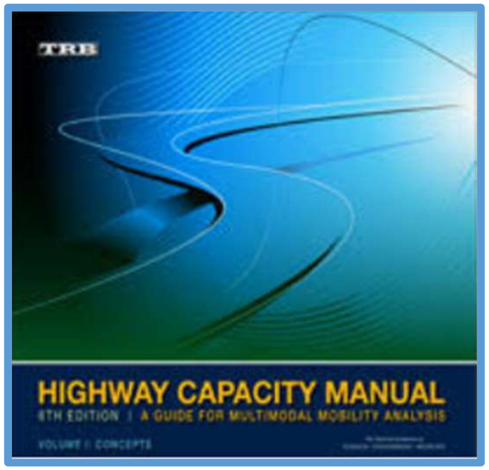
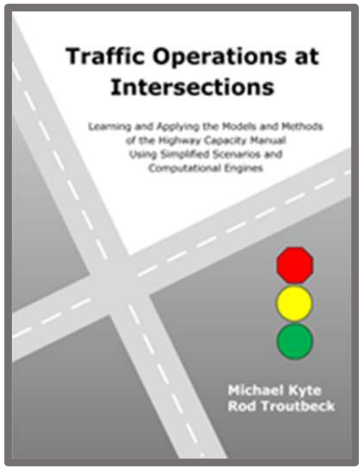


Highway Capacity Manual
6^{th} Edition

Transportation Research Board

Learning and Applying the Methods and Models of the HCM

A Short Course
Day #2



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

- **Check-in**
- Diving in: Exploring the simplified scenarios
- Check-out and closure

Topics for today

- Check-in
- **Diving in: Exploring the simplified scenarios**
  - **Scenario 3-2 – impedance**
  - **Scenario 4.1 – capacity of a lane**
  - **Scenario 4.4 – critical movement analysis**
  - **Scenario 4.2 – predicting delay**
- Check-out and closure

Topics for today

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5. Scenario 3-2. Calculating the Capacity of Each Movement for a T-Intersection

- T-intersection
- Three movements

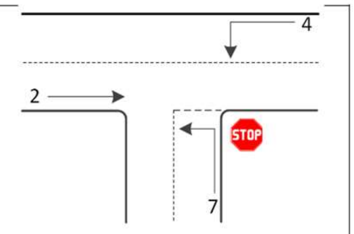


Figure 3-8. Scenario 3-2

The Big Picture

- What is impedance?
- How does movement 4 impede movement 7?
- How does this impedance affect the capacity for movement 7?

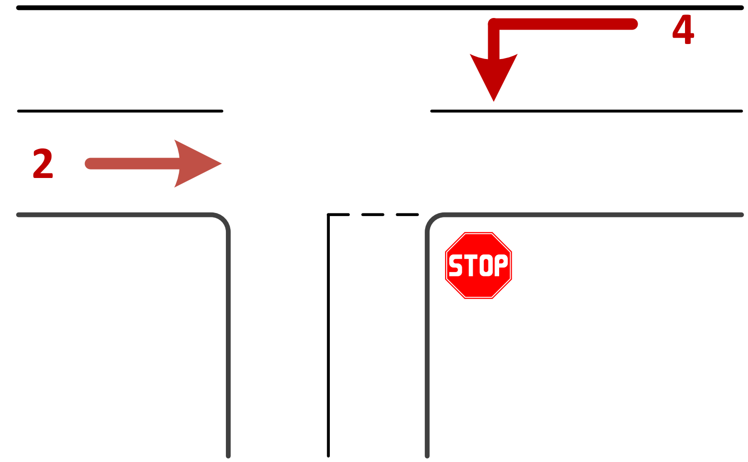
Terms We Will Use

- Critical headway and follow-up headway
- Conflicting flow rate
- Impedance
- Potential and movement capacity
- Queue free state

5. Scenario 3-2. Calculating the Capacity of Each Movement for a T-Intersection

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

c = capacity (veh/hr
v_c = conflicting flow (veh/hr)
t_c = critical headway (sec)
t_f = follow up headway (sec)



$$c_4 = \frac{v_{c,4} e^{-v_{c,4} t_{c,4}/3600}}{1 - e^{-v_{c,4} t_{f,4}/3600}}$$

capacity for movement 4

$$c_4 = \frac{600 e^{-(600)(4.1)/3600}}{1 - e^{-(600)(2.2)/3600}}$$

$$c_4 = 987\ veh/hr$$

$$\frac{v_4}{c_4} = \frac{100\ veh/hr}{987\ veh/hr} = 0.101$$

volume-to-capacity ratio for movement 4

Table 3-6. Given conditions for Example Calculation 3-4

Movement	Volume (veh/hr)	Rank	t_c (sec/veh)	t_f (sec/veh)
2	600	1	-	-
4	100	2	4.1	2.2
7	50	3	7.1	3.5

5. Scenario 3-2. Calculating the Capacity of Each Movement for a T-Intersection

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

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t_c = critical headway (sec)
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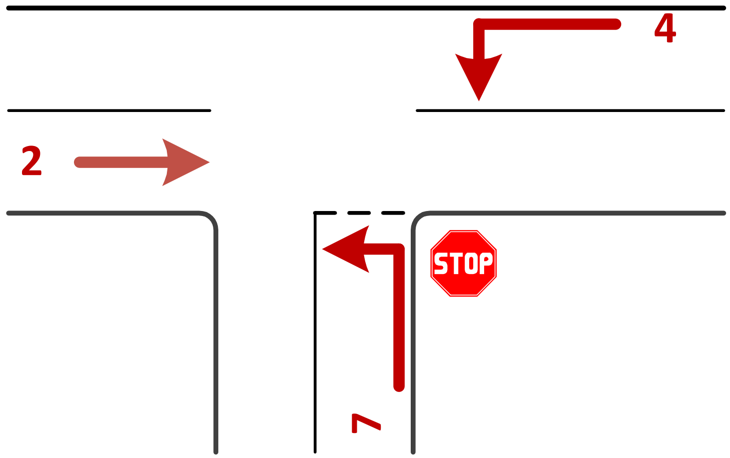


$$c_7 = \frac{v_{c,7} e^{-v_{c,7} t_{c,7}/3600}}{1 - e^{-v_{c,4} t_{f,4}/3600}}$$

$$c_7 = \frac{800 e^{-(600)(7.1)/3600}}{1 - e^{-(600)(3.5)/3600}}$$

$$c_7 = 306\ veh/hr$$

$$c_{p,7} = 306\ veh/hr$$

Table 3-6. Given conditions for Example Calculation 3-4

Movement	Volume (veh/hr)	Rank	t_c (sec/veh)	t_f (sec/veh)
2	600	1	-	-
4	100	2	4.1	2.2
7	50	3	7.1	3.5

5. Scenario 3-2. Calculating the Capacity of Each Movement for a T-Intersection

$$c_{p,7} = 306\ veh/hr$$

Potential capacity movement 7

$$\frac{v_4}{c_4} = \frac{100\ veh/hr}{987\ veh/hr} = 0.101$$

Probability of queue for movement 4

$$p_{0,4} = 1 - \frac{v_4}{c_4} = 1 - 0.101 = 0.899$$

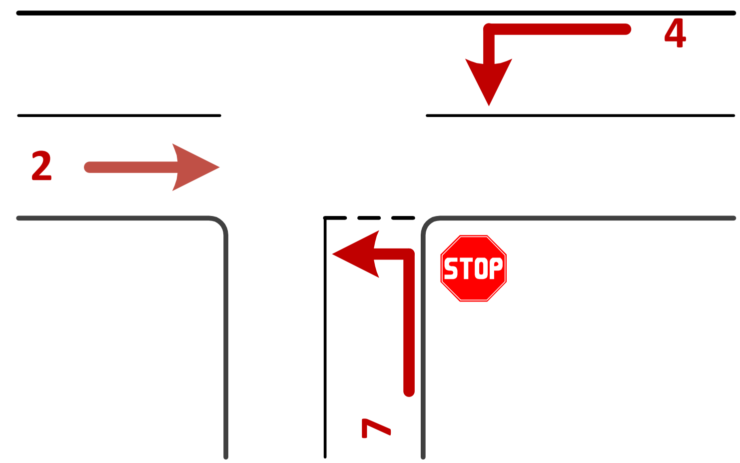
Probability of queue-free state for movement 4

$$c_{m,7} = \left(1 - \frac{v_4}{c_4}\right) c_{p,7}$$

Movement capacity Movement 7

$$c_{m,7} = (0.899)\,(306) = 275\ veh/hr$$

Movement capacity movement 7



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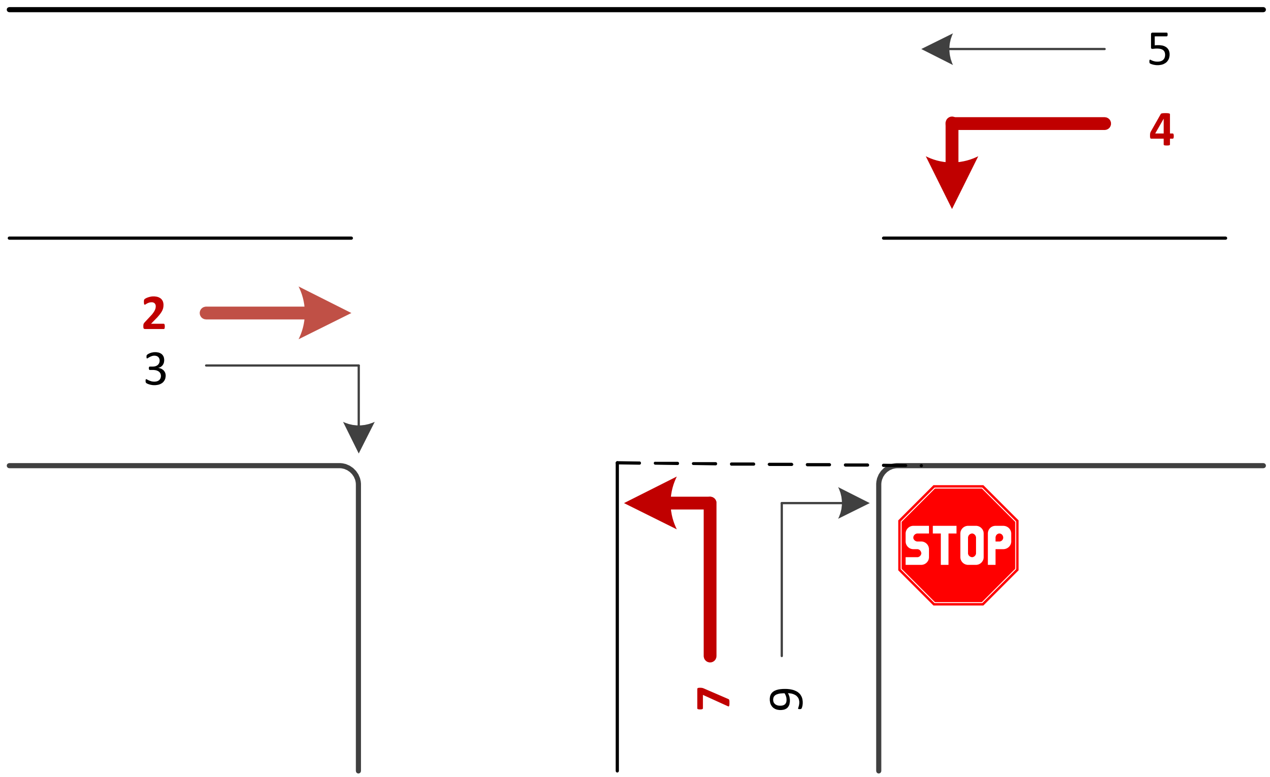

