

Chapter 17: Basic principles of intersection signalization (objectives)

Chapter objectives: By the end of this chapter the student will be able to:

- Explain the meanings of the terms related to signalized intersections
- Explain the relationship among discharge headway, saturation flow, lost times, and capacity
- Explain the “critical lane” and “time budget” concepts
- Model left-turn vehicles in signal timing
- State the definitions of various delays taking place at signalized intersections
- Graph the relation between delay, waiting time, and queue length
- Explain three delay scenarios (uniform, random, oversaturate)
- Explain the component of Webster’s delay model
- Explain the concept behind the modeling of overflow delay
- Accept inconsistencies that exist between stochastic and overflow delay models

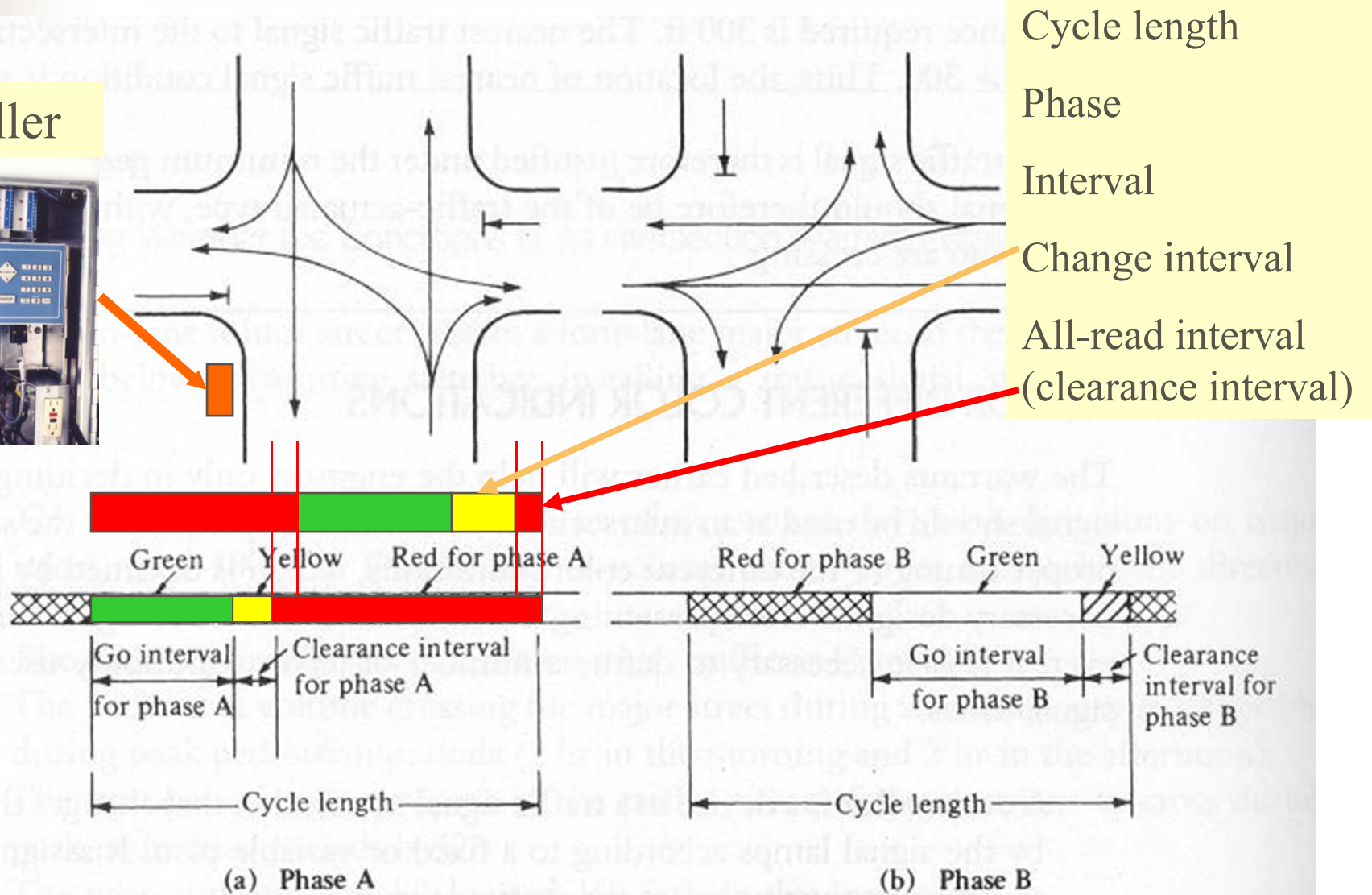


Four critical aspects of signalized intersection operation discussed in this chapter

1. Discharge headways, saturation flow rates, and lost times
2. Allocation of time and the critical lane concept
3. The concept of left-turn equivalency
4. Delay as a measure of service quality

17.1 Terms and Definitions

Controller



Signal timing with a pedestrian signal: Example

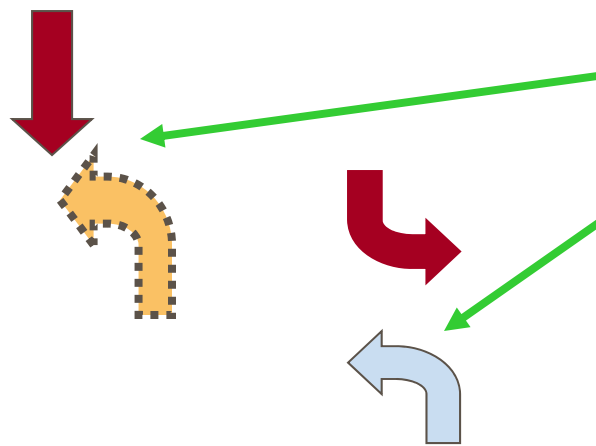
Interval	Pine St.		Oak St.		%
	Veh.	Ped.	Veh.	Ped.	
1	G-26	W-20	R-31	DW-31	36.4
2		FDW-6			10.9
3	Y-3.5	DW-29			6.4
4	R-25.5				AR 2.7
5			G-19	W-8	14.5
6				FDW-11	20.0
7		Y-3	DW-5	5.5	
8		R-2		AR 3.6	

Cycle length = 55 seconds

17.1.2 Signal operation modes and left-turn treatments & 17.1.3 Left-turn treatments

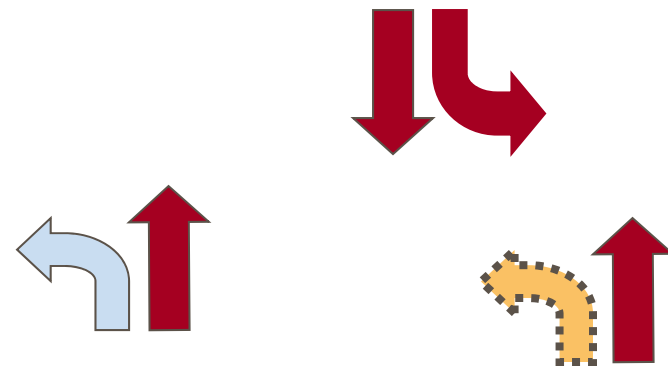
Operation modes:

- Pretimed (fixed) operation
- Semi-actuated operation
- Full-actuated operation
- Computer control



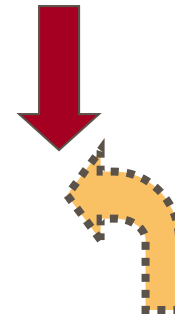
Left-turn treatments:

- ✱ Permitted left turns
- ✱ Protected left turns
- ✱ Protected/permitted (compound) or permitted/protected left turns



