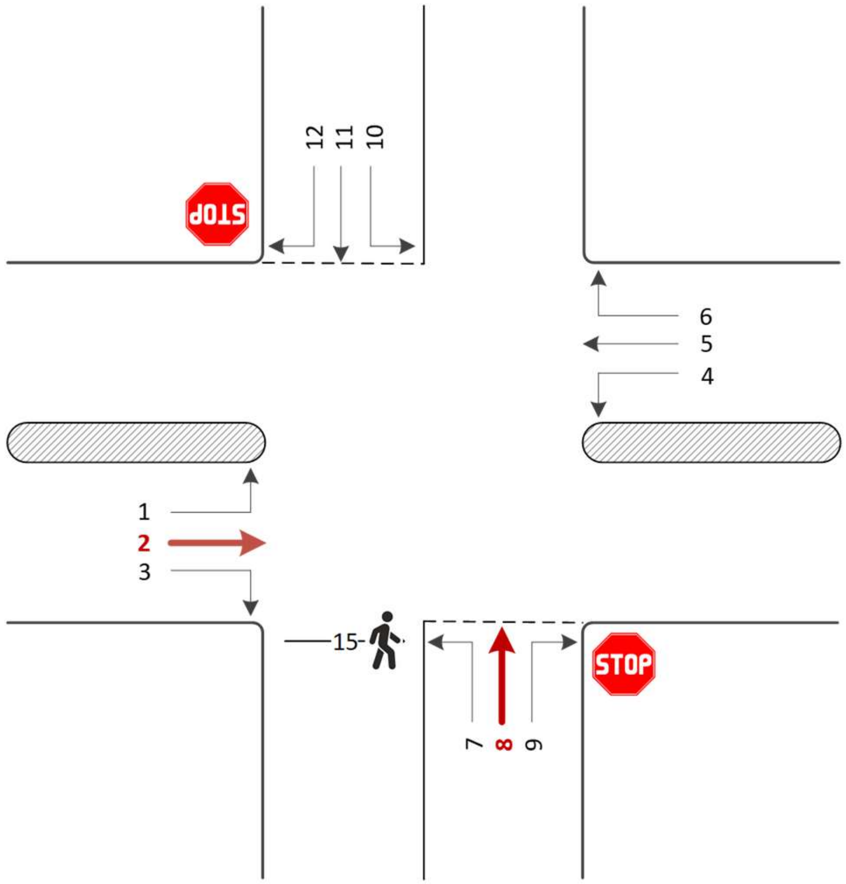


Figure 3-4. Scenario 3-1



4. Scenario 3-1. Calculating the Capacity of Each Movement for an Intersection of Two One-Way Streets

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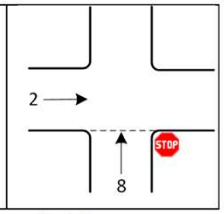


Figure 3-4. Scenario 3-1

The Big Picture

- How large are the headways in the major traffic stream?
- What size headways do minor stream drivers need?

Table 4-1. Roadmap to Chapter 4

Section	Topic
Fundamentals	
1	What's in this chapter?
2	What do we observe in the field?
3	Movements and phases
4	Actuated control processes
5	Formulating the model
Simplified Scenarios	
6	Scenario 4-1. Calculating the capacity of a lane based on one signal cycle
7	Scenario 4-2. Calculating the delay on a lane when demand is less than capacity
8	Scenario 4-3. Calculating the capacity of an exclusive left turn lane for permitted LT phasing
9	Scenario 4-4. Calculating the capacity utilization for an intersection using critical movement analysis
10	Scenario 4-5. Calculating the delay on a lane when demand exceeds capacity
11	Scenario 4-6. Calculating delay on a lane when the arrival pattern is non-uniform
12	Scenario 4-7. Predicting average green time for a phase under actuated control
Learning in Depth	
13	Calculating saturation headways
14	Building the computational engines and exploring the model
Closing	
15	Summary
16	Glossary
17	References