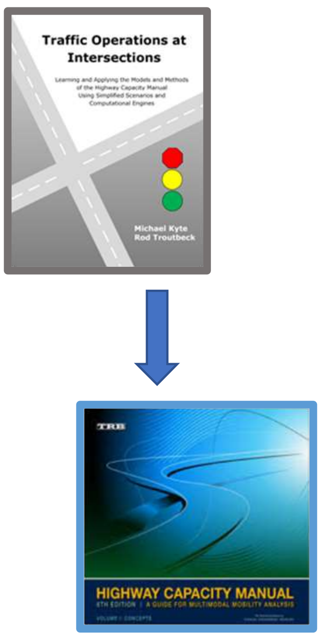

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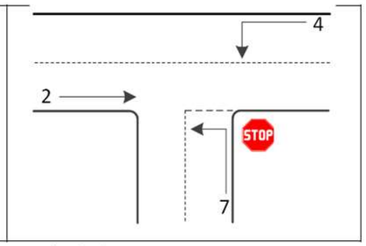
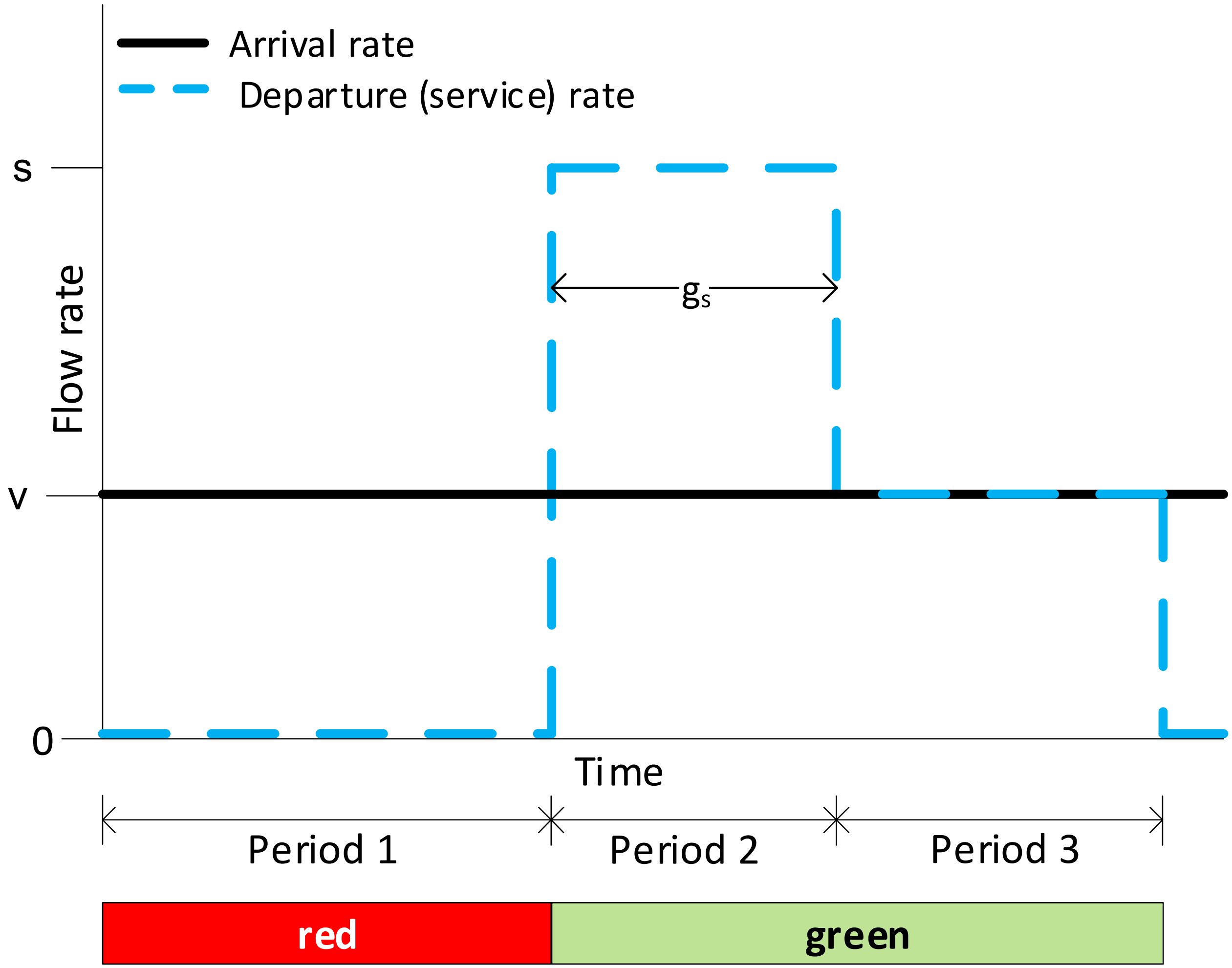
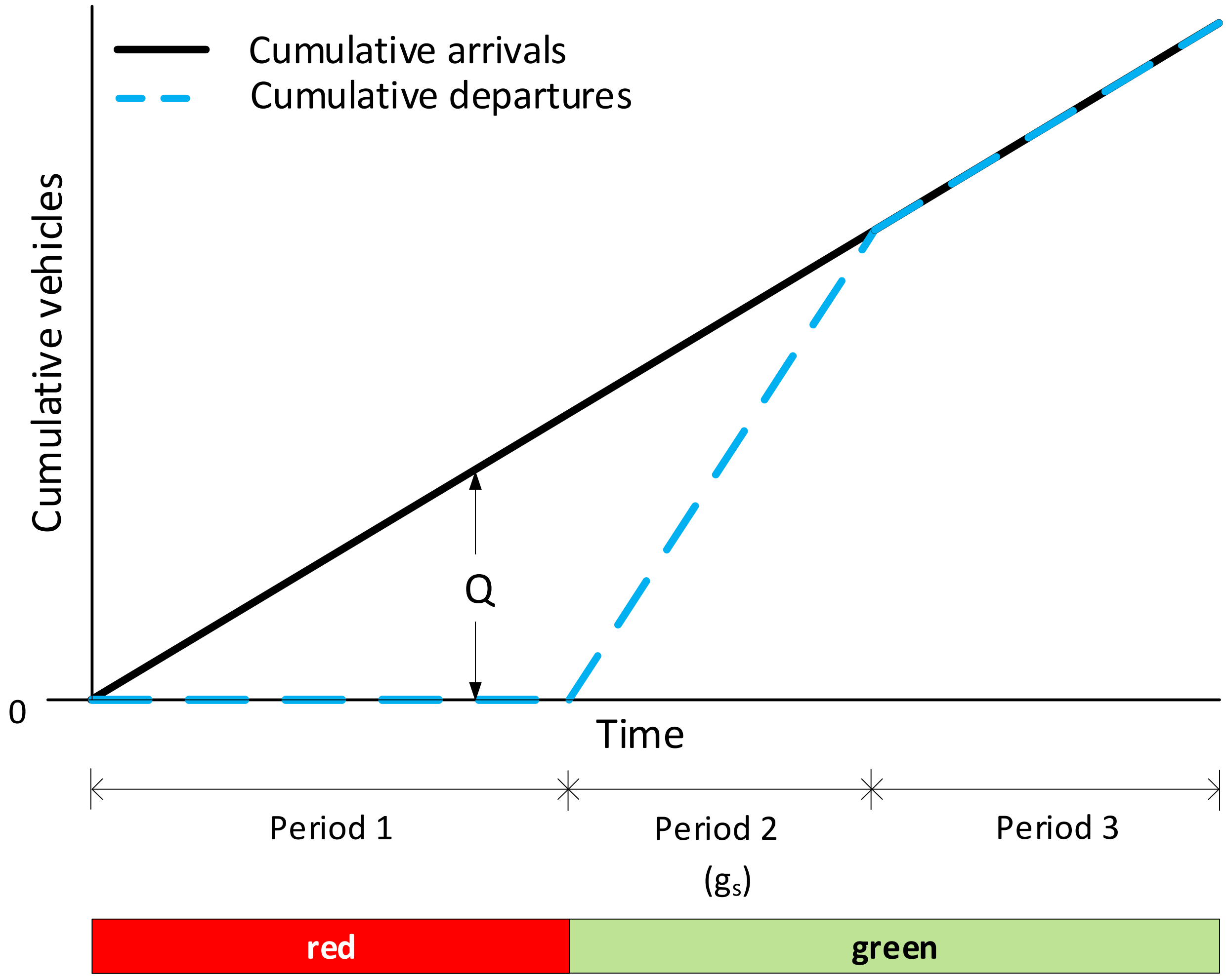