Factors affecting the permitted LT movement

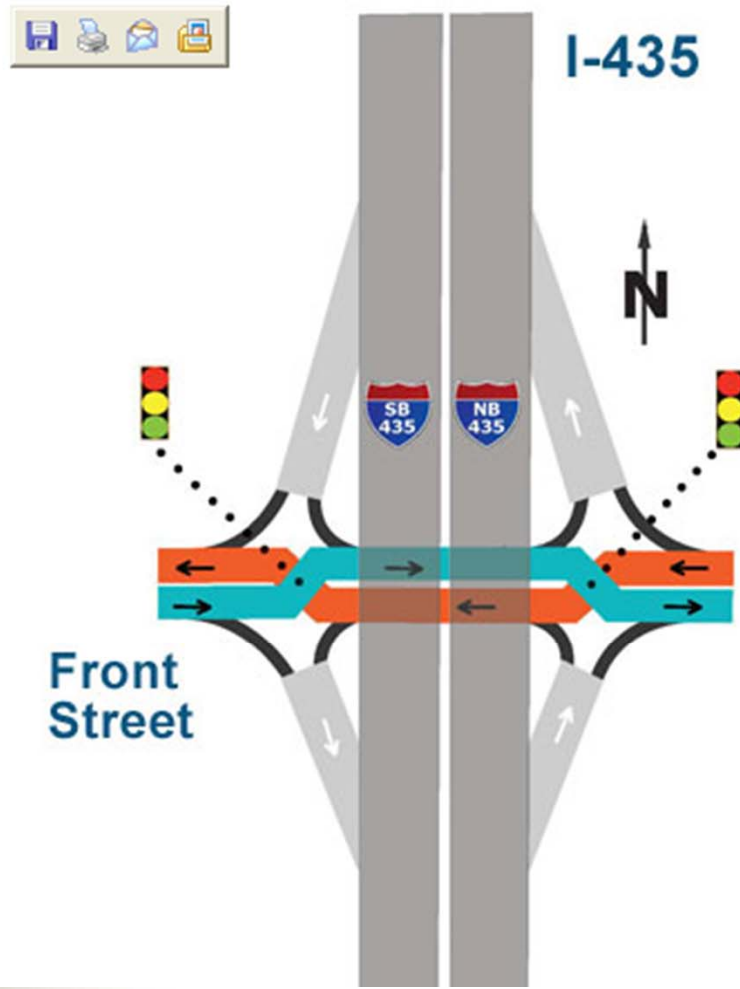
- LT flow rate
- Opposing flow rate
- Number of opposing lanes
- Whether LTs flow from an exclusive LT lane or from a shared lane
- Details of the signal timing



CFI (Continuous Flow Intersection)



DDI (Diverging Diamond Interchange)



An Innovative Design

The conventional diamond interchange at I-435 and



Watch the Videos:

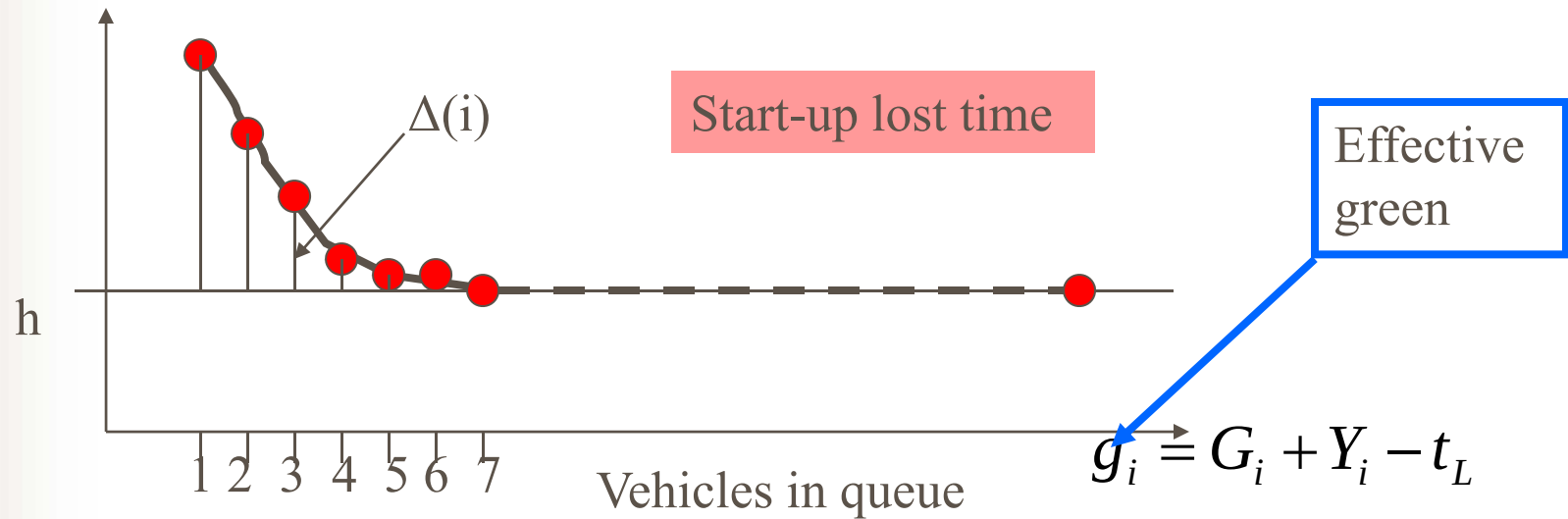
TRAVELING EAST ON FRONT ST.



Four basic mechanisms for building an analytic model or description of a signalized intersection

- Discharge headways at a signalized intersection
- The “critical lane” and “time budget” concepts
- The effects of LT vehicles
- Delay and other MOEs (like queue size and the number of stops)

17.2 Discharge headways, saturation flow, lost times, and capacity



$$S = \frac{3600}{h} \quad \text{Saturation flow rate}$$

$$l_1 = \sum \Delta(i)$$

$$T = l_1 + nh$$

(Show a simulation example)