3. Movements and Phases

4. Actuated Signal Control Timing Processes

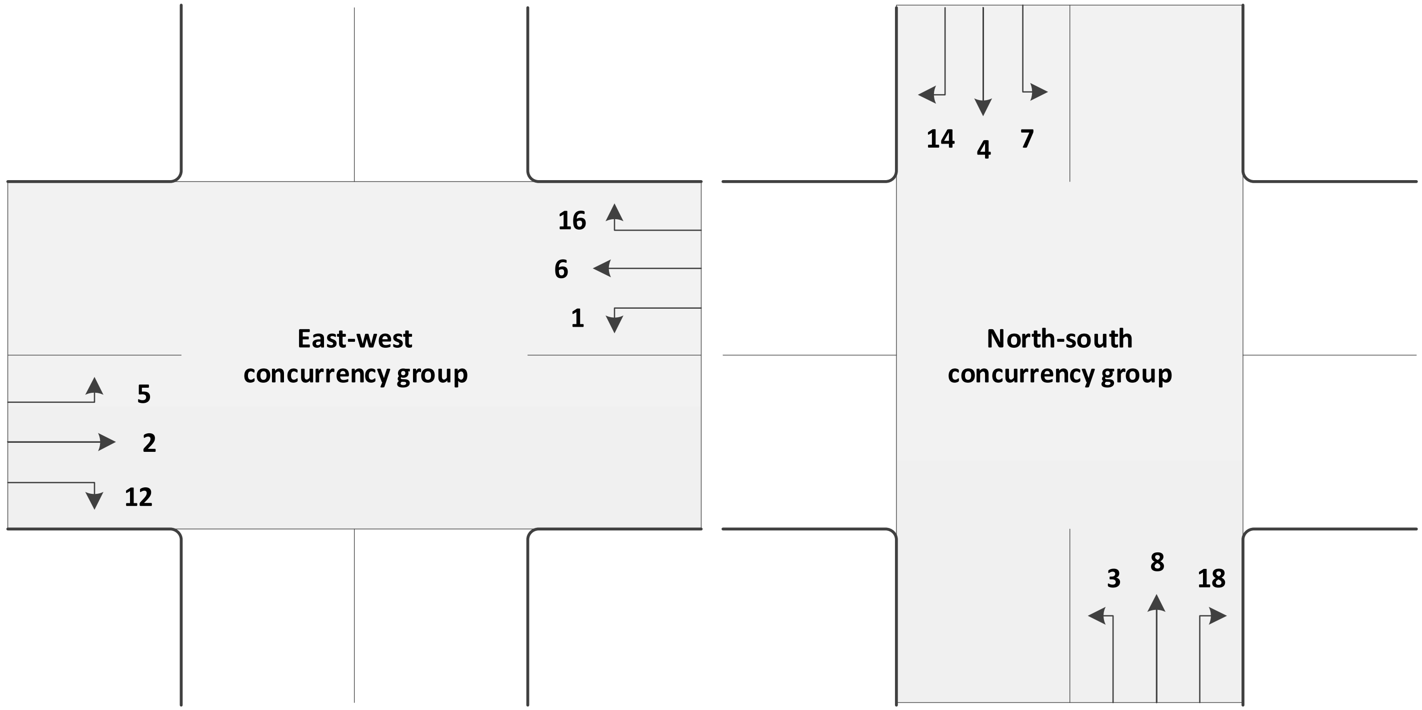
The Big Picture

- How does a traffic signal work
- What do you need to know about this process?