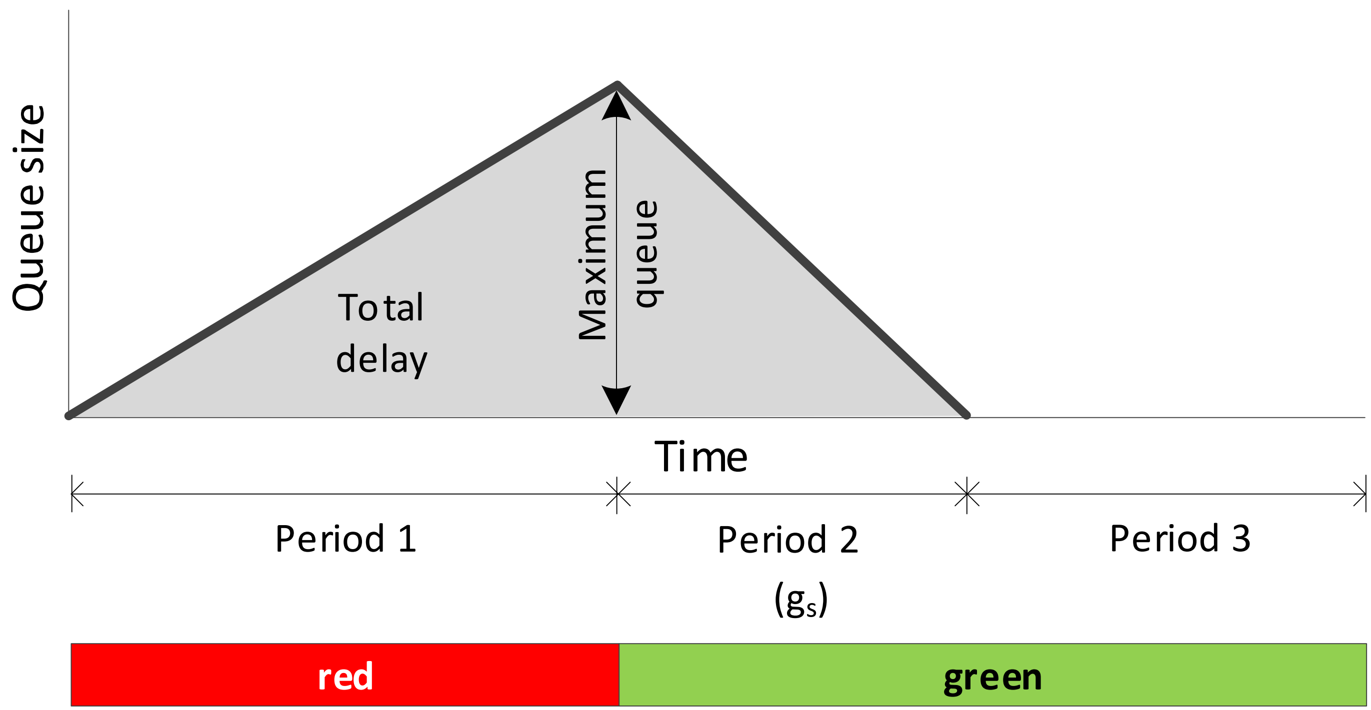
Figure 3-8. Scenario 3-2

The Big Picture

- What is impedance?
- How does movement 4 impede movement 7?
- How does this impedance affect the capacity for movement 7?


Arrival rate
Departure (service) rate
s
v
0
Flow rate
gs
Time
Period 1
Period 2
Period 3
red
green


Cumulative arrivals
Cumulative departures
Cumulative vehicles
Q
0
Time
Period 1
Period 2
(gs)
Period 3
red
green


Queue size
Total
delay
Maximum
queue
Time
Period 1
Period 2
(g$_s$)
Period 3
red
green

Topics for today

- Check-in
- Diving in: Exploring the simplified scenarios
  - Scenario 3-2 – impedance
  - **Scenario 4.1 – capacity of a lane**
  - Scenario 4.4 – critical movement analysis
  - Scenario 4.2 – predicting delay
- Check-out and closure

6. Scenario 4-1. Calculating the Capacity of a Lane

- Pretimed
- Demand < capacity
- TH movements only
- Uniform arrivals
- Isolated

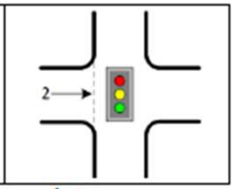


Figure 4-36. Scenario 4-1

The Big Picture

- How do we calculate capacity of a lane at a signalized intersection?
- We measure or predict green times, we measure or predict cycle length, and we measure or predict the saturation flow rate.
- Simply put, the capacity is the product of the green ratio (green time divided by cycle length) and the saturation flow rate.

Terms We Will Use

- Green time
- Cycle length
- Green ratio
- Saturation flow rate

6. Scenario 4-1. Calculating the Capacity of a Lane

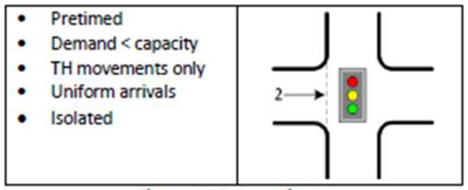
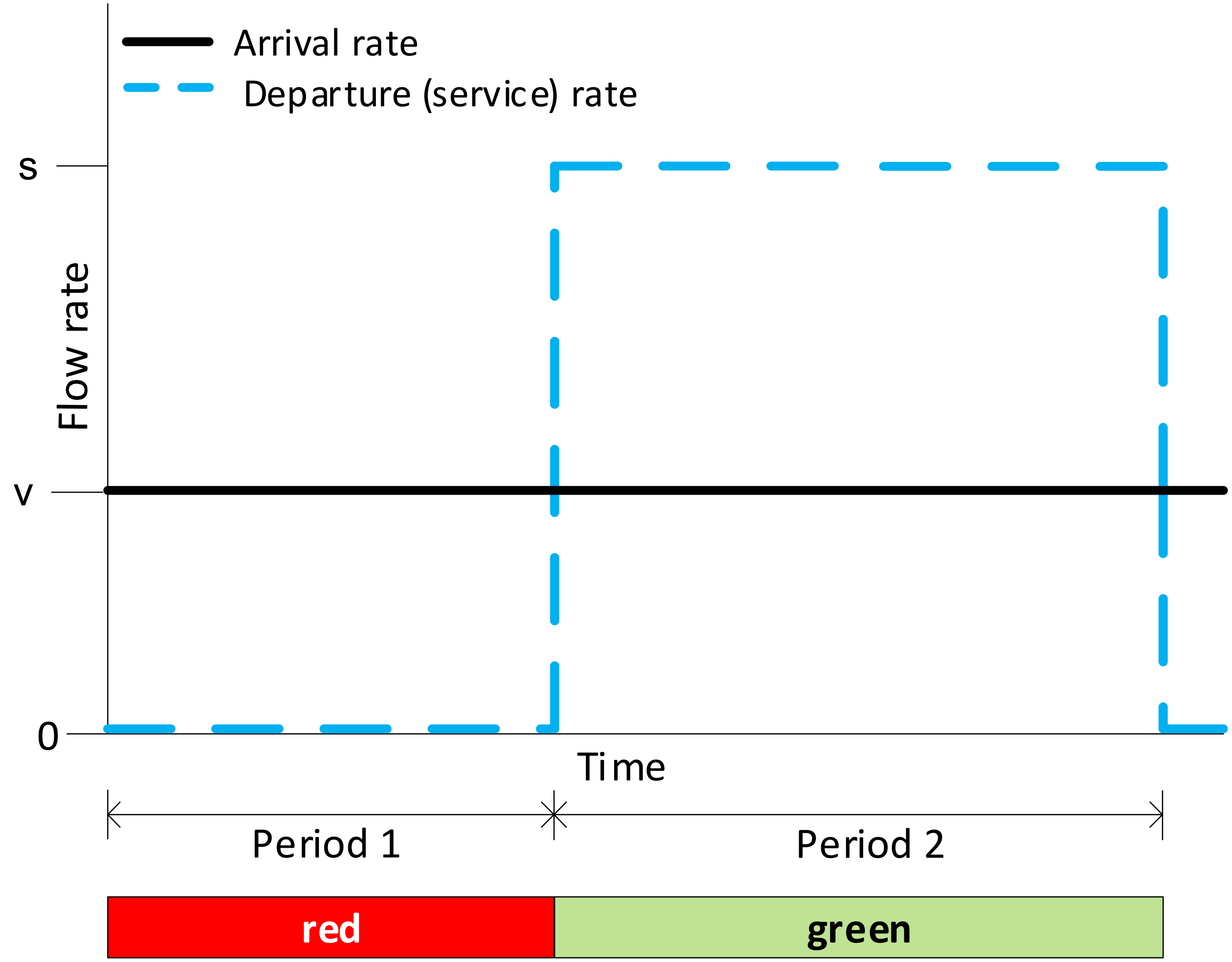


Figure 4-36. Scenario 4-1

$$c = s\left(\frac{g}{C}\right)$$

c = capacity, veh/hr
s = saturation flow rate, veh/hr
g = effective green time, sec
C = cycle length, sec



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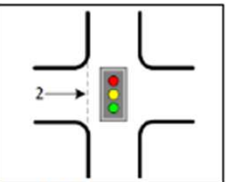

Figure 4-36. Scenario 4-1

Example Calculation 4-9. Determining Lane Capacity

For one lane of a signalized intersection (Figure 4-38), the saturation flow rate is 1900 vehicles per hour. The green is displayed for 15 sec, while the yellow time is 4 sec and the red clearance time is 1 sec. The lost time per phase is 4 sec. There are 60 cycles in one hour. What is the capacity of the lane?

$$C = \frac{3600\ sec/hr}{60\ cycles/hr} = 60\ sec$$

6. Scenario 4-1. Calculating the Capacity of a Lane

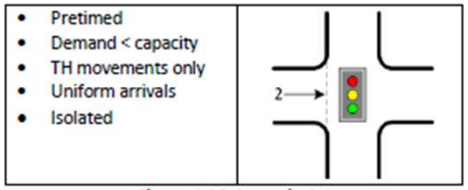

Figure 4-36. Scenario 4-1

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$$D_p = G + Y + R_c$$

$$D_p = 15 + 4 + 1 = 20\ sec$$

D_p = phase duration, sec
G = displayed green, sec
Y = displayed yellow, sec
R_c = red clearance time, sec
R = displayed red, sec

$$g = G + Y + R_c - l_t$$

$$g = 15 + 4 + 1 - 4 = 16\ sec$$

6. Scenario 4-1. Calculating the Capacity of a Lane

- Pretimed
- Demand < capacity
- TH movements only
- Uniform arrivals
- Isolated

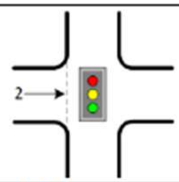

Figure 4-36. Scenario 4-1

Example Calculation 4-9. Determining Lane Capacity

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g/C = (16 sec)/(60 sec) = 0.27 green ratio

$c = s\left(\frac{g}{C}\right)$ = (1900)(0.27) = 513 veh/hr capacity

6. Scenario 4-1. Calculating the Capacity of a Lane

- Pretimed
- Demand < capacity
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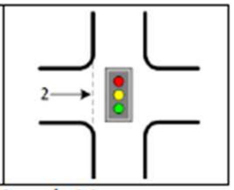

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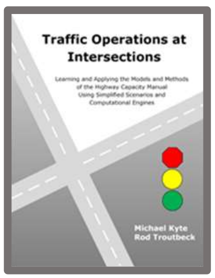