Start-up lost time

Effective green

$$g_i = G_i + Y_i - t_L$$

$$Y_i = y_i + ar_i$$

$$t_L = l_1 + l_2$$

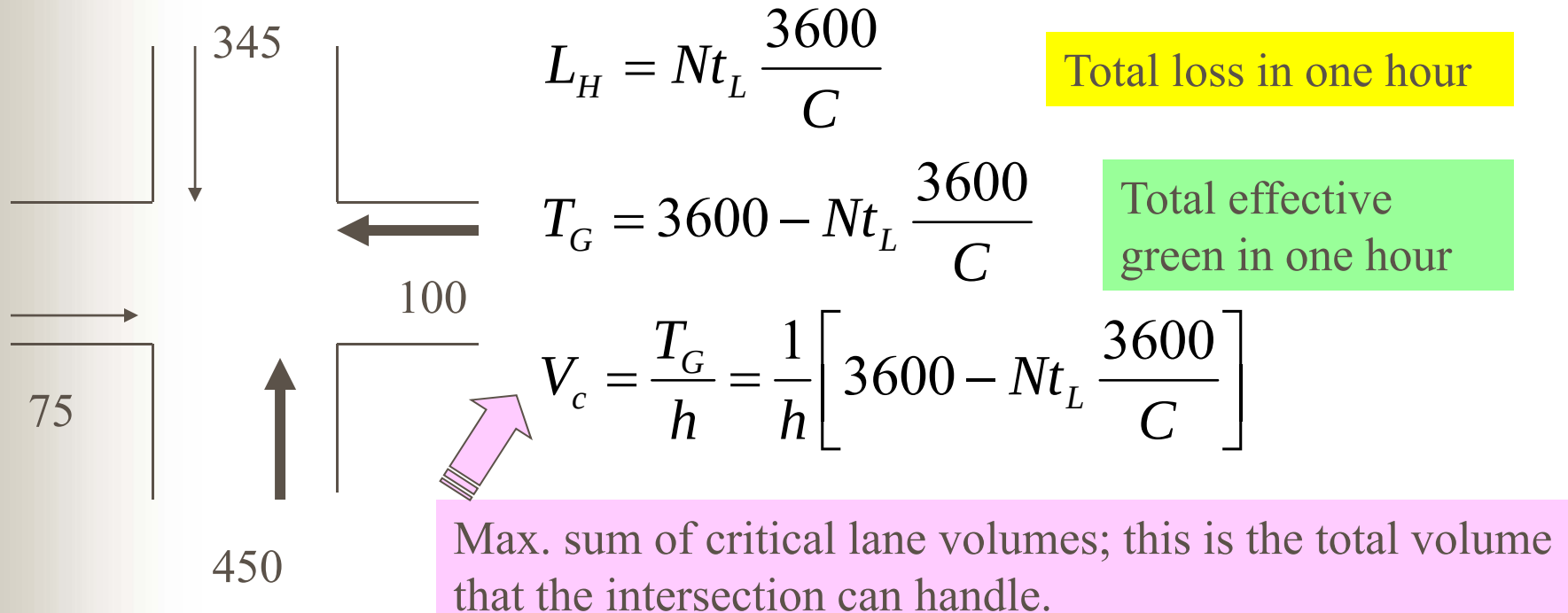
$$l_2 = y + ar - e$$

Capacity $\rightarrow c_i = s_i \frac{g_i}{C}$

Cycle length

17.3 The “critical lane” and “time budget” concepts

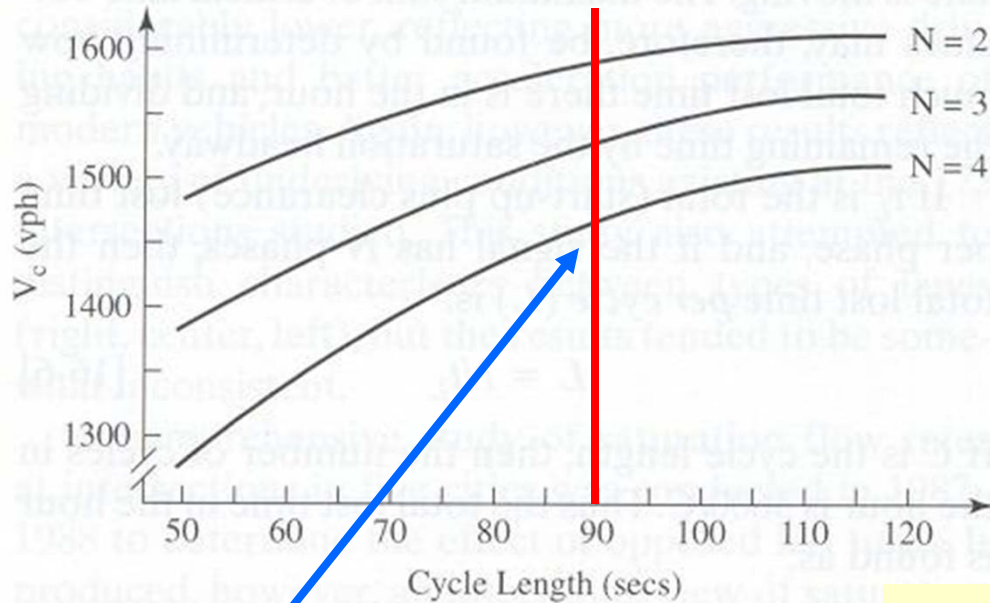
Each phase has one and only one critical lane (volume). If you have a 2-phase signal, then you have two critical lanes.



N = No. of phases, t_L = Lost time, C = Cycle length, h = saturation headway

17.3.2 Finding an Appropriate Cycle Length

Desirable cycle length, incorporating PHF and the desired level of v/c



The benefit of longer cycle length tapers around 90 to 100 seconds. This is one reason why shorter cycle lengths are better. $N = \#$ of phases. Larger N , more lost time, lower V_c .

$$C_{\min} = \frac{Nt_L}{1 - \left(\frac{V_c}{3600/h} \right)} \quad \text{Eq. 7-13}$$

$$C_{\text{des}} = \frac{Nt_L}{1 - \frac{V_c}{PHF(v/c)(3600/h)}} \quad \text{Eq. 7-14}$$

Doesn't this look like the Webster model?

$$C_0 = \frac{1.5L + 5}{1 - \sum_{i=1}^{\phi} Y_i}$$

$$Y_i = \text{flow_ratio}(v/s)_i$$

(Review the sample problem on page 482.)