3. Movements and Phases

Signal timing concepts

- **Concurrency group**
- Phase
- Ring barrier diagram
- Timers
- Traffic control process diagram
- Effective and displayed times
- Phase duration



Signal timing concepts

- Concurrency group
- **Phase**
- **Ring barrier diagram**
- Timers
- Traffic control process diagram
- Effective and displayed times
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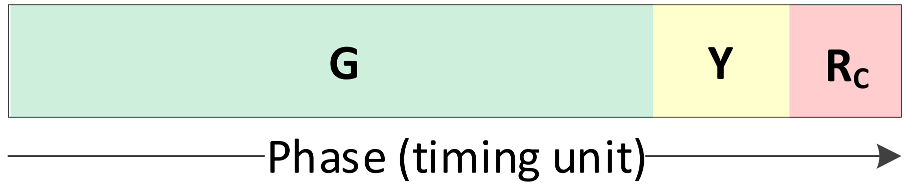
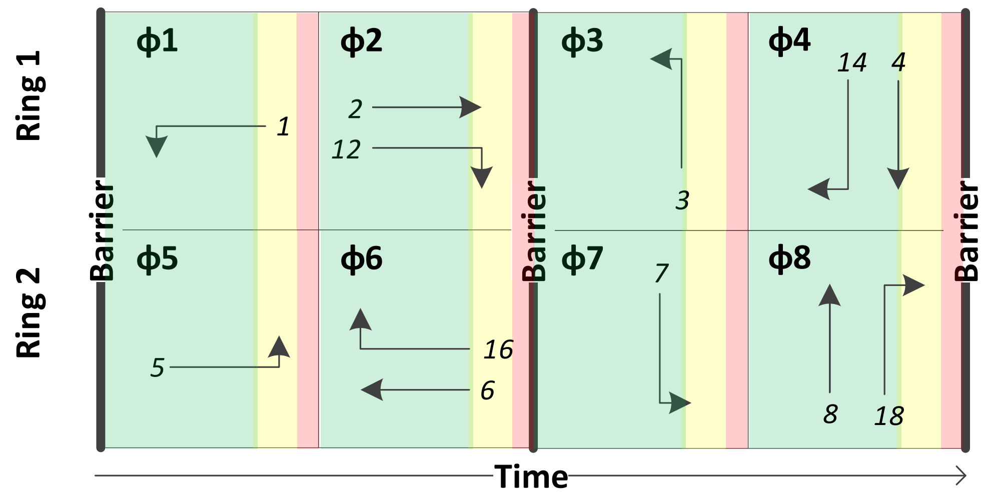
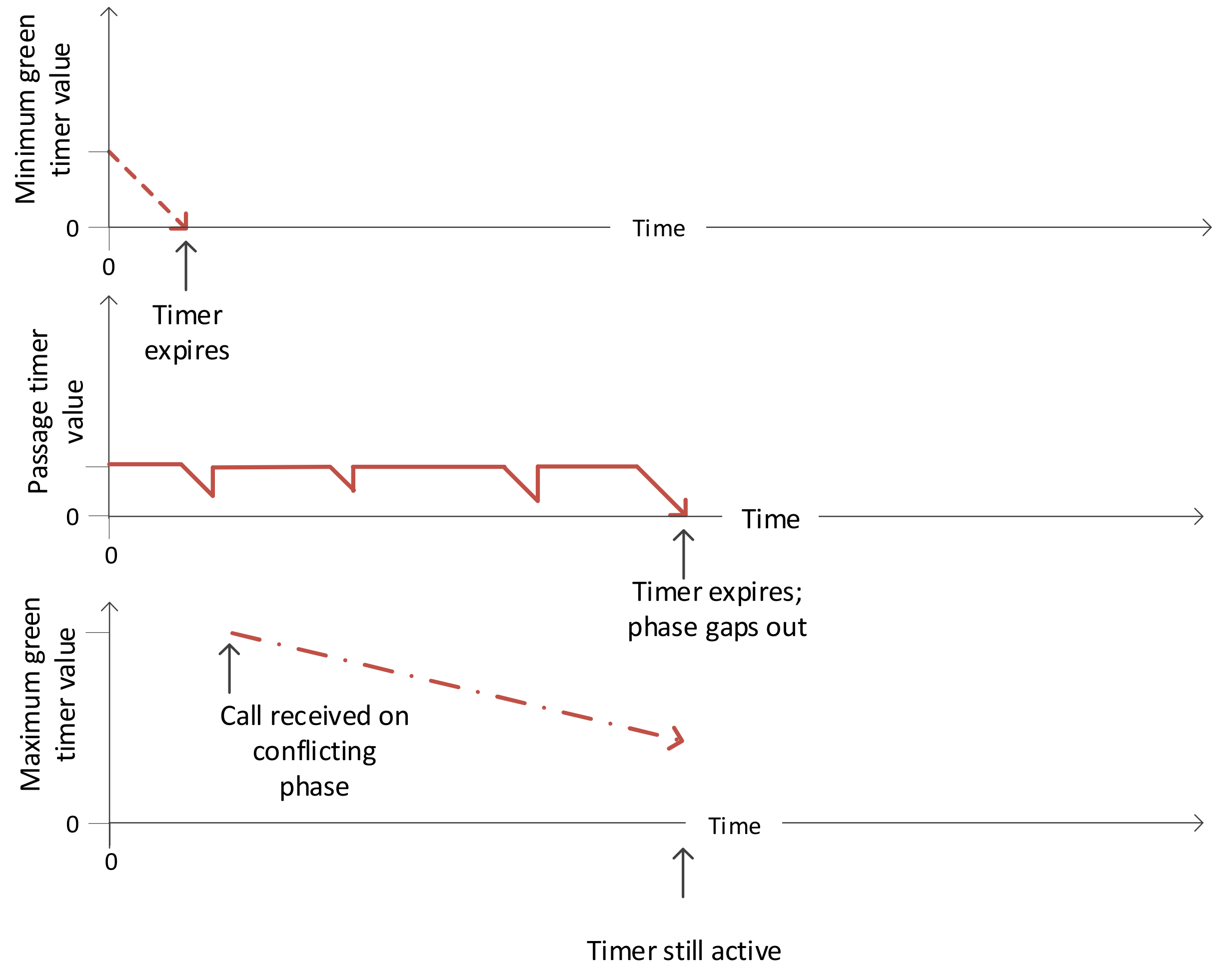




