CE 269
Traffic Engineering

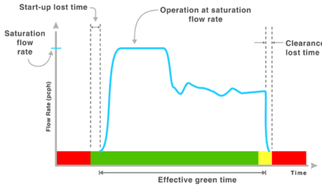
Lecture 14

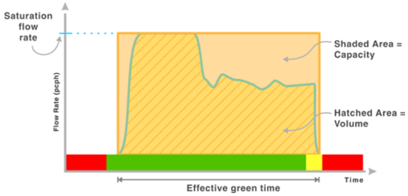
Delay Analysis and LoS

Previously on Traffic Engineering

When signals change from red to green, reaction times of travelers result in *start-up lost time*.

Likewise, when the signal turns amber, vehicles avoid entering the intersection and some time is lost at the end, called *clearance lost time*.

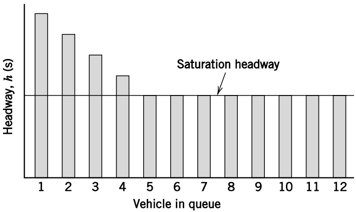




The *effective green* $g_i = G_i + Y_i - t_L$, where t_L is the sum of the above two lost times.

Previously on Traffic Engineering

When a signal turns green, the time headways between consecutive vehicles decrease since the vehicles behind the first one will take lesser time to react.



The *saturation flow* is the rate of vehicles that can pass through a movement if it receives a green light throughout.

$$s = \frac{3600}{h}$$

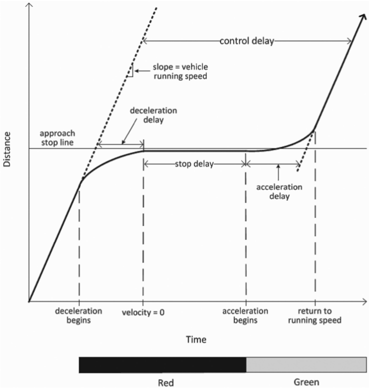
s is the saturation flow rate and h is the saturation headway.

Capacity of a lane or approach i can be computed using its saturation flow and effective green time

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

Previously on Traffic Engineering

Two types of delay—stop delay and control delay are important in signal design.



Previously on Traffic Engineering

To estimate the cycle time, we first estimate the *critical flow ratio* v/s of each phase by considering the maximum flow of a through or turn movement in that phase using peak-hour traffic counts.

The minimum cycle length recommended by HCM is

$$C = \frac{NLX_c}{X_c - \sum(v/s)_{ci}}$$

X_c is the critical v/c ratio of the intersection and is typically set to 0.9. It indicates the utilization rate of the intersection.

L is the lost time in seconds, N is the number of phases, $(v/s)_{ci}$ is the critical flow ratio for phase i.

Lecture Outline

1. Delay Analysis
2. Level of Service

Lecture Outline

Delay Analysis

Delay Analysis

Introduction

We can easily analyze delays at a junction in the case of deterministic arrivals and departures. This is an example of D/D/1 queues. More general settings will be discussed later in the course.

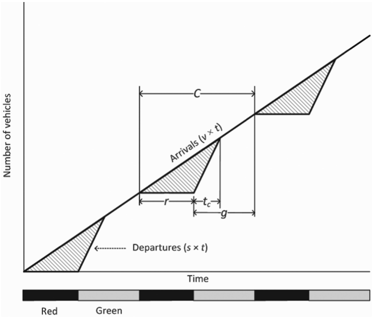
Suppose the arrival rate of vehicles at an approach be v and saturation flow rate be s. If the cycle time is C,

- The number of vehicles arriving at the junction in one cycle is vC.
- The maximum number of vehicles that can leave is sg, where g is the effective green.

Delay Analysis

Under-saturated Intersections

Suppose $sg > vC$. Calculate the following quantities:



- The time to clear the queues after the start of the effective green.