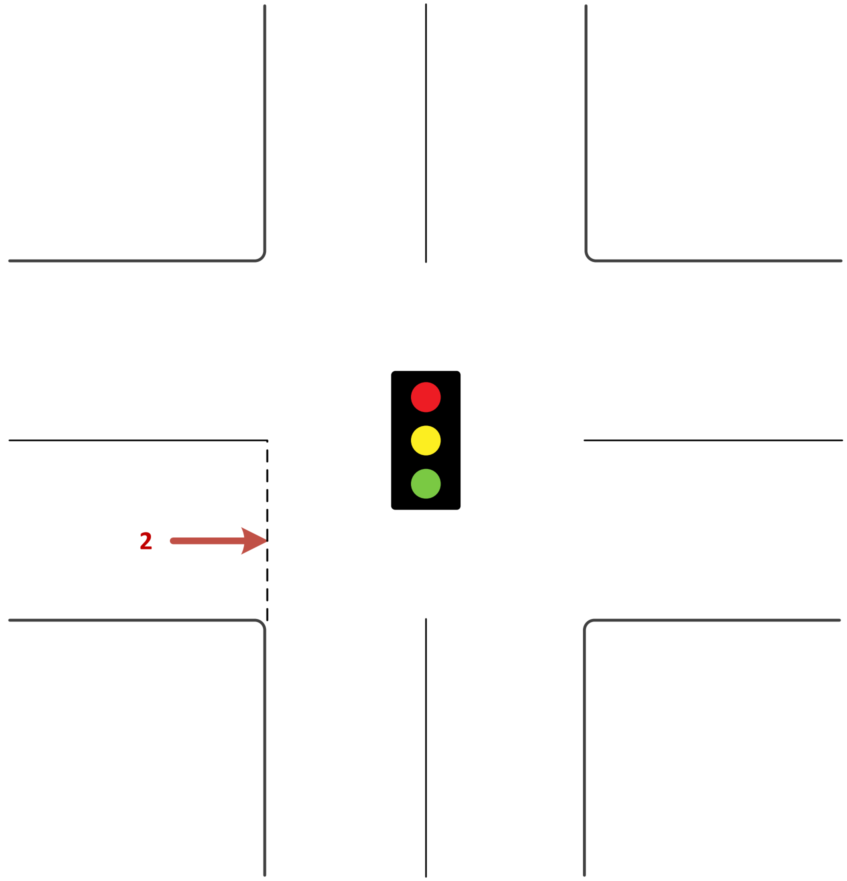

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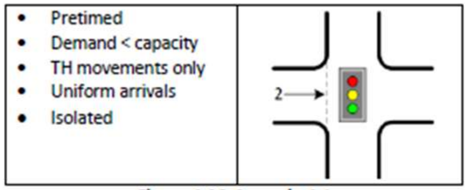

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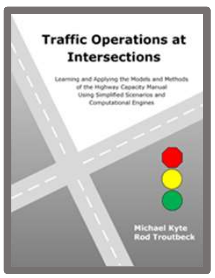

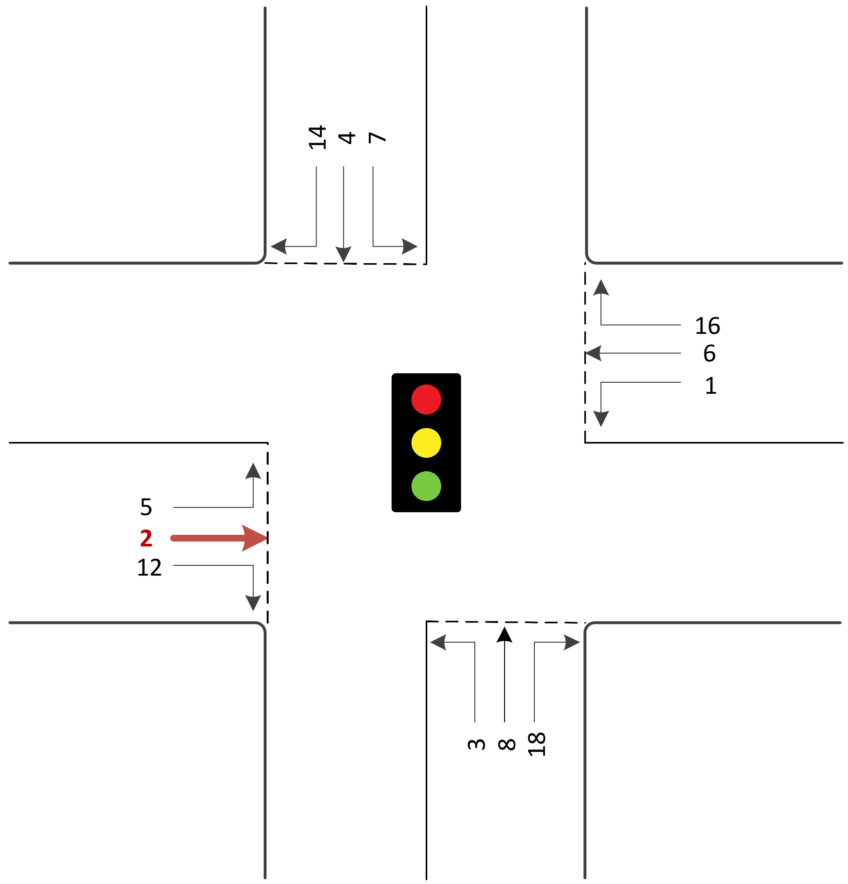

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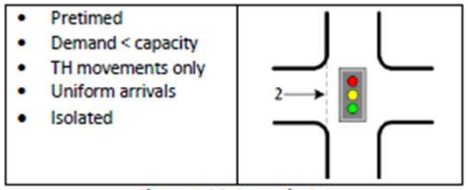

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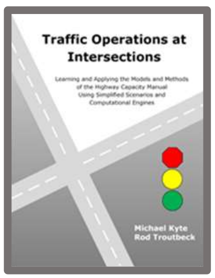

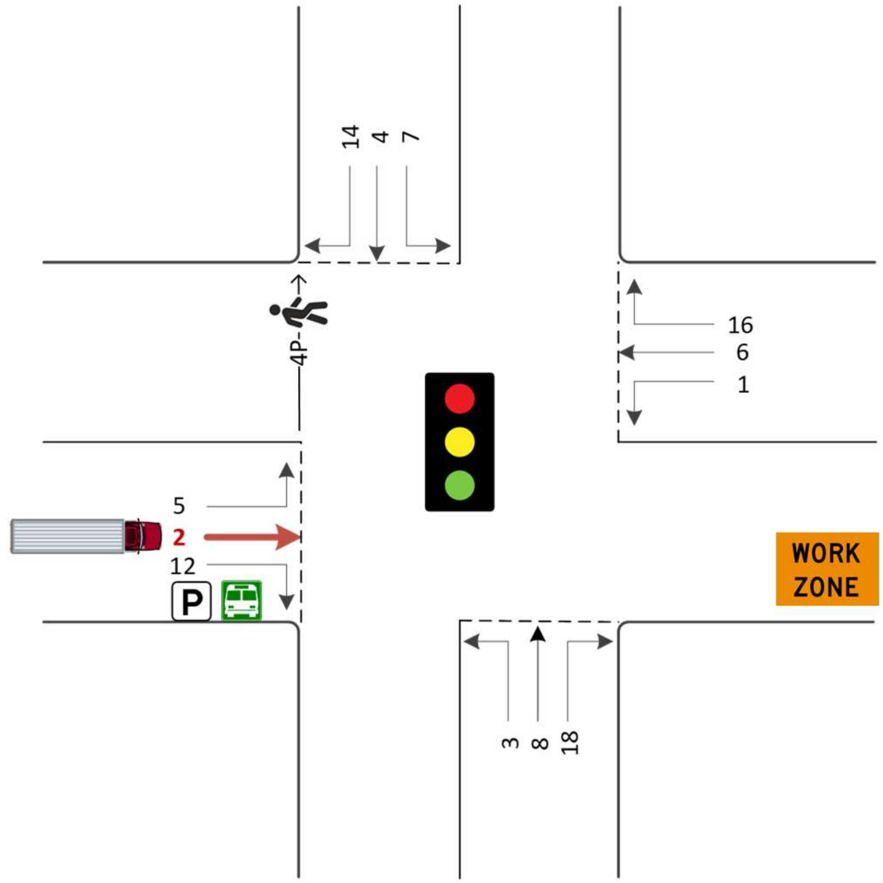

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- Pretimed
- Demand < capacity
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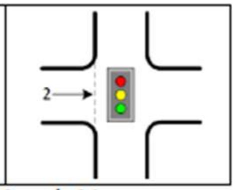
- Uniform arrivals
- Isolated



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- Simply put, the capacity is the product of the green ratio (green time divided by cycle length) and the saturation flow rate.

Topics for today

- Check-in
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    - Scenario 3-2 – impedance
    - Scenario 4.1 – capacity of a lane
    - **Scenario 4.4 – critical movement analysis**
    - Scenario 4.2 – predicting delay
- Check-out and closure

9. Scenario 4-4. Calculating the Capacity Utilization of an Intersection Using Critical Movement Analysis

- Pretimed
- Demand < capacity
- Protected or permitted LTs
- Uniform arrivals
- Isolated

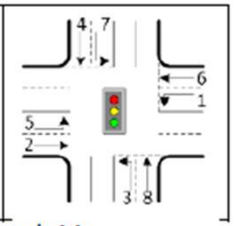


Figure 4-51. Scenario 4-4

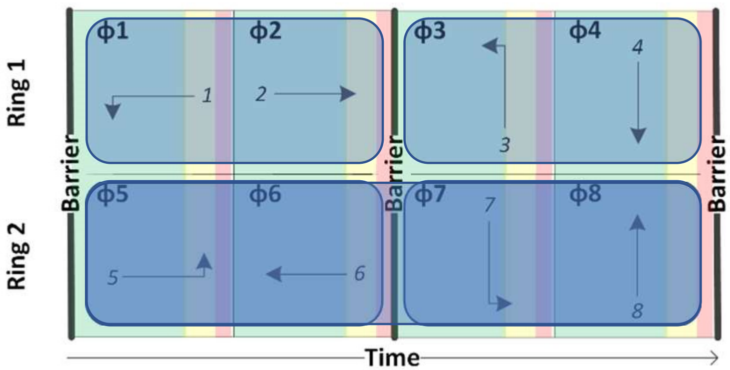
The Big Picture

- Does our intersection design provide sufficient capacity to accommodate the projected or measured traffic volumes?

