

Traffic Engineering
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Lecture 38

Operational Analysis of Signalized Intersection - IV

Welcome to module E lecture 12. In this lecture also, we shall continue our discussion about Operational Analysis of Signalized Intersection.

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Recap of Lecture of E.11

Operational analysis of signalized intersection

- Step 6: Determine capacity & volume-to-capacity ratio
- Step 7: Determine delay
- Step 8: Determine LOS
- Step 9: Determine queue storage ratio



In lecture 11, we discussed primarily about step 6, how to determine the capacity and volume to capacity ratio, then step 7 determined delay, 8 how to determine level of service based on the control delay and then we started our discussion and a few concepts also I explained in relation to queue storage ratio calculation.

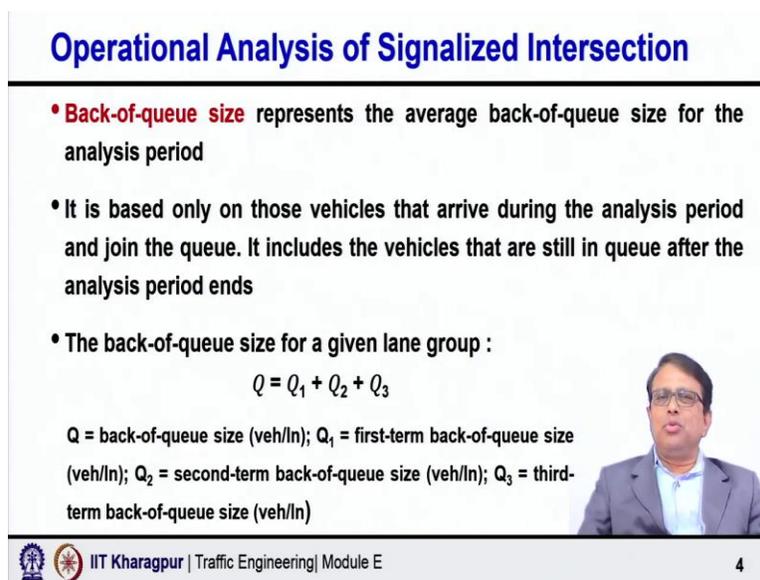
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Operational Analysis of Signalized Intersection
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Operational Analysis of Signalized Intersection

- **Back-of-queue size** represents the average back-of-queue size for the analysis period
- It is based only on those vehicles that arrive during the analysis period and join the queue. It includes the vehicles that are still in queue after the analysis period ends
- The back-of-queue size for a given lane group :

$$Q = Q_1 + Q_2 + Q_3$$

Q = back-of-queue size (veh/lh); Q_1 = first-term back-of-queue size (veh/lh); Q_2 = second-term back-of-queue size (veh/lh); Q_3 = third-term back-of-queue size (veh/lh)



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Now, in previous lecture, we talked about N_f number of stopped vehicles and also T_f , the clearance time for clearing those or time required to clear those vehicles. Now, back of queue size represents the average back of queue size for the analysis period. So, what we considered there, so, far, N_f and T_f it is only one part of it, there are more considerations while we are calculating the back of queue size.

Now, back of queue size is based on those vehicles, which arrive at the intersection during the analysis period. And of course, it also includes the vehicles that are still in the queue after the

analysis period ends. Because still all the vehicles which have arrived the intersection during the analysis period are cleared, we have to continue the process.

So, actually, if you see the back of the queue size for a given lane group is actually summation of Q_1 , Q_2 , Q_3 , what are the Q_1 , Q_2 , Q_3 ? They are may be the first term of the back of the queue size, second term of the back of the queue size, and third of the back of the queue size respectively. So, Q is actual back of the queue size is sum of over first term second term and the third term.

$$Q = Q_1 + Q_2 + Q_3$$

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Operational Analysis of Signalized Intersection

Step c: Compute the First-Term Back-of-Queue Size (Q_1)

- Accounts for queue caused by signal cycling through its phase sequence

$$Q_1 = N_f$$

c = lane group capacity (veh/h)
 d_2 = incremental delay (s/veh)
 N = number of lanes in lane group (ln)

Step d: Compute the Second-Term Back-of-Queue Size (Q_2)

$$Q_2 = \frac{c}{3600N} d_2 \text{ (for calculation of } d_2, \text{ refer slide 10 (E.11))}$$

- Consists of two queue components
 - ✓ Effect of random, cycle-by-cycle fluctuations in demand that occasionally exceed capacity
 - ✓ Queuing due to a sustained oversaturation during the analysis period




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Now, coming to the first term, that is actually what we have discussed in the previous lecture. These accounts for queue caused by signal cycling through its phase sequence. So, Q_1 is straightway equal to N_f number of stop vehicles and you remember our discussion in the previous lecture that how to calculate the N_f , graphically I have shown you also what N_f means, what interpretation of this one. So, Q_1 component the first term is clear to us.

$$Q_1 = N_f$$

Now, the second term second term also is known to you the second term includes actually two components, one effect of random cycle by cycle fluctuations in demand and that occasionally exceeds capacity, that means over the entire analysis period, not that demand is more than the

capacity, but individual cycle because of the effect of random arrival individual cycle some cases capacity may be lower than the actual demand, that effect is considered.