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

- The proportion of the cycle time with a queue.

$$t_c = \frac{r + t_c}{C}$$

- Total vehicle delay per cycle and average delay per vehicle.

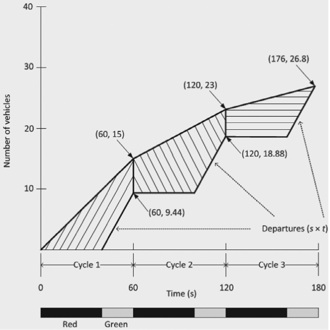
$$D_t = \frac{vr^2}{2(1 - v/s)} \quad D_{avg} = \frac{0.5C(1 - g/C)^2}{1 - (v/c)(g/C)}$$

Delay Analysis

Over-saturated Intersections

Suppose $s < v$. Then, queues can last longer than one cycle and can grow unbounded.

An approach to a pretimed signal has a saturation flow rate of 1700 veh/h. The signal's cycle length is 60 seconds and the duration of red is 40 seconds. During three consecutive cycles 15, 8, and 4 vehicles arrive.



- Determine the total vehicle delay over the three cycles assuming D/D/1 queuing.
- Estimate the percentage of flow that has to wait for more than one cycle.

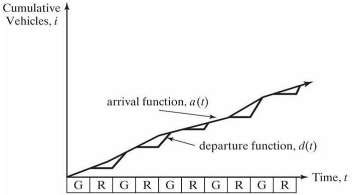
The earlier examples makes a few implicit assumptions.

- Arrival rates are uniform, which is not always true. Vehicles at isolated intersection usually follow a random arrival process. If the signal is part of a coordinated network, then arrivals are in batches or platoons.
- The queues are assumed to stack vehicles on top of one another. This is also called a *point-queue* model.

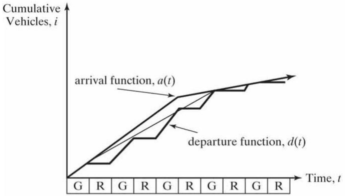
Also, in practice traffic can switch between under-saturated and over-saturated conditions. To address this issue, the delay is usually broken down into *uniform delay* and *overflow delay*.

Delay Analysis

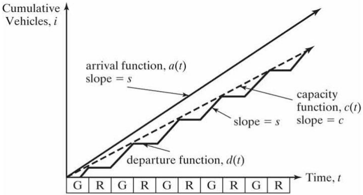
Delay Components



(a) Stable Flow



(b) Individual Cycle Failures Within a Stable Operation



(c) Demand Exceeds Capacity for a Significant Period

Delay Analysis

Random Delay

To account for stochasticity in arrivals, Webster analyzed a model with Poisson arrivals and deterministic departure rates and proposed the following approximation of the average *random delay*.

$$RD = \frac{(v/c)^2}{2v(1 - v/c)}$$

However, the sum of average random and uniform delay overestimated the actual average delay. The total average delay was hence defined as

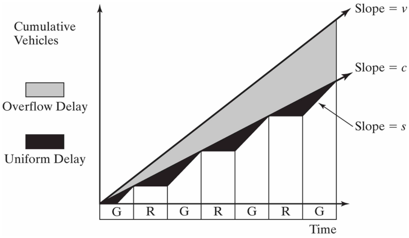
$$D = 0.9(UD + RD)$$

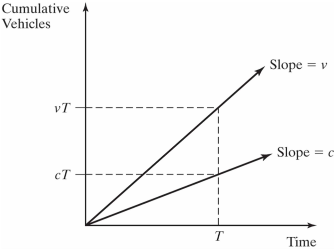
where $UD = \frac{0.5C(1-g/C)^2}{1-(v/c)(g/C)}$

Delay Analysis

Overflow Delay

The earlier expressions accounted for under-saturated scenarios where $v/c < 1$. For over-saturated conditions, the following formula can be derived.