Terms We Will Use

- Flow ratio
- Capacity utilization
- Lost time

9. Scenario 4-4. Calculating the Capacity Utilization of an Intersection Using Critical Movement Analysis



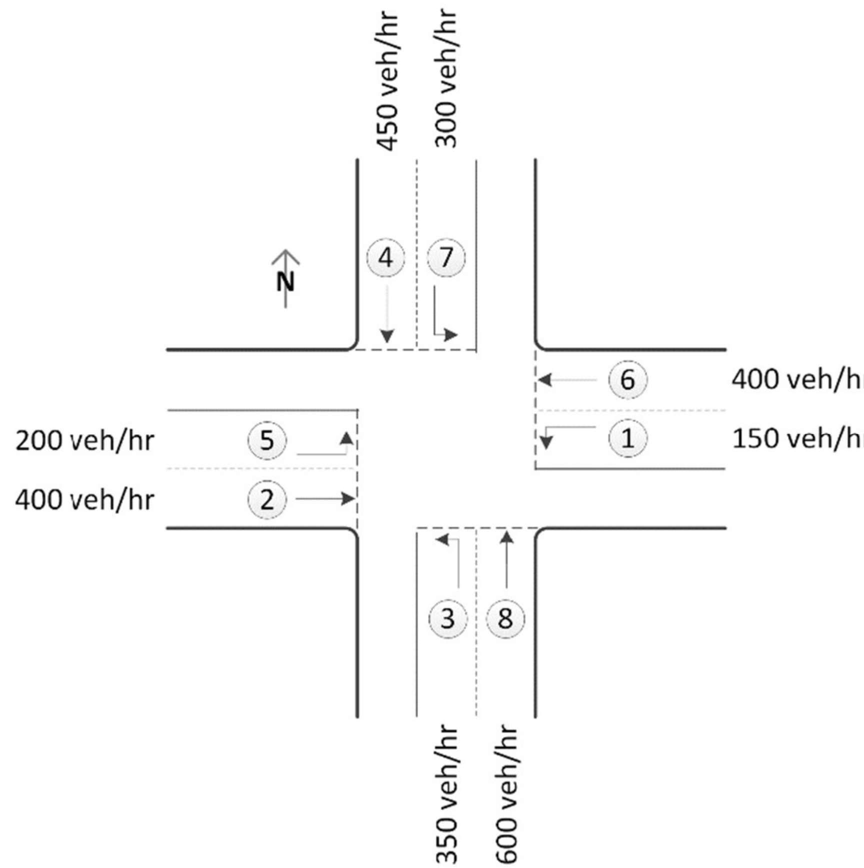
1 + 2 = 150 + 400 = 550 veh/hr

5 + 6 = 200 + 400 = 600 veh/hr

3 + 4 = 350 + 300 = 650 veh/hr

7 + 8 = 300 + 600 = 900 veh/hr

(5 + 6) + (7 + 8) = 600 + 900 = 1500 veh/hr



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- Demand < capacity
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- Isolated

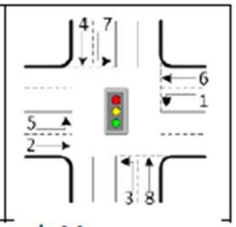
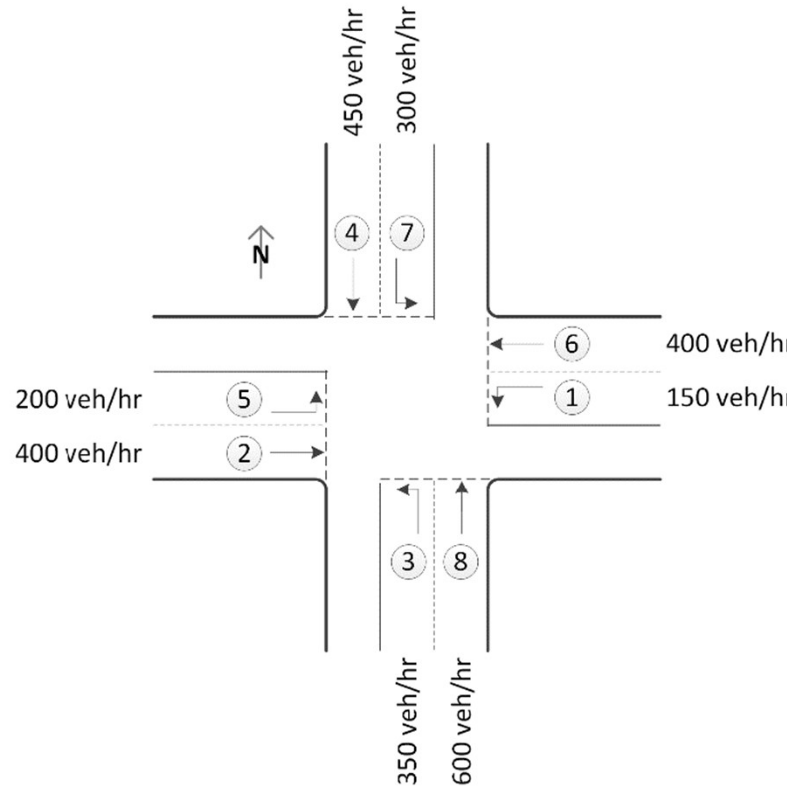


Figure 4-51. Scenario 4-4



9. Scenario 4-4. Calculating the Capacity Utilization of an Intersection Using Critical Movement Analysis

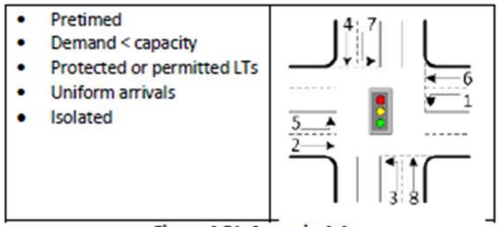


Figure 4-51. Scenario 4-4

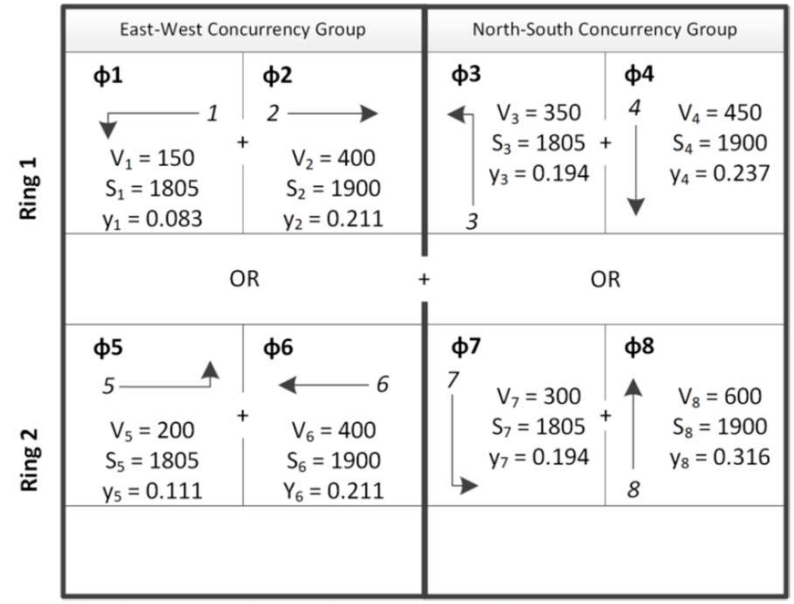


Figure 4-59. Flow ratios for each movement for Example Calculation 4-15

Concept:

- Flow ratio: proportion of the hour required to serve the given demand

$y = v/s$

v = arrival volume, veh/hr
s = saturation flow rate, veh/hr
y = flow ratio

9. Scenario 4-4. Calculating the Capacity Utilization of an Intersection Using Critical Movement Analysis

- Pretimed
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Figure 4-51. Scenario 4-4

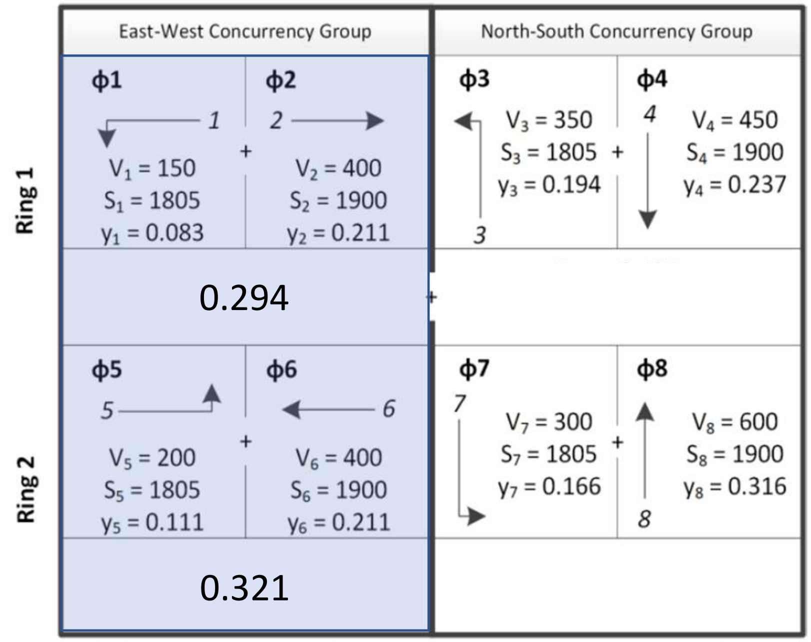

Figure 4-59. Flow ratios for each movement for Example Calculation 4-15

9. Scenario 4-4. Calculating the Capacity Utilization of an Intersection Using Critical Movement Analysis

- Pretimed
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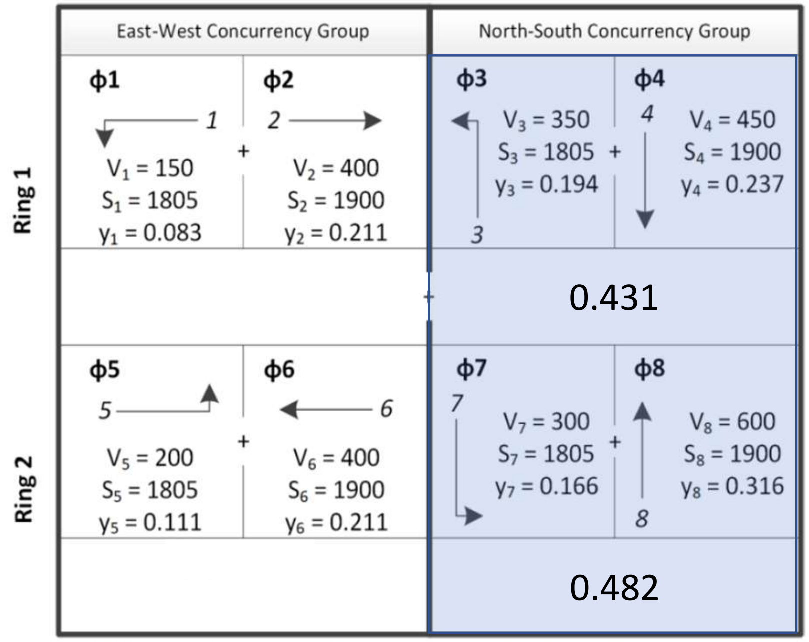
Figure 4-51. Scenario 4-4