4. Actuated Signal Control Timing Processes

Signal timing concepts

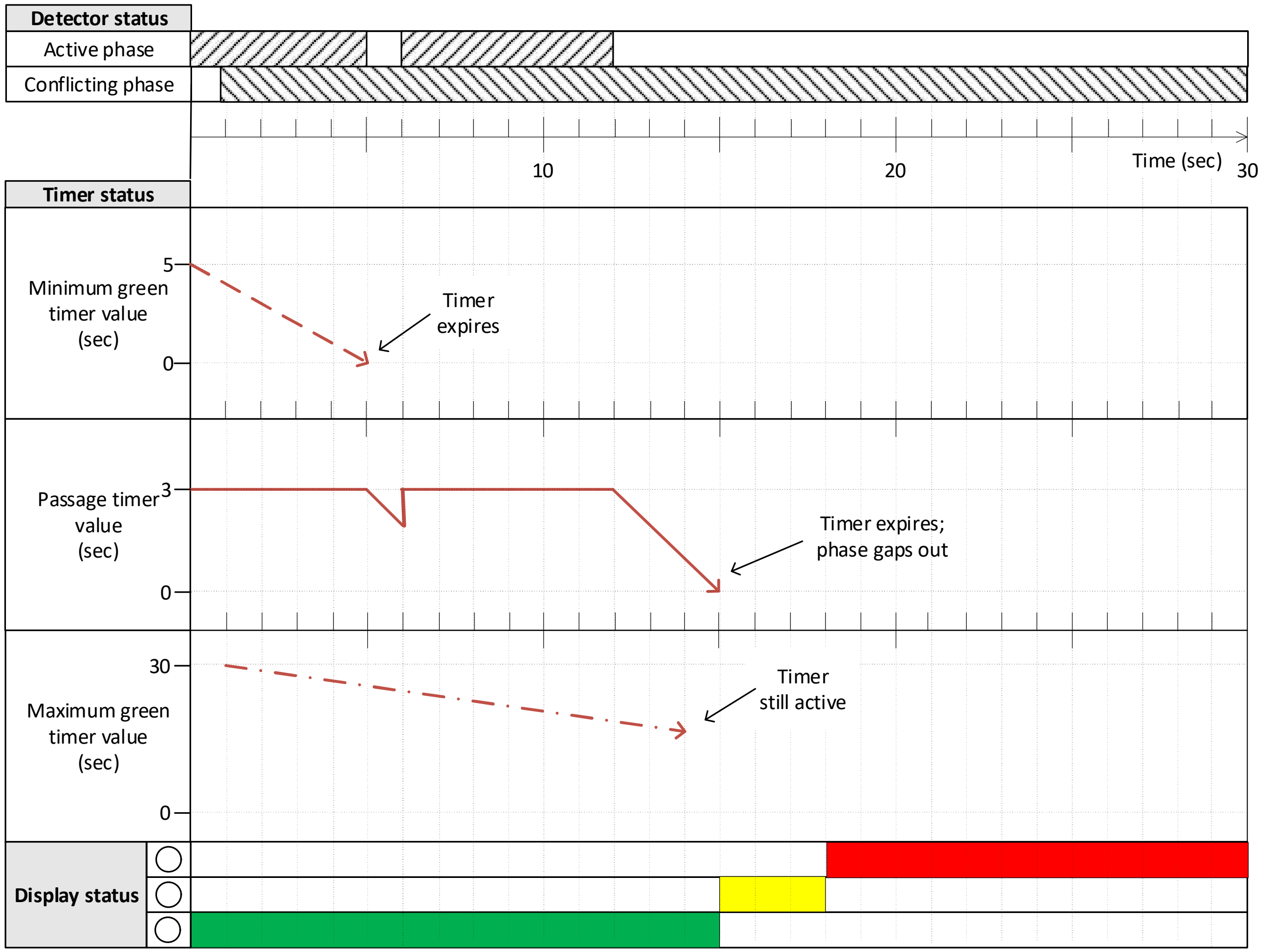
- Concurrency group
- Phase
- Ring barrier diagram
- **Timers**
- Traffic control process diagram
- Effective and displayed times
- Phase duration



4. Actuated Signal Control Timing Processes

Signal timing concepts

- Concurrency group
- Phase
- Ring barrier diagram
- Timers
- **Traffic control process diagram**
- Effective and displayed times
- Phase duration



4. Actuated Signal Control Timing Processes

Signal timing concepts

- Concurrency group
- Phase
- Ring barrier diagram
- Timers
- Traffic control process diagram
- **Effective and displayed times**
- **Phase duration**

3. Movements and Phases

4. Actuated Signal Control Timing Processes

The Big Picture

- How does a traffic signal work
- What do you need to know about this process?