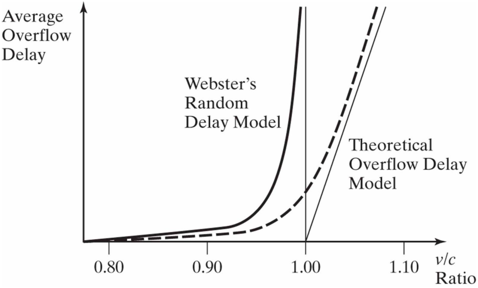
$$OD = \frac{1}{2} T \left(\frac{v}{c} - 1 \right)$$

The total delay is divided by cT and not vT since the other vehicles have not left and are still in the queue.

Delay Analysis

Boundary Issues

When v/c ratios is less than 1, we can use *UD* and *RD* and when it is greater than 1, we can use *UD* and *OD* (or all three of them). However, these expressions at the boundary are not smooth.



Delay Analysis

Boundary Issues

Based on empirical and simulation studies, the following formula has been proposed in US-HCM for average additional delay per vehicle due to random arrivals and oversaturation.

$$d_2 = 900T\left[(v/c-1)+\sqrt{(v/c-1)^2+\frac{8kI(v/c)}{cT}}\right]$$

- T is set to 0.25 if a 15-min peak hour traffic is considered for analysis.
- k is set to 0.5 for pre-timed controllers and is a function of v/c for actuated signals.
- The metering factor I which accounts for the presence of an upstream signal since it can reduce the randomness at the junction being analyzed. It is set to 1 for isolated intersections.

The total average signal delay is estimated as

$$d = d_1 + d_2 + d_3$$

where d_1 is the uniform delay (same as UD) and d_3 is set to the delay due to initial queues that exist at the start of the analysis period.

Lecture Outline

Level of Service

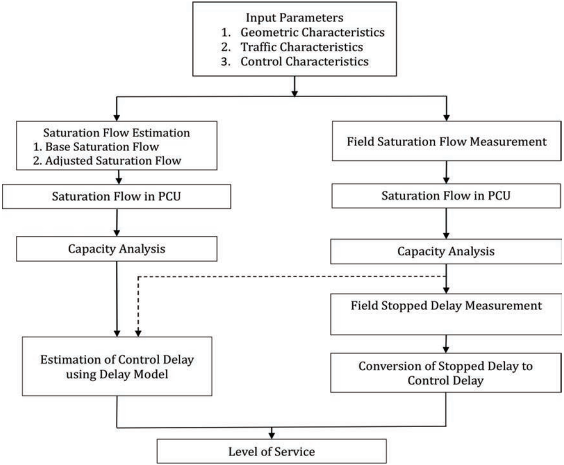
Level of Service
Introduction

The methods studied for setting signal timing plans and delay analysis for an approach can be used to decide from candidate phasing schemes.

The overall delay is used to classify the performance of a junction into different Level of Service (LoS) bins.

The Indo-HCM provides guidelines for this analysis taking some additional features such as heterogeneity, presence of bus stops, and flare effects at start of green.

The manual suggests two methods including one where field data is available for saturation flows.



Level of Service

Input Parameters

Parameter Type	Parameter
Geometric Characteristics	1. Approach width, *w (m)* 2. Presence/absence of exclusive lanes for an exclusive right turn phase/or free left turn 3. Presence / absence of bus bays or curbside bus stops
Traffic Characteristics	1. Classified peak hour traffic volume of all movements 2. Passenger Car Units 3. Unit base-saturation flow rate, USF_0 *(PCU/h/m)* 4. Number of buses stopping at intersection, *(bus/h)* 5. Presence or absence of approach flare and anticipated early movement and resulting initial surge
Control Characteristics	1. Cycle Time, *C (seconds)* 2. Green Time, *G (seconds)* 3. Change and clearance interval, *Y (seconds)* 4. Phase Plan 5. Analysis Period, *T (hours)*

$$
\mathrm{USF}_0 = \begin{cases} 630; & for \quad w < 7.0m \\ 1140 - 60w; & for \quad 7.0 \leq w \leq 10.5m \\ 500; & for \quad w > 10.5m \end{cases} \qquad \text{Equation 6.2}
$$

Where,

USF_0 = Unit base saturation flow rate *(in PCU / hour / m)*

w = effective width of approach in meters (m).