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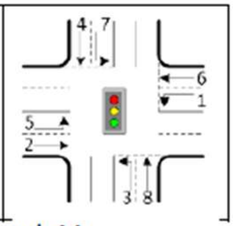
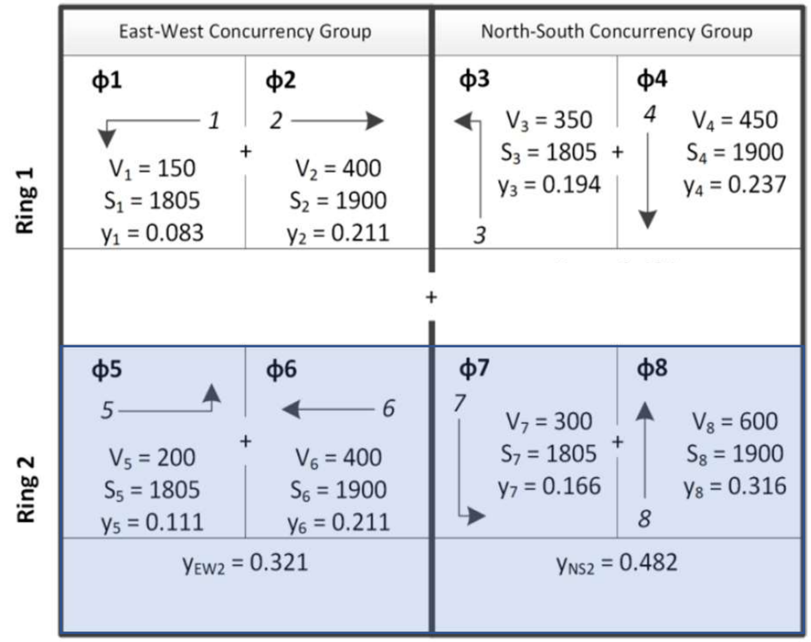


Figure 4-51. Scenario 4-4



sum = 0.803

Figure 4-59. Flow ratios for each movement for Example Calculation 4-15

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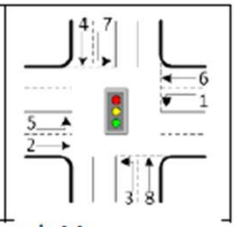
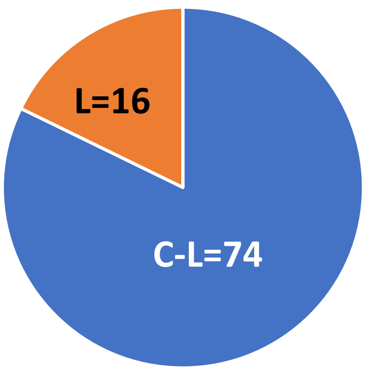


Figure 4-51. Scenario 4-4



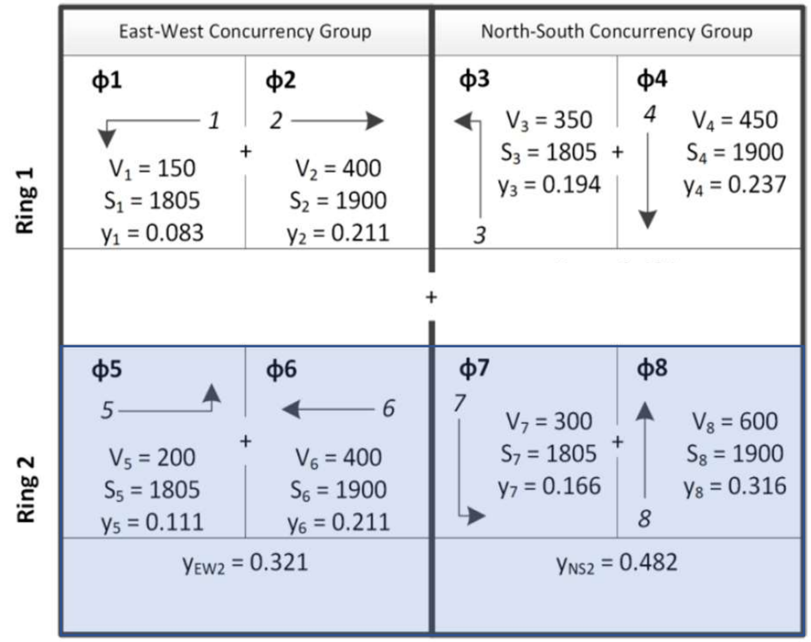


Figure 4-59. Flow ratios for each movement for Example Calculation 4-15

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

$$X_c = \frac{(0.321 + 0.482)}{74/90} = \left(\frac{0.803}{0.82}\right) = 0.98$$

X_c = critical volume-to-capacity ratio

y_{EW}-critical = critical flow ratio for EW

y_{NS}-critical = critical flow ratio for NS

C = cycle length, sec

L = lost time per phase, sec

9. Scenario 4-4. Calculating the Capacity Utilization of an Intersection Using Critical Movement Analysis

- Pretimed
- Demand < capacity
- Protected or permitted LTs
- Uniform arrivals
- Isolated

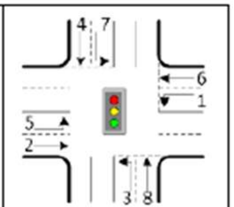


Figure 4-51. Scenario 4-4

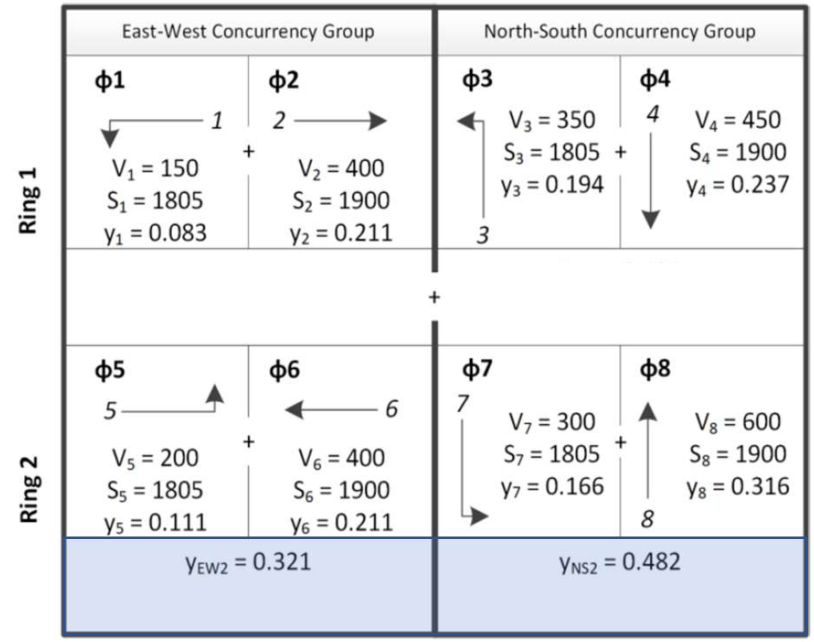


Figure 4-59. Flow ratios for each movement for Example Calculation 4-15

0.98

Table 4-6. Sufficiency of capacity

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

9. Scenario 4-4. Calculating the Capacity Utilization of an Intersection Using Critical Movement Analysis

- Pretimed
- Demand < capacity
- Protected or permitted LTs
- Uniform arrivals
- Isolated

Figure 4-51. Scenario 4-4

The Big Picture

- Does our intersection design provide sufficient capacity to accommodate the projected or measured traffic volumes?

Topics for today

- Check-in
- Diving in: Exploring the simplified scenarios
  - Scenario 3-2 – impedance
  - Scenario 4.1 – capacity of a lane
  - Scenario 4.4 – critical movement analysis
  - **Scenario 4.2 – predicting delay**
- Check-out and closure

7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

- Pretimed
- Demand < capacity
- TH movements only
- Uniform arrivals
- Isolated

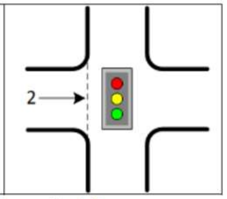


Figure 4-39. Scenario 4-2

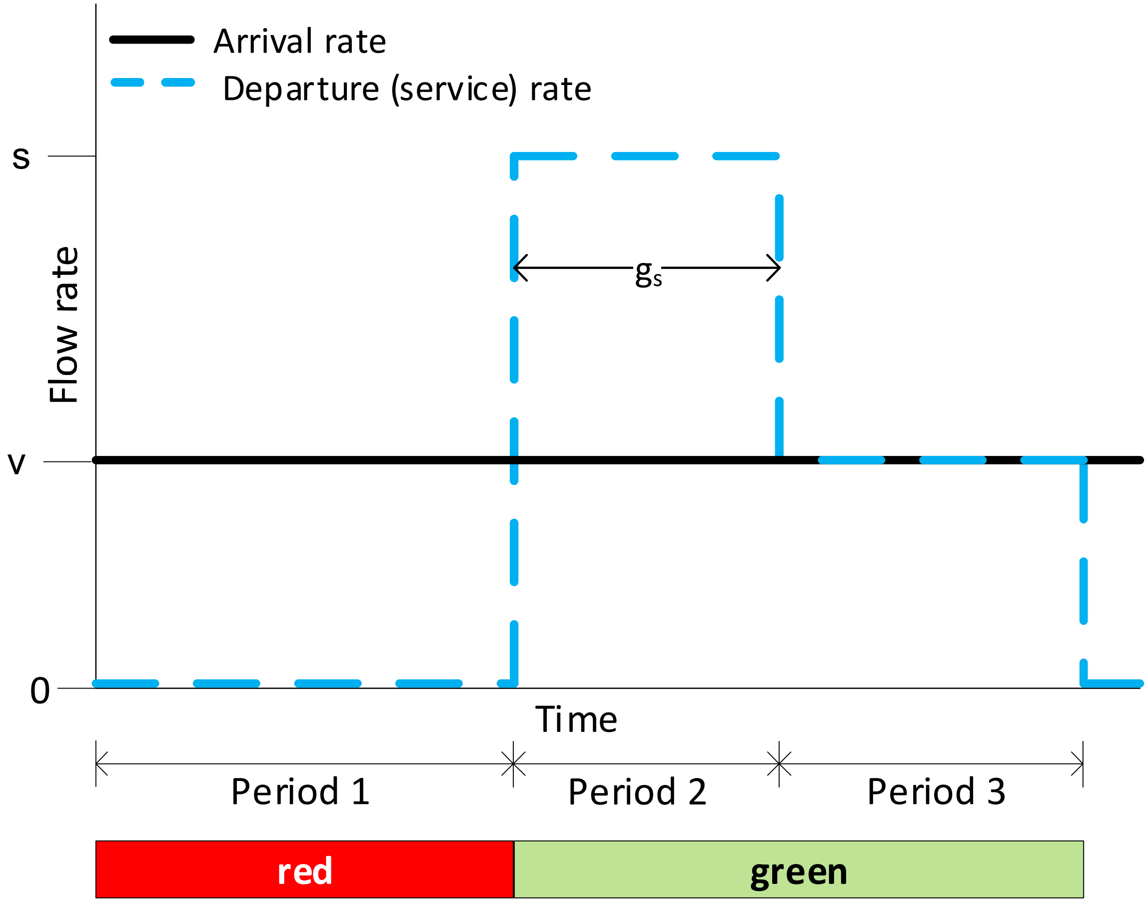
The Big Picture

- We assume that volume is less than capacity.
- We assume uniform flow (rates).
- The total delay during one cycle is the area of the QAP.
- The average delay per vehicle is the total delay divided by the number of vehicles served during the cycle.