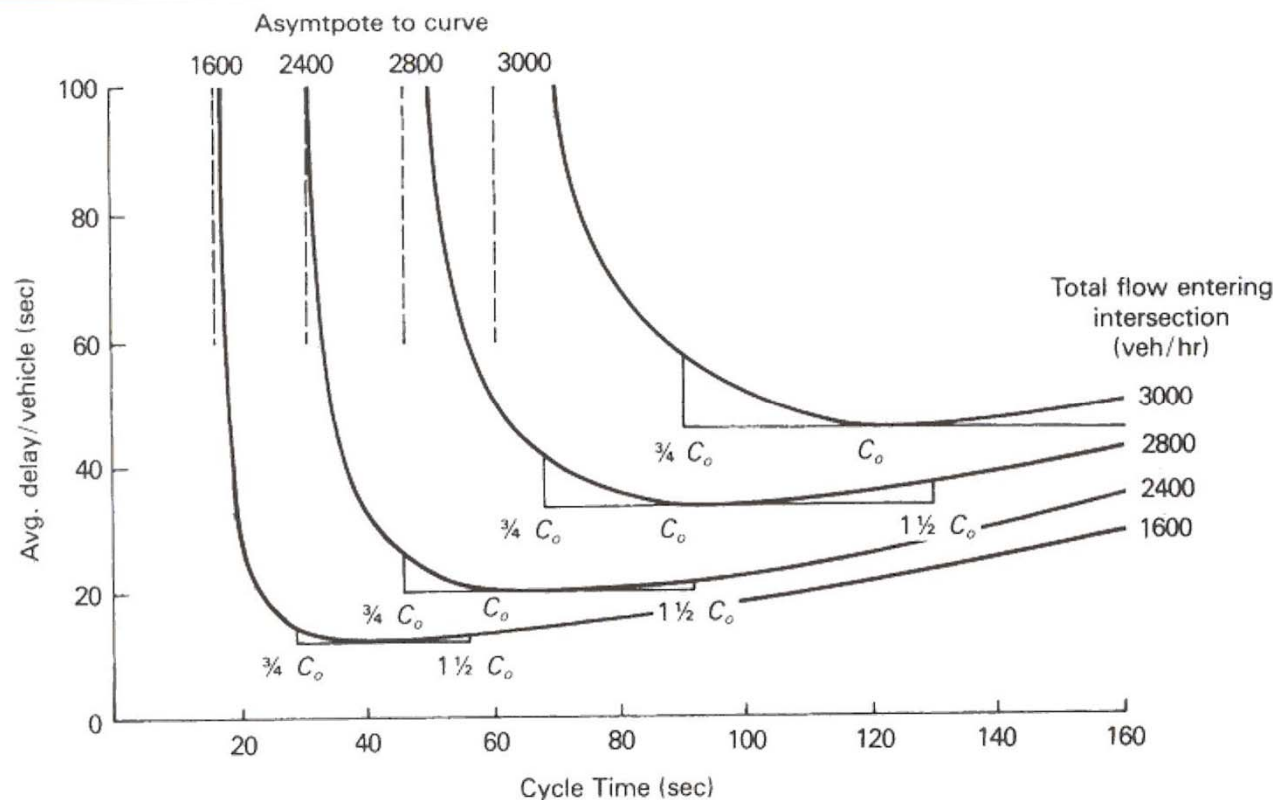
Webster's optimal cycle length model

$$C_0 = \frac{1.5L + 5}{1 - \sum_{i=1}^{\phi} (v/s)_i}$$

C_0 = optimal cycle length for minimum delay, sec

L = Total lost time per cycle, sec

Sum $(v/s)_i$ = Sum of v/s ratios for critical lanes

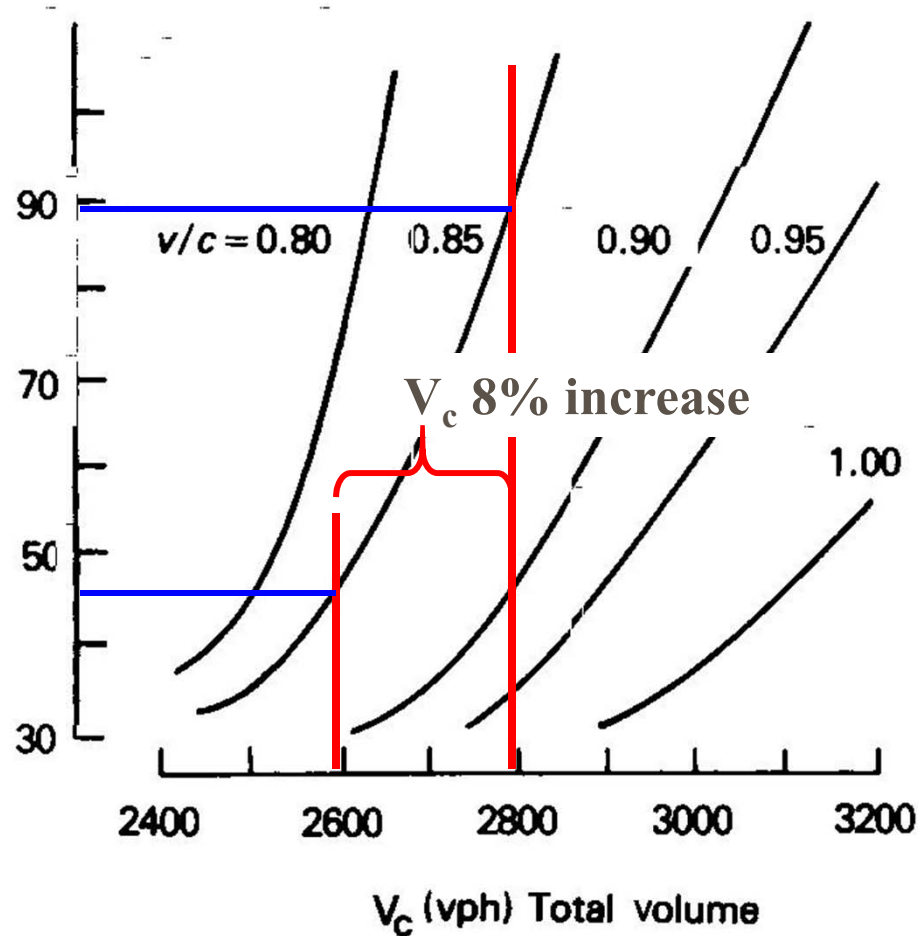


Delay is not so sensitive for a certain range of cycle length → This is the reason why we can round up the cycle length to, say, a multiple of 5 seconds.

17.3.2 Desirable cycle length vs. sum of critical lane volumes (example)

Desirable cycle length, C_{des}

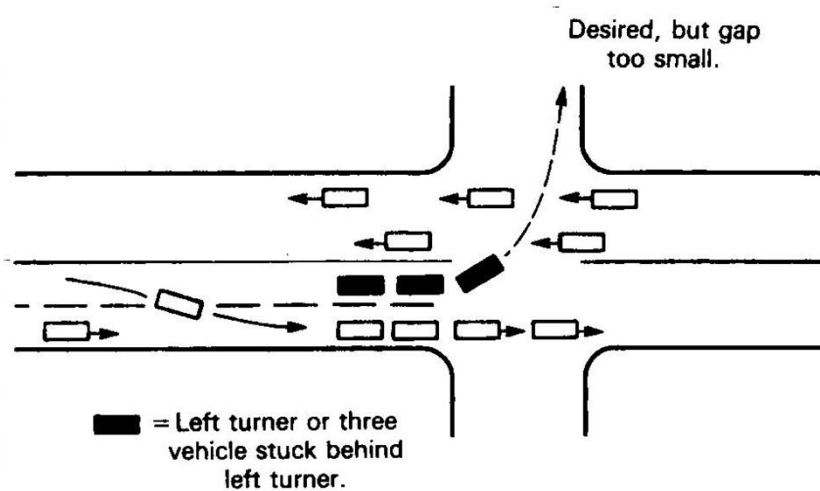
Cycle length
100%
increase



Marginal gain in V_c decreases as the cycle length increases.

(Review the sample problem on page 482)

17.4 The effect of left-turning vehicles and the concept of “through car equivalence”



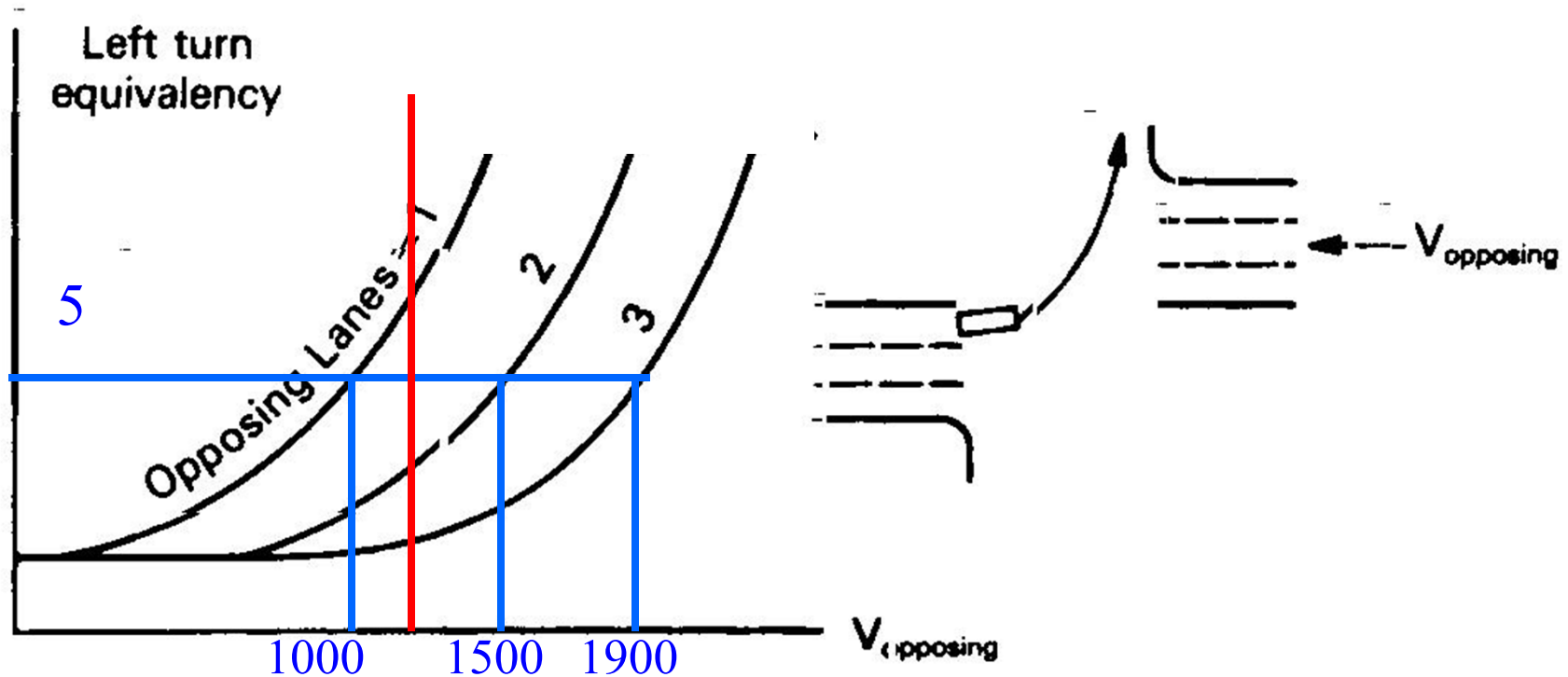
In the same amount of time, the left lane discharges 5 through vehicles and 2 left-turning vehicles, while the right lane discharges 11 through vehicles.

$$5 + 2E_{LT} = 11$$

and :

$$E_{LT} = \frac{11 - 5}{2} = 3.0$$

Left-turn vehicles are affected by opposing vehicles and number of opposing lanes.