5. Formulating the Model

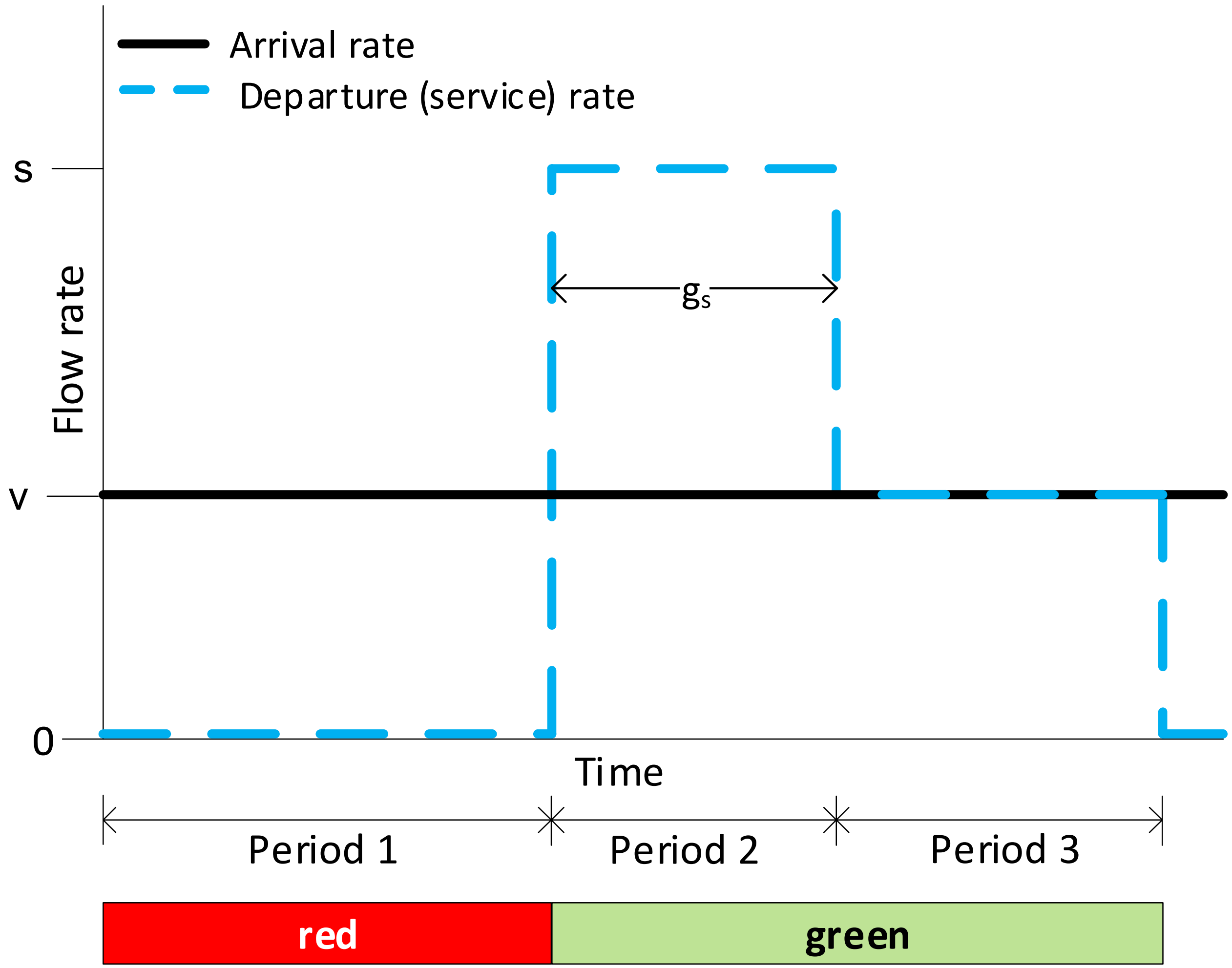
The Big Picture

- How do we model traffic flow at a signalized intersection?
- Basic queuing model representations
  - Flow profile diagram
  - Cumulative vehicle diagram
  - Queue accumulation polygon