The prevailing saturation flow of the intersection approach for the movement group under consideration is then obtained as presented in Equation 6.3.

$$
SF = w \times USF_0 \times f_{bb} \times f_{br} \times f_{is} \qquad \text{Equation 6.3}
$$

Where,

SF = Prevailing saturation flow rate in PCU/hour

w = effective width of the approach in 'm' used by the movement group

USF_0 = Unit base saturation flow rate

f_{bb} = Adjustment factor for bus blockage due to curbside bus stop

f_{br} = Adjustment factor for blockage of through vehicles by standing right turning vehicles waiting for their turn.

f_{is} = Adjustment factor for the initial surge of vehicles due to approach flare and anticipation effect.

An adjustment factor for bus blockage f_{bb} is used if bus stops are located within 75 m of the intersection. It is set to 1 if there are exclusive bus bays.

$$f_{bb} = \frac{w - 3\left(t_b n_B / 3600\right)}{w}$$

where w is the approach width in m, t_b is the average blockage time during green, and n_B is the number of buses stopping in an hour.

Similarly, another adjustment factor f_{br} is used for blockage due to right-turning vehicles (for roads with no exclusive right-turn lanes and with width greater than 7 m)

$$f_{br} = \frac{w - w_r}{w}$$

where w_r is the width of the approach in m along the median occupied by standing vehicles waiting to turn right.

Flare effects are observed for two-wheelers while anticipation effect applies to all types of vehicles.

Green Time of Phase *(seconds)*	Only Anticipation Effect	Only Approach Flare Effect		Anticipation and Approach Flare Effect	
		Low (S_R=1.15)	High (S_R=1.35)	Low (S_R=1.15)	High (S_R=1.35)
< 15	1.133	1.020	1.047	1.153	1.180
15 - 30	1.067	1.010	1.023	1.077	1.090
30 - 45	1.044	1.007	1.016	1.051	1.060
45 - 60	1.033	1.005	1.012	1.038	1.045
60 - 75	1.027	1.004	1.009	1.031	1.036
75 - 90	1.022	1.003	1.008	1.026	1.030
90 - 120	1.017	1.002	1.006	1.019	1.023
> 120	1.000	1.000	1.000	1.000	1.000

f_{is} = 1 when no surge flow is observed on the approach

$$c_i = SF_i \left({}^{g_i}/_{C} \right) \qquad \text{Equation 6.6}$$

Where,

C_i = capacity of movement group 'i' in PCU/hour,

SF_i = Prevailing *(after adjustments)* saturation flow of the movement group *(in PCU/hour),*

g_i = Effective green time for movement group *'i' (in seconds)*, and

$$X_i = \left(\frac{v}{c}\right)_i = \frac{v_i}{SF_i\left({}^{g_i}/_{CY\_Time}\right)} = \frac{v_i * CY\_Time}{SF_i * g_i} \qquad \text{Equation 6.7}$$

Where,

X_i = Degree of saturation or volume to capacity ratio of movement group 'i'

v_i = Volume of movement group 'i'

c_i = capacity of movement group i *(in PCU/hour)*,

SF_i = Prevailing *(after adjustments)* saturation flow of the movement group *(in PCU/hour)*,

g_i = Effective green time for movement group 'i' *(in seconds)* and

CY_Time = Overall cycle time *(in seconds)*.