The LT equivalent increases as the opposing flow increases. For any given opposing flow, however, the equivalent decreases as the number of opposing lanes is increased.

Left-turn consideration: 2 methods

Given conditions:

- 2-lane approach
- Permitted LT
- 10% LT, TVE=5
- $h = 2$ sec for through

Solution 1: Each LT consumes 5 times more effective green time.

$$h_{avg} = (0.1)(10.00) + (0.9)(2.00) = 2.80 \text{ sec/ } h$$

$$s = \frac{3600}{h_{ave}} = \frac{3600}{2.80} = 1286 \text{ vphgpl}$$

Solution 2: Calibrate a factor that would multiply the saturation flow rate for through vehicles to produce the actual saturation flow rate.

$$s = 3600/2 = 1800 \text{ vphgpl}$$

$$s = 1800(0.714) = 1286 \text{ vphgpl}$$

$$\begin{aligned} f_{LT} &= \frac{h}{h_{avg}} = \frac{h}{[P_{LT} E_{LT} h] - [(1 - P_{LT})(1.0)h]} \\ &= \frac{1}{1 + P_{LT}(E_{LT} - 1)} = \frac{1}{1 + 0.10(5 - 1)} = 0.714 \end{aligned}$$

17.5 Delay as an MOE

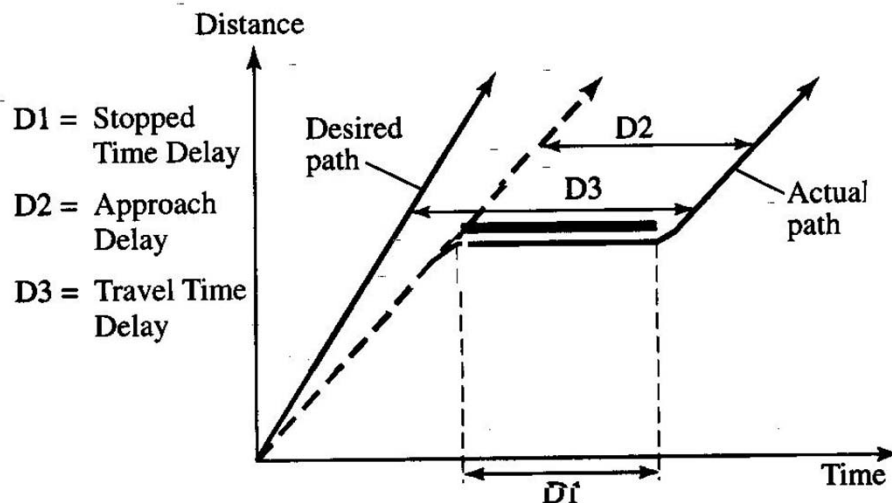


Figure 16-10 Delay measures illustrated.

Common MOEs:

- Delay
- Queuing
- No. of stops (or percent stops)

Stopped time delay: The time a vehicle is stopped while waiting to pass through the intersection

Approach delay: Includes stopped time, time lost for acceleration and deceleration from/to a stop

Travel time delay: the difference between the driver's desired total time to traverse the intersection and the actual time required to traverse it.

Time-in-queue delay: the total time from a vehicle joining an intersection queue to its discharge across the stop-line or curb-line.

Control delay: time-in-queue delay + acceleration/deceleration delay)

17.5.2 Basic theoretical models of delay

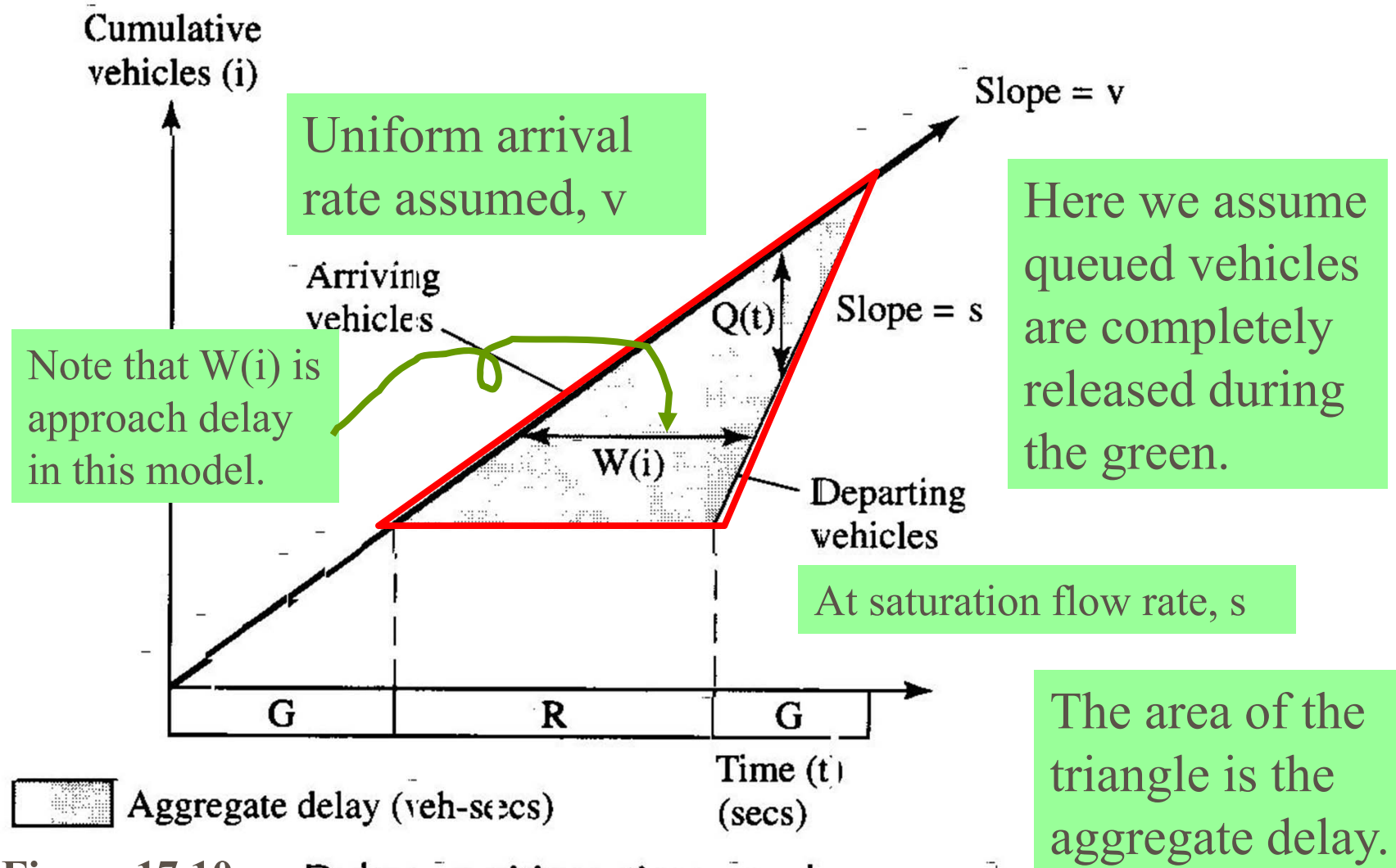
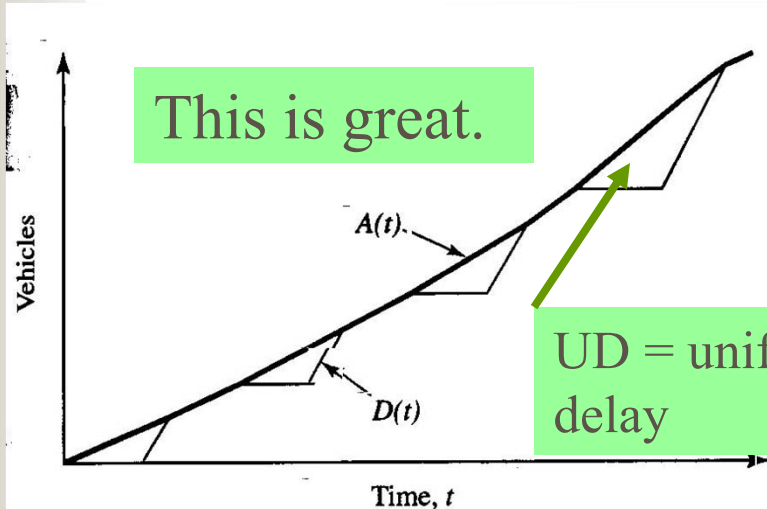
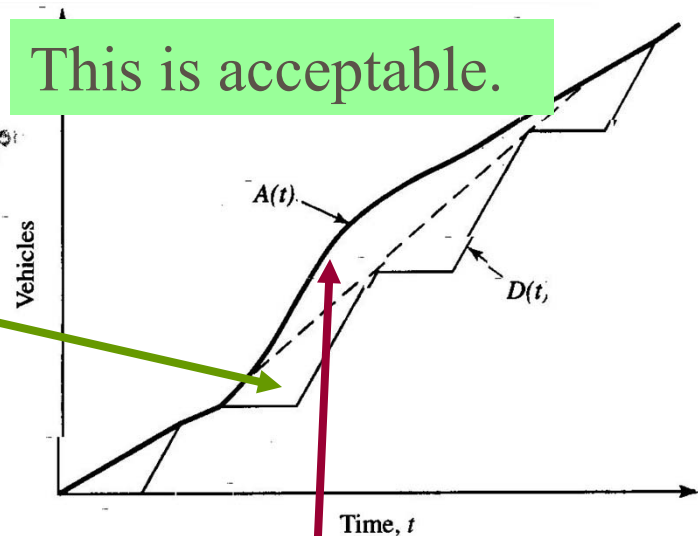