5. Formulating the Model

Traffic flow concepts

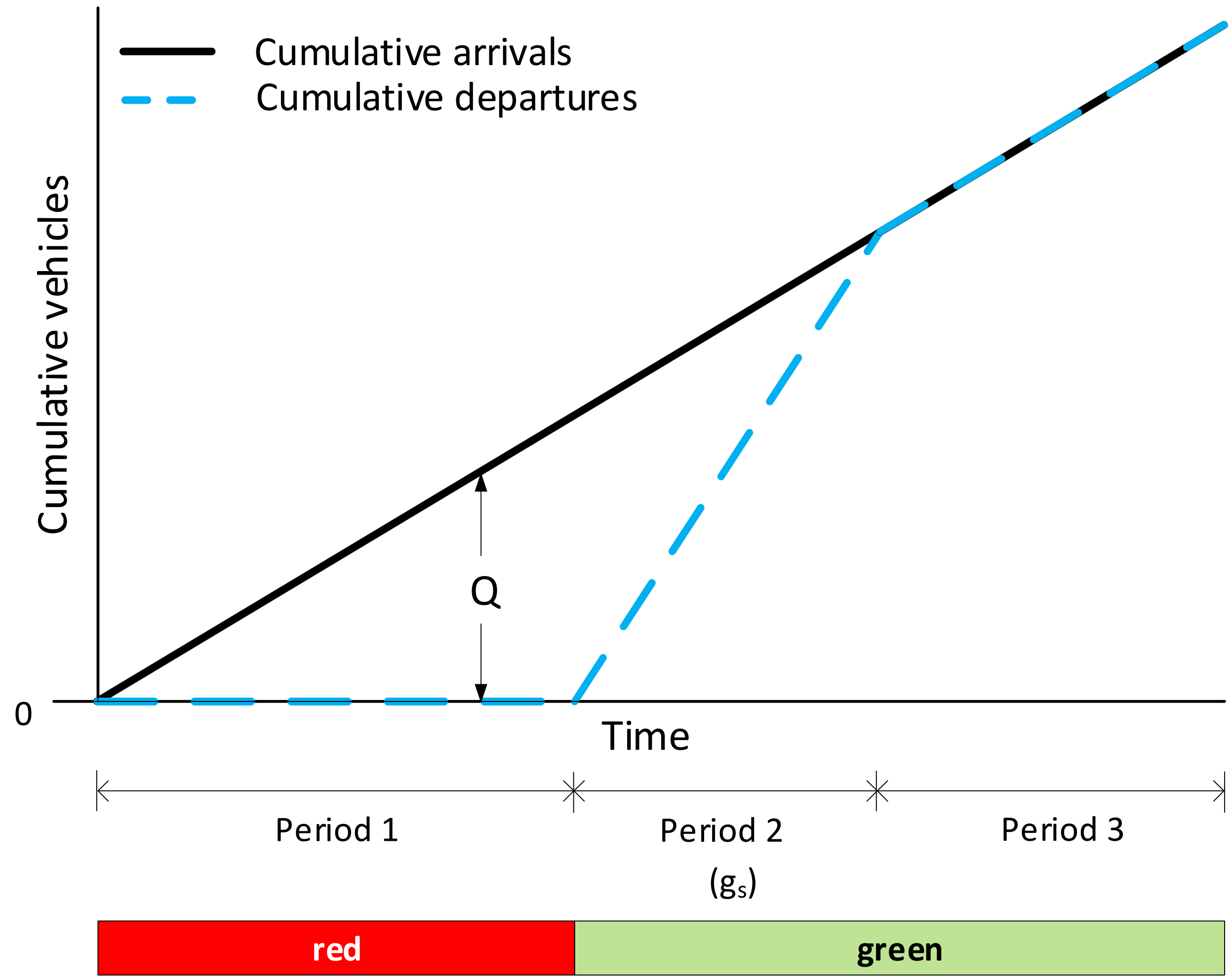
- **Flow profile diagram**
- Cumulative vehicle diagram
- Queue accumulation polygon