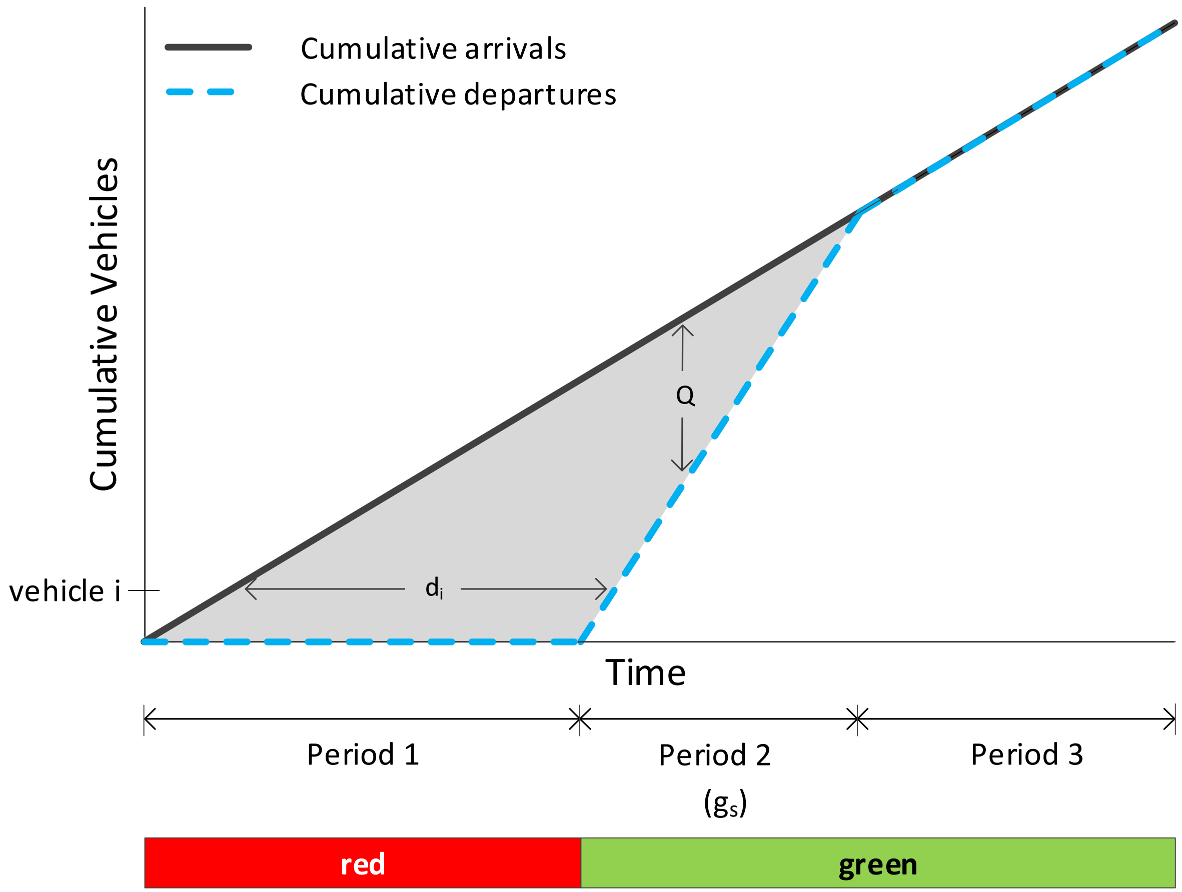
Terms We Will Use

- Queue size
- Total delay
- Average (control) delay

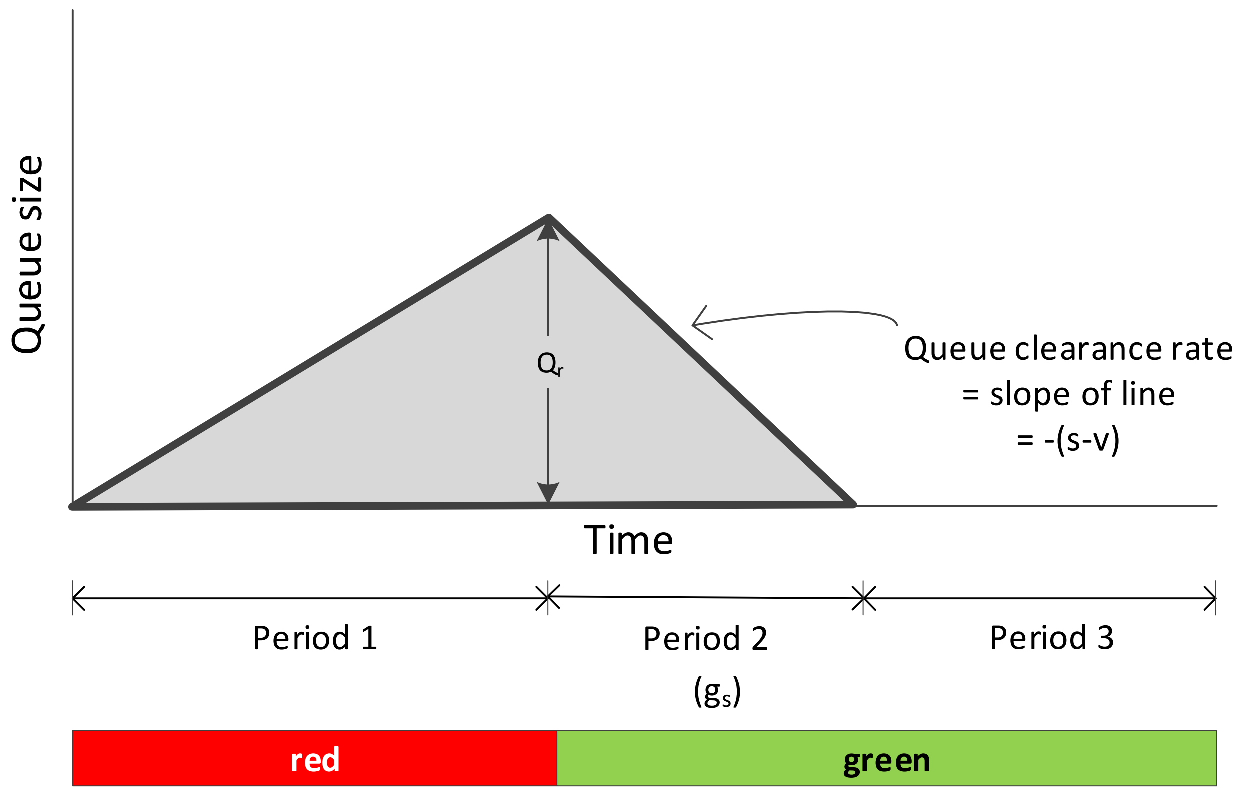
7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity



7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

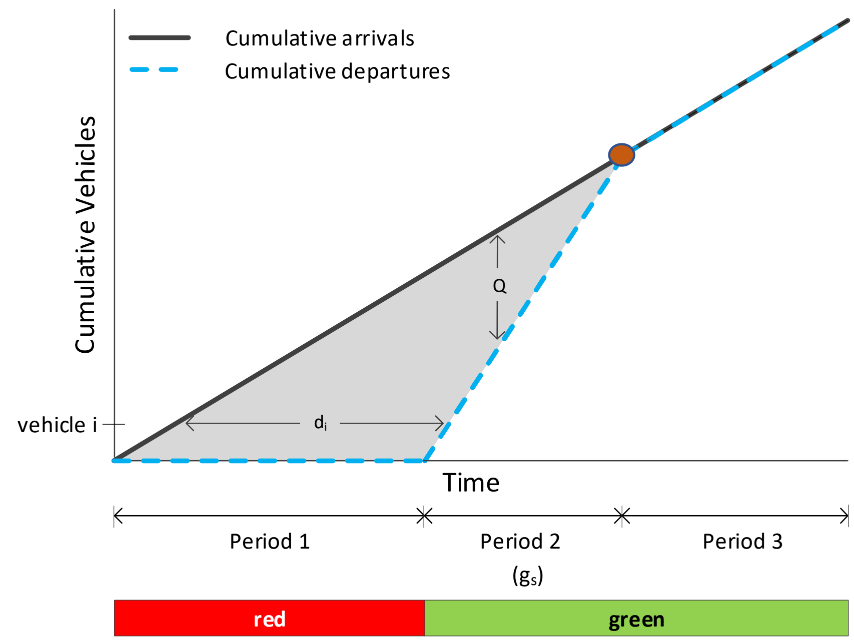


7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity



7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

$v(r + g_s) = sg_s$	When queue clears: number of arrivals equals number of departures
$g_s = \dfrac{vr}{s - v}$	Queue service time
$D_t = (0.5)(r)(vr + vg_s)$	Total delay (area of triangle)
vC	Vehicle arrivals or departures during cycle
$d_{avg} = 0.5r\left[\dfrac{1 - g/C}{1 - v/s}\right]$	Average (uniform) delay per vehicle



7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

$$v(r + g_s) = s g_s$$

When queue clears: number of arrivals equals number of departures

$$g_s = \frac{vr}{s - v}$$

Queue service time

$$D_t = (0.5)(vr)(r + g_s)$$

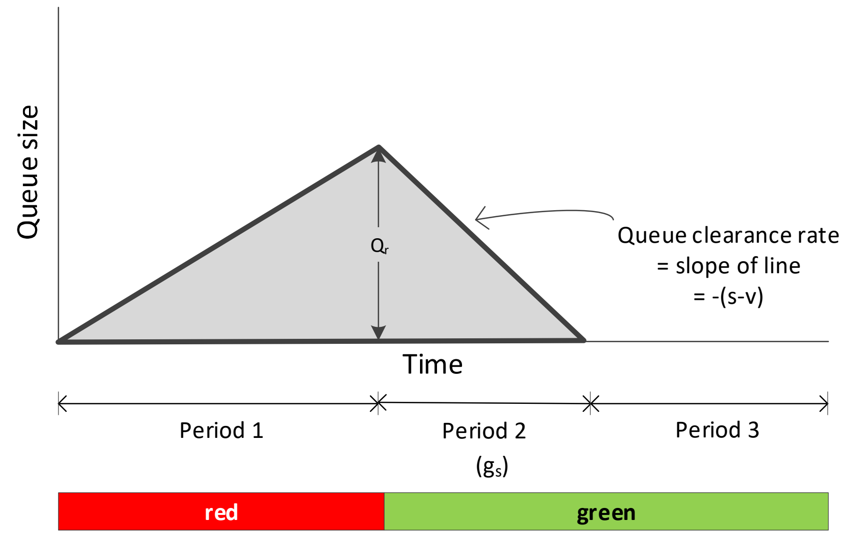
Total delay (area of triangle)

$$vC$$

Vehicle arrivals or departures during cycle

$$d_{avg} = 0.5r\left[\frac{1 - g/C}{1 - v/s}\right]$$

Average (uniform) delay per vehicle



7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

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

Given data:

- Arrival rate = 630 veh/hr
- s = 1900 veh/hr
- C = 100 sec
- r = 60 sec
- g = 40 sec

capacity

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

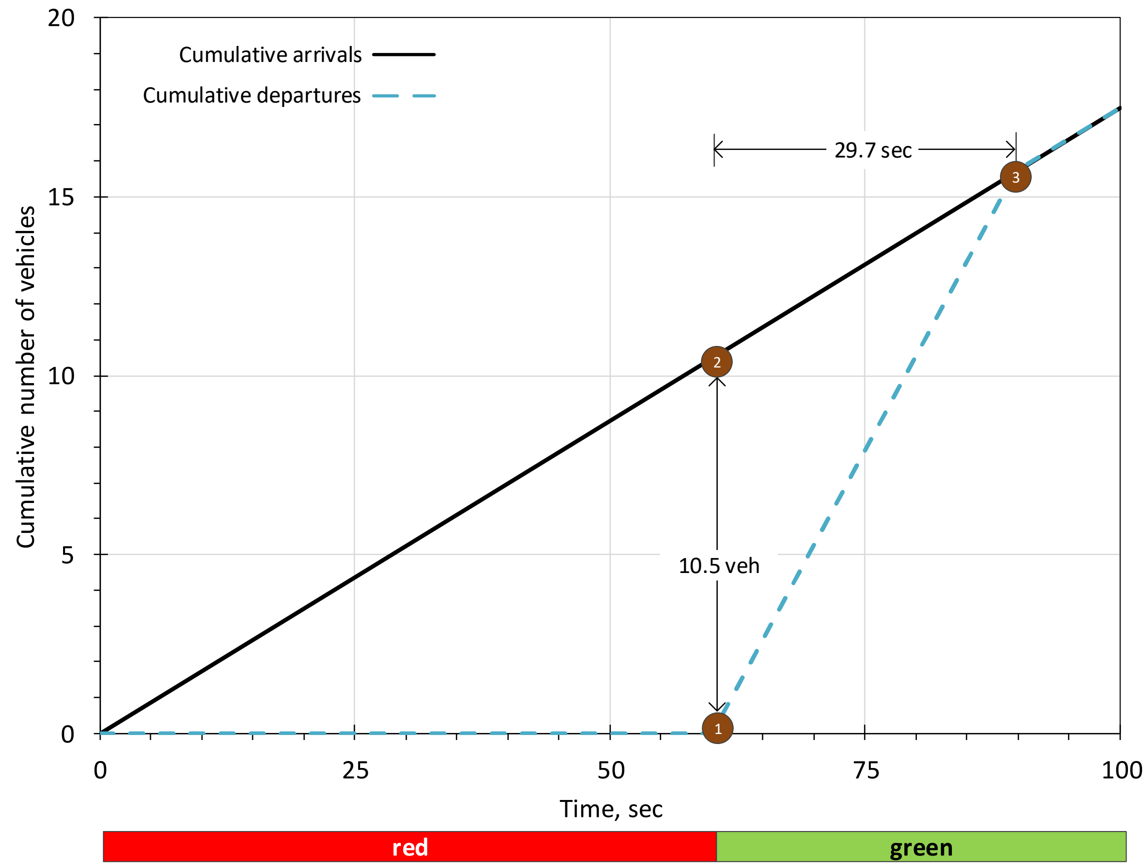
queue service time

$$g_s = \frac{vr}{s - v} = \frac{(630)(60)}{(1900\ - 630)} = 29.7\ sec\ sec$$

7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

$$Q_{max} = (v)(r) = (630/3600)(60) = 10.5\ veh$$

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



7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

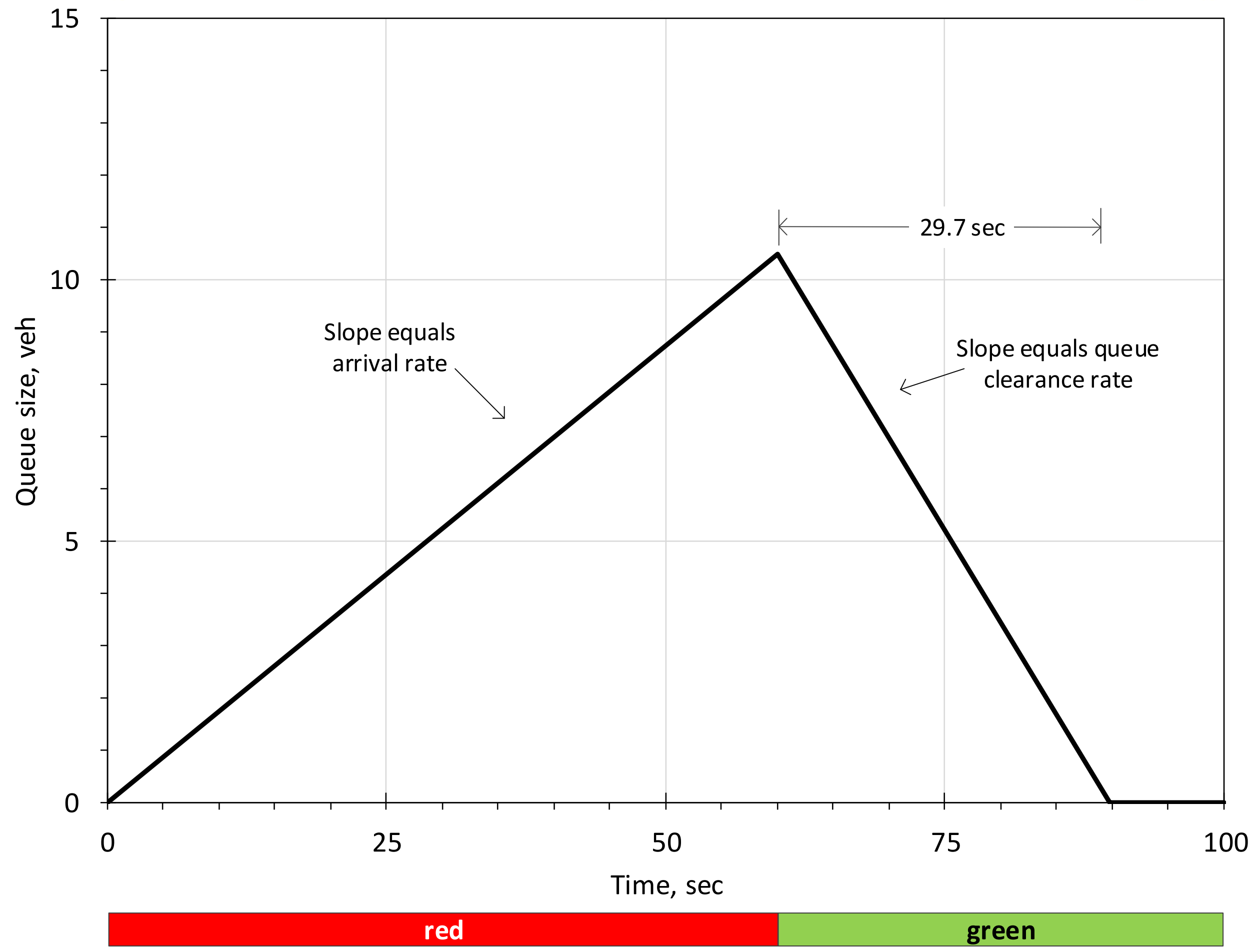
Average uniform delay

$$d_{avg} = 0.5r\left[\frac{1 - g/C}{1 - v/s}\right]$$

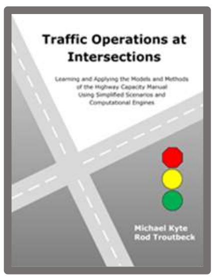
$$d_{avg} = (0.5)(60)\left[\frac{1 - 40/100}{1 - 630/1900}\right]$$

$$d_{avg} = 26.9\ sec/veh$$

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



7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity



INTERSECTION CONTROL DELAY WORKSHEET

General Information

Analyst ______
Agency or Company ______
Date Performed ______
Analysis Time Period ______

Site Information

Intersection ______
Area Type ☐ CBD ☐ Other
Jurisdiction ______
Analysis Year ______

Input Initial Parameters

Number of lanes, N ______
Approach speed, S_a (mi/h) ______
Survey count interval, I_s (s) ______
Total vehicles arriving, V_{tot} ______
Stopped-vehicle count, V_{stop} ______
Cycle length, C (s) ______

Input Field Data

Clock Time	Cycle Number	Number of Vehicles in Queue									
		Count Interval									
		1	2	3	4	5	6	7	8	9	10
Total											

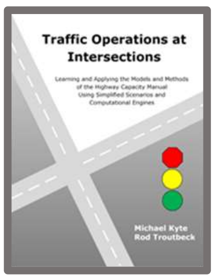
7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

Average control delay

$$d = d_1 + d_2 + d_3$$

Uniform delay

$$d_1 = PF\,\frac{0.5\,C(1-g/C)^2}{1-[\min(1,X)\,g/C]}$$



Incremental delay

$$d_2 = 900\,T\left[(X_A-1)+\sqrt{(X_A-1)^2+\frac{8\,k\,I\,X_A}{c_A\,T}}\right]$$

Initial queue delay

$$d_3 = \frac{3{,}600}{v\,T}\left(t_A\frac{Q_b+Q_e-Q_{eo}}{2}+\frac{Q_e^2-Q_{eo}^2}{2\,c_A}-\frac{Q_b^2}{2\,c_A}\right)$$

7. Scenario 4-2. Calculating Delay on a Lane When Demand is less than Capacity

- Pretimed
- Demand < capacity
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- Isolated

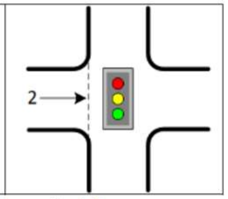

Figure 4-39. Scenario 4-2

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Topics for today

- Check-in
- Diving in: Exploring four simplified scenarios
  - Scenario 3-2 – impedance
  - Scenario 4.1 – capacity of a lane
  - Scenario 4.4 – critical movement analysis
  - Scenario 4.2 – predicting delay
- **Check-out and closure**

Final Questions