Figure 17.10 Delay, waiting time, and queue length illustrated.

Three delay scenarios

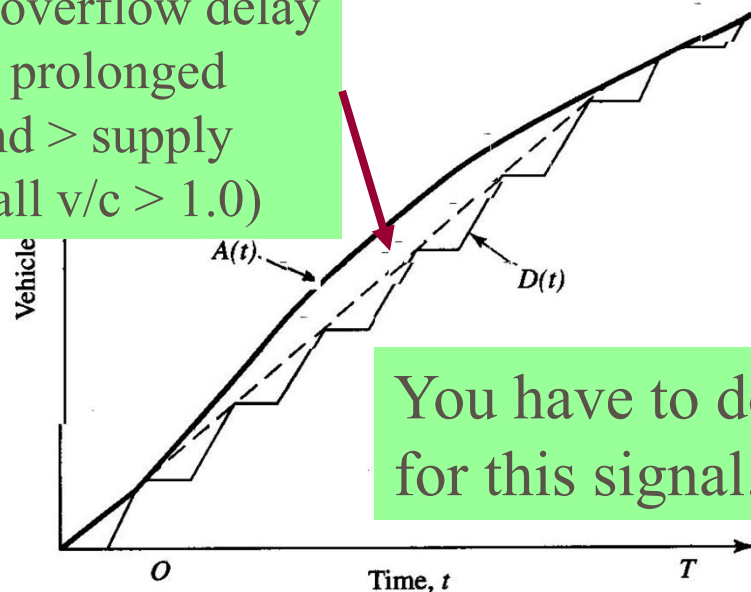


(a) No overflow



(b) Overflow due to stochastic variation in arrivals

OD = overflow delay due to prolonged demand > supply (Overall $v/c > 1.0$)



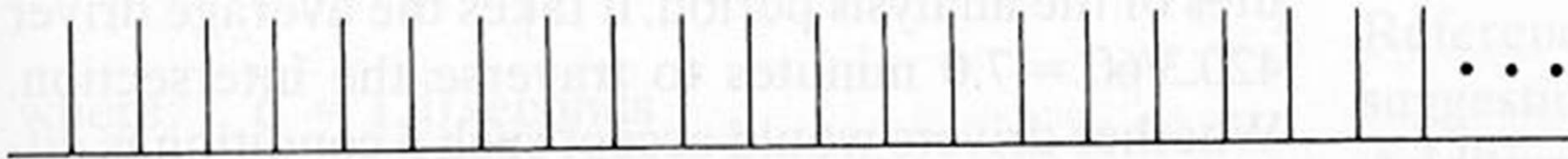
(c) Overflow due to long-term shortage of capacity

You have to do something for this signal.

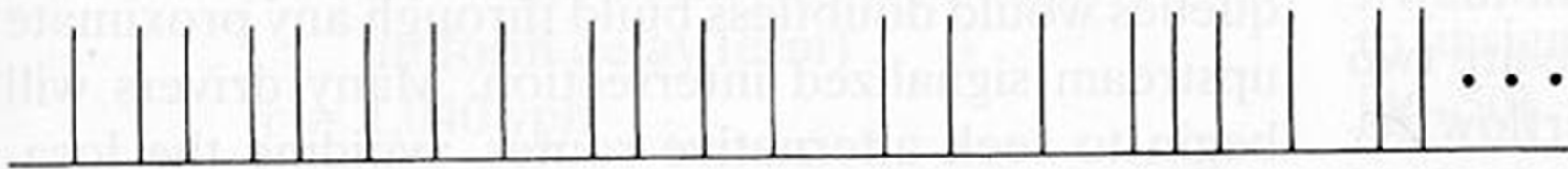
$A(t)$ = arrival function

$D(t)$ = discharge function

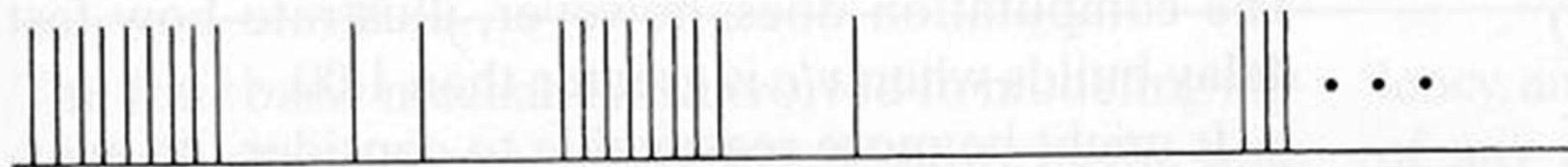
Arrival patterns compared



(a) Perfectly uniform arrivals, giving rise to Webster's first term



(b) Poisson arrivals (exponential interarrival times), giving rise to Webster's second term