Table 6.8: LOS based on *v/c* Ratio Criteria for Signalized Intersections

LOS	Volume - Capacity Ratio (*v/c*)
A	< 0.45
B	0.46 - 0.75
C	0.76 - 0.95
D	0.96 - 1.05*
E	1.06 - 1.10*
F	> 1.10*

Alternately, one can estimate the average delay for each approach using the following formula. X is the degree of saturation or the v/c ratio.

$$d = 0.9 * d_1 + d_2 + d_3 \qquad \text{Equation 6.9}$$

Where,

d = control delay, *(in seconds/PCU)*

$$d_1 = 0.50\, C \frac{\left(1-\frac{g}{CY\_Time}\right)^2}{\left(1-\frac{g}{CY\_Time}\min(X,1)\right)} \qquad \text{Equation 6.10}$$

$$d_2 = 900T\left[(X-1) + \sqrt{(X-1)^2 + \frac{4X}{C_{SI}T}}\right] \qquad \text{Equation 6.11}$$

$$d_3 = \begin{cases} 0, & Q_b = 0 \\ \frac{1800\, Q_b\, (1+u)t}{c_{SI}T}, & Q_b \neq 0 \end{cases} \qquad \text{Equation 6.12}$$

Level of Service

Delay Method

The average delay for a specific approach and the average intersection delay is calculated using

$$d_A = \frac{\sum d_i \times V_i}{\sum V_i} \qquad \text{Equation 6.15}$$

Where,

d_A = Average control delay of a specific approach 'A' *(in sec/PCU)*

d_i = Average control delay for movement group 'i, *(in sec/PCU)*

V_i = Volume of the movement group 'i'

Intersection delay can be calculated as the weighted average of delay for each approach as given in Equation 6.16.

$$d_I = \frac{\sum d_A \times V_A}{\sum V_A} \qquad \text{Equation 6.16}$$

Where,

d_i = Average control delay of a specific approach 'A' *(in sec/PCU)*

d_A = Average control delay for movement group 'i, *(in sec/PCU)* and

V_A = Volume on approach 'A'.

Level of Service

Delay Method

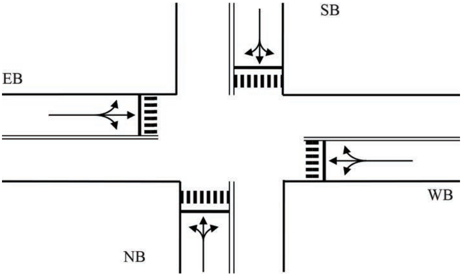
Table 6.7: LOS based on Delay Criteria for Signalized Intersections

LOS	**Control Delay** *(in seconds/ PCU)*
A	20
B	20 and 40
C	40 and 65
D	65 and 95
E	95 and 130
F	> 130

Level of Service

Example

Calculate the LoS of the following four-legged intersection using both delay and v/c methods.

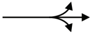


Level of Service

Example

Details	SB	WB	NB	EB
Approach Width, w (m)	7	7	7	7
Demand Volume, PCU/h	935	856	756	587
PHF	0.9	0.9	0.9	0.9
Peak Hour Volume, PCU/h	842 (0.9 x 935)	770 (0.9 x 856)	680 (0.9 x 756)	528 (0.9 x 587)
Presence/absence of exclusive lanes for an exclusive right phase	Absent	Absent	Absent	Absent
Presence/absence of Bus bays	Absent	Absent	Absent	Absent
Number of buses stopping at intersections, n_B *(buses/h)*	0	45	112	0

Details	SB	WB	NB	EB
Initial Surge	Present	Absent	Absent	Absent
(A) Anticipation effect	Present	Absent	Absent	Absent
(B) Approach Flare Effect	Absent	Absent	Absent	Absent
(C) Surge Ratio	1.15	-	-	-

Phase Number	Phase Movement	Green Time (sec)	Amber Time (sec)
1		25	3
2		25	3
3		25	3
4		25	3

Additional Reading

Mannering, F. L., & Washburn, S. S. (2020). Principles of highway engineering and traffic analysis. John Wiley & Sons.

Roess, R. P., Prassas, E. S., & McShane, W. R. (2004). Traffic engineering. Pearson/Prentice Hall.

Your Moment of Zen