5. Formulating the Model

Traffic flow concepts

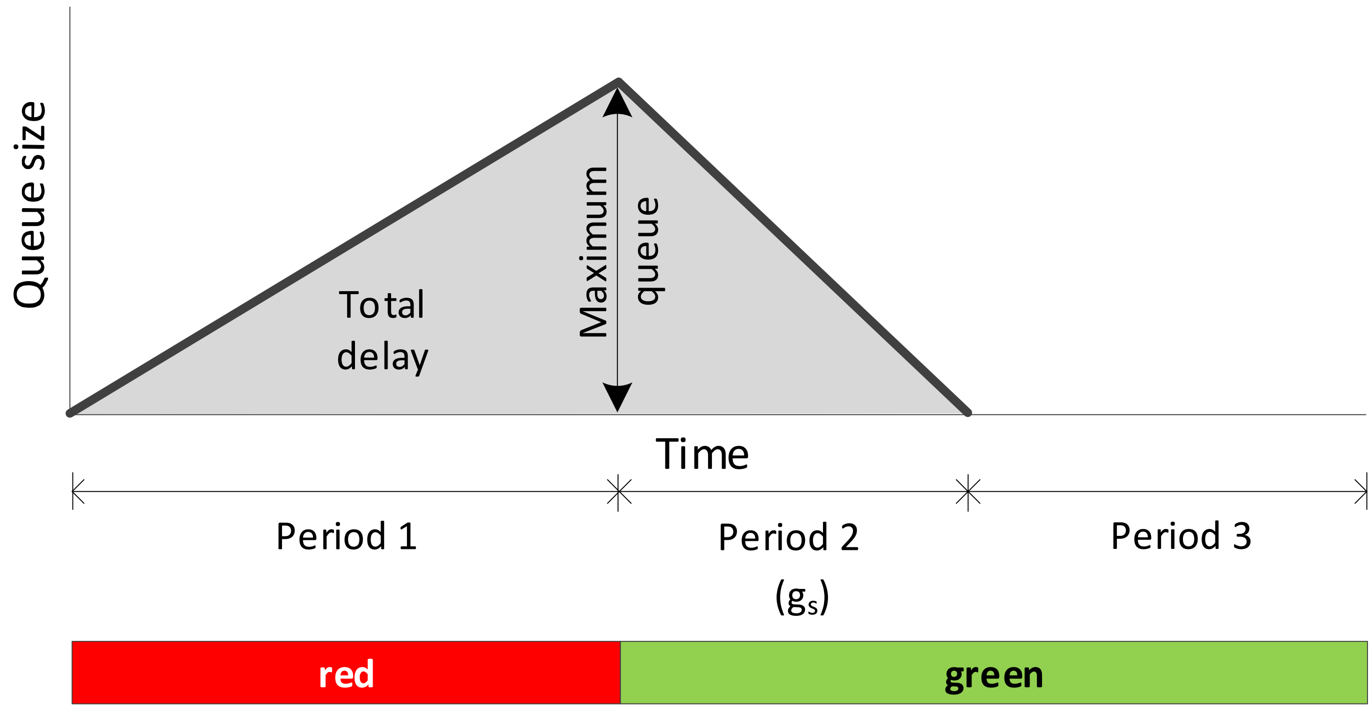
- Flow profile diagram
- **Cumulative vehicle diagram**
- Queue accumulation polygon



5. Formulating the Model

Traffic flow concepts

- Flow profile diagram
- Cumulative vehicle diagram
- **Queue accumulation polygon**



5. Formulating the Model

The Big Picture

- How do we model traffic flow at a signalized intersection?
- Basic queuing model representations
  - Flow profile diagram
  - Cumulative vehicle diagram
  - Queue accumulation polygon

Topics for today

- Welcome and overview
- Introductions
- Learning the HCM: what this course is … and isn’t
- What resources do you have available to you?
- Overview of our book
- Diving in: Exploring four simplified scenarios
- **Assignment for next time**
- Check-out

Team Assignment: Explore a Simplified Scenario

Rules:

1. **2 slides with graphics (little or no text)**
2. **Tell us 2 things that you learned about this scenario**
3. **Tell us 2 questions that you have after reviewing the scenario**
4. **4 minutes per presentation**

Topics for today

- Welcome and overview
- Introductions
- Learning the HCM: what this course is … and isn't
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Final Questions