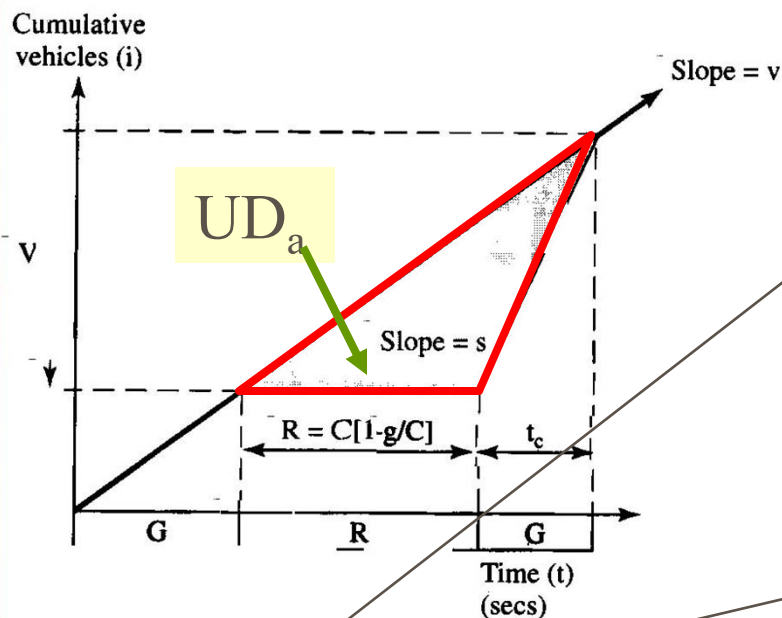
(c) Not covered: platooned arrivals, with or without randomness

Isolated intersections

Signalized arterials

HCM uses the Arrival Type factor to adjust the delay computed as an isolated intersection to reflect the platoon effect on delay.

Webster's uniform delay model



$$R = C \left[1 - \frac{g}{C} \right]$$

$$V = v(R + t_c) = st_c$$

$$t_c = \frac{vR}{s - v}$$

$$V = C \left[1 - \frac{g}{C} \right] \left[\frac{vs}{s - v} \right]$$

$$UD_a = \frac{1}{2} (\text{base} : R) (\text{height} : V) = \frac{1}{2} C^2 \left[1 - \frac{g}{C} \right]^2 \left[\frac{vs}{s - v} \right]$$

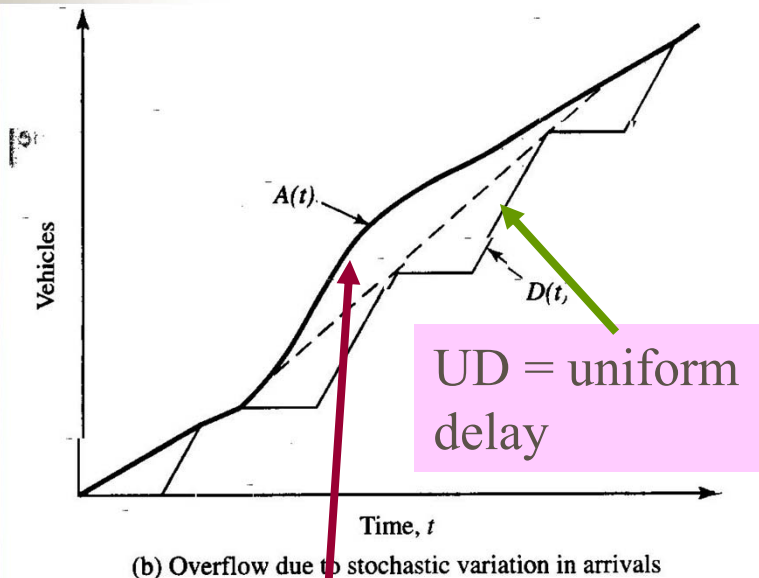
← Total approach delay

The area of the triangle is the aggregated delay, "Uniform Delay (UD)".

To get average approach delay/vehicle, divide this by vC

$$UD = \frac{C}{2} \frac{[1 - (g/C)]^2}{[1 - (v/s)]}$$

Modeling for random delay



OD = overflow delay due to randomness (in reality “random delay”). Overall $v/c < 1.0$

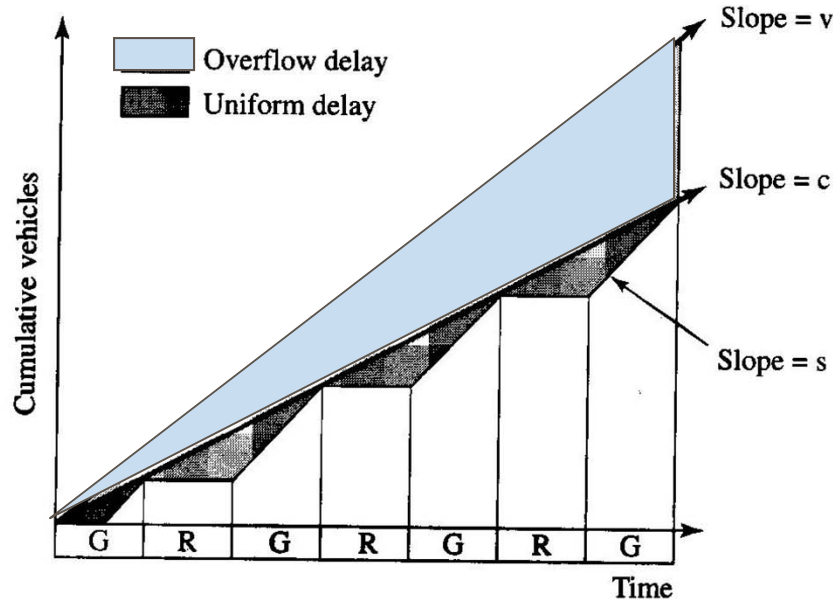
$$D = \frac{C}{2} \frac{[1 - (g/C)]^2}{[1 - (v/s)]} + \frac{(v/c)^2}{2v[1 - (v/c)]} - \left[0.65(c/v^2)^{1/3} (v/c)^{2+(g/C)} \right]$$

Adjustment term for overestimation (between 5% and 15%)

Analytical model for random delay

$$D = 0.90[UD + RD]$$

Modeling overflow delay



$$UD_o = \frac{C [1 - (g/C)]^2}{2 [1 - (v/s)]} = \frac{C [1 - (g/C)]^2}{2 [1 - (g/C)(v/c)]}$$

$$= \frac{C(1 - (g/C))}{2}$$

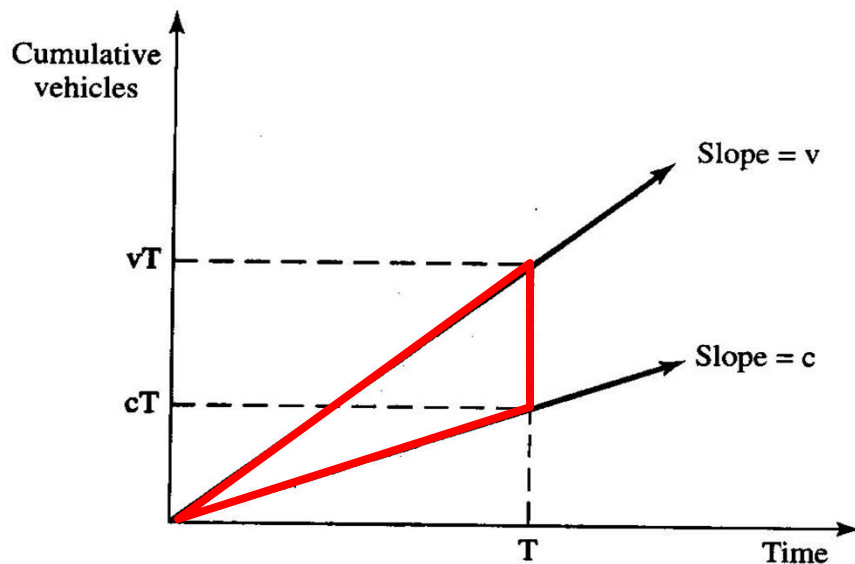
because $c = s (g/C)$, divide both sides by v and you get $(g/C)(v/c) = (v/s)$.
And $v/c = 1.0$.

The aggregate overflow delay is:

$$OD_a = \frac{1}{2} T (vT - cT) = \frac{T^2}{2} (v - c)$$

Since the total vehicle discharged during T is cT ,

$$OD = \frac{T}{2} ((v/c) - 1) \quad OD = \frac{T_1 + T_2}{2} ((v/c) - 1)$$

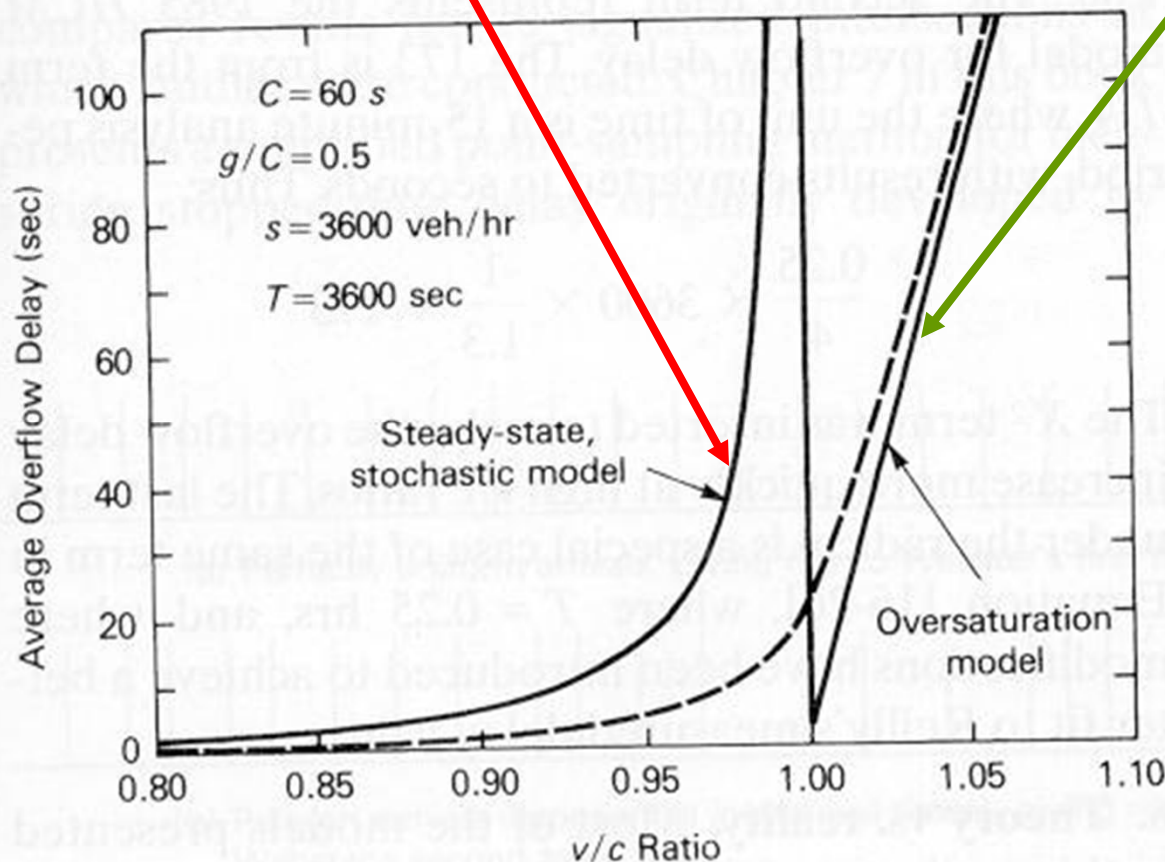


See the right column of p.493 for the characteristics of this model.

17.5.3 Inconsistencies in random and overflow delay

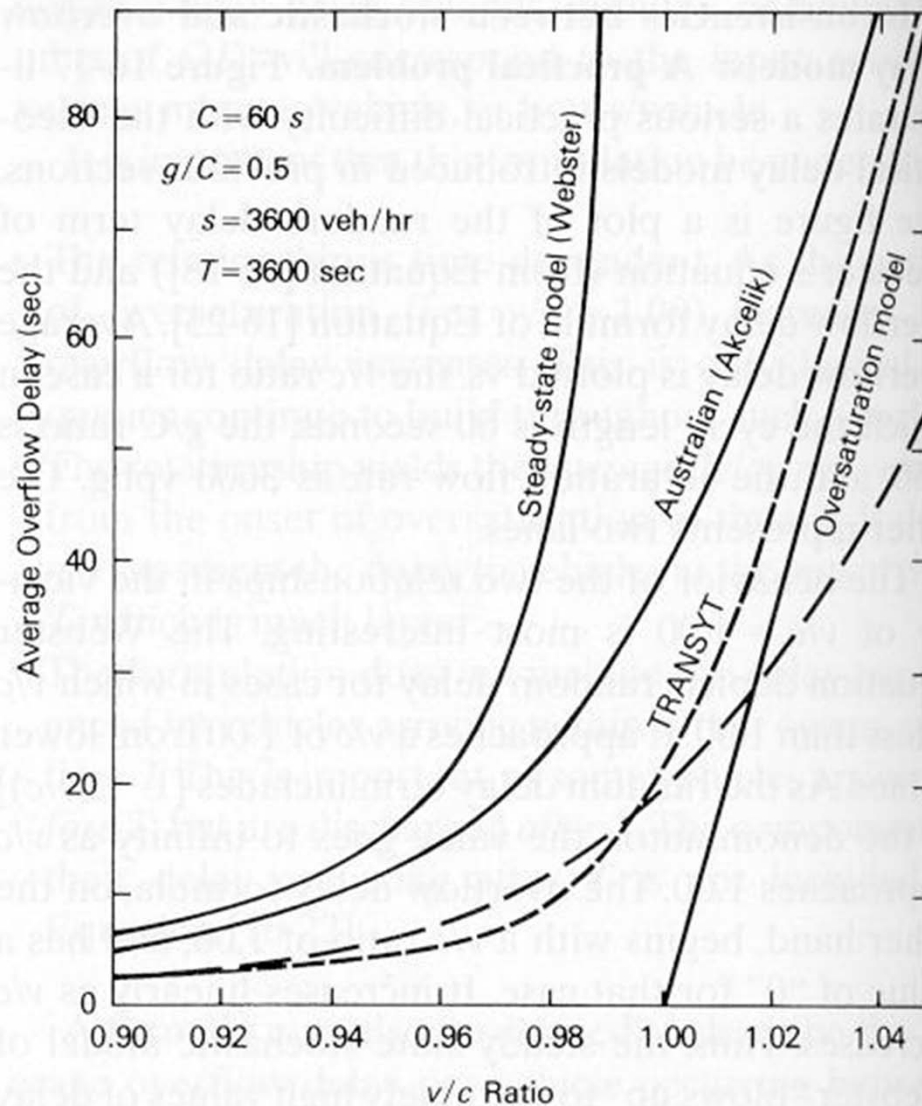
$$D = \frac{C}{2} \frac{[1 - (g/C)]^2}{[1 - (v/s)]} + \frac{(v/c)^2}{2v[1 - (v/c)]} - \left[0.65(c/v^2)^{1/3} (v/c)^{2+(g/C)} \right]$$

$$OD = \frac{T}{2} ((v/c) - 1)$$



The stochastic model's overflow delay is asymptotic to $v/c = 1.0$ and the overflow model's delay is 0 at $v/c = 0$. The real overflow delay is somewhere between these two models.

Comparison of various overflow delay model



17.5.4 Delay model in the HCM 2000

See Equation 17-27 and its similarities with the Akcelik's model (eq. 17-26).

These models try to address delays for $0.85 < v/c < 1.15$ cases.

17.5.5 Sample delay computations

We will walk through sample problems (pages 495-496).

Start reading Synchro 6.0 User Manual and SimTraffic 6.0 User Manual. We will use these software programs starting Wednesday, October 21, 2007.