Second also queuing due to sustained over situations that means, entire period also during this analysis period, your demand maybe more than the capacity. So, queuing due to sustained over saturation due to during this analysis period. So, this calculation, how to calculate Q2? I have again explained to you for your reference, this has been mentioned in slide 10 of the previous lecture E dot 11. So, you know how to calculate this Q2. So, this is again known basically d2 is the incremental delay. So, the first term and the second term both are known to you now and both, I have mentioned to you earlier and we have discussed as well.

$$Q_2 = \frac{c}{3600N} d_2$$

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Operational Analysis of Signalized Intersection

Step e: Compute the Third-Term Back-of-Queue Size (Q₃)

- Accounts for the additional queuing that occurs during the analysis period because of an initial queue
- This queue is a result of unmet demand in the previous time period

$$Q_3 = \frac{1}{NT} \left(t \frac{Q_b + Q_e + Q_{eo}}{2} \right)$$

$$Q_e = Q_b + t(v - c)$$

If $v < c$, then $Q_{eo} = 0.0$ veh & $t = Q_b / (c - v) \leq T$

t = duration of unmet demand in the analysis period (h),

T = analysis period duration (h),

Q_b = initial queue at the start of the analysis period (veh),

Q_e = queue at the end of the analysis period (veh), and

Q_{eo} = queue at the end of the analysis period when $v \geq c$ and $Q_b = 0.0$ (veh)





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Next step is actually calculation of the third term for back of queue size Q3. Now, this Q3 accounts for the additional queuing that occurs during the analysis period, because of an initial queue, my period of analysis is known, when I am starting my analysis, that time itself there is a queue, it is not that it starts with 0 queue.

So, that queue effect effect of that queue will be also there on the overall queue and the delay. So, that is the component what is called as Q3. So, this accounts for additional queuing that occurs

during the analysis period because of an initial Q, when you are starting the analysis. So, this Q result is the result of the or this queue is the result of unmet demand in the previous time period.

So, maybe you have carried out some analysis or whatever operation has happened during the previous analysis period. The unmet demand that is left out from the previous analysis, that if the starting point of our present analysis period. So, that is the Q3. Now, how this Q3 can be calculated? This Q3 again, can we calculate it based on a few things as shown in the equation primarily Qb, what is the Qb? Initial Q at the start of the analysis period. Whatever is the queue that you take over from the previous analysis period, that is the Qb, but that is there in the beginning.

$$Q_3 = \frac{1}{NT} \left(t \frac{Q_b + Q_e + Q_{e0}}{2} \right)$$

$$Q_e = Q_b + t(v - c)$$

If $v < c$, then $Q_{e0} = 0.0$ veh & $t = Q_b / (c - v) \leq T$

But then, depending on this analysis period, what is the arrival rate and what is the capacity or the discharge based on that two more term may come 1 Qe, Qe is the queue at the end of analysis period and Qe0 that is Q at the end of the analysis period when volume is greater than equal to c and considering that Qb equal to 0.

Now, considering Qb equal to 0 means you can interpret that that Qe0 does not consider the effect of or does not consider the Qb component within its calculation. So, assuming that Qb equal to 0, but Qb actually may not be 0. You are actually calculating then, what is the Qe0. Now, Qe0 or Qe sorry Qe is actually Qb whatever is the Q in the beginning of analysis period plus t into v minus c.

Suppose, your whatever will be the difference, sometimes v may be greater than c, sometimes c maybe v may be lower than c. So, this v minus c term could be positive could be negative could be 0 as well all possible situations are there. So, the volume could be greater than capacity volume could be less than capacity and the volume could be equal to capacity.

Accordingly, this sign will get decided whatever this plus plus may remain plus plus maybe minus and also this whole term maybe 0 as well. So, the additional queue either it will grow or it may reduce also, if the demand is more than the capacity, then whatever is your Qb value end up the

day Q_e will be larger than that and if the capacity is higher than the volume, then either this whole Q_b will get dispersed. You will may get a 0 value of Q or you may get a Q which is lesser than the present queue that is Q_b all possibilities are there.

Now, if v is less than c , then what will happen capacity is higher discharge is higher than the vehicle which is arriving during this analysis period. So, that whatever initial Q you have Q_b those vehicles some of those vehicles will get discharged. Now, if the value t you calculate like this Q_b divided by c minus v because we are assuming here c is greater than v .

So, c minus v if this value is less than capital T the analysis period that means, what will happen? The whole Q_b which was there in the during the analysis beginning of the analysis period all vehicles will get discharged there will not be any queue. So, in that case if you take this equation and put this value as t equal to Q_b divided by c minus v , then what will happen? This will be actually Q_b minus Q_b equal to 0.

So, you started with Q_b your arrival rate is lower than your capacity discharge and t is what small t duration of unmet demand in the analysis period. Duration of unmet demand is less than the analysis period. So, if your analysis period is 15 minute and your t is 10 minutes, then after 10 minutes, there is no unmet demand. So, the queue will vanish. So, end of this analysis period you will not get any queue. So, this calculation is valid it will be 0 then Q_b minus Q_b equal to 0.

Now, if this duration of unmet demand in the analysis period is suppose greater than t that, yes, there is a difference my discharge or capacity is higher than my demand. So, obviously, the Q_b will start reducing whatever was that initial queue over during this analysis period, this number of vehicles will be lesser and lesser over time, but my time or the duration of unmet demand in the analysis period is higher than my analysis period.

So, the whole value Q_3 or Q_e sorry Q_e will not be 0 in the end, but it will be lesser than the present Q_b value, how much will get discharged? How much will be Q_b minus how much? Q_b minus then capital T into v minus c capital T into v minus c , but c is higher. So, it will be actually Q_b minus capital T into c minus v . What is the difference between c and v ? Over a time period capital T that much reduction will happen. So, Q_b minus that term. How to calculate this value when v is greater than or equal to c ? We will discuss in after 2-3 slides. We will come back to this part and discuss again.

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Operational Analysis of Signalized Intersection

Step f: Compute the Back-of-Queue Size (Q)

• The average back-of-queue estimate (Q) for a lane group (in vehicles per lane) is computed:

$$Q = Q_1 + Q_2 + Q_3$$

For EB: TH Lane Group:

$Q_1 = N_f = 3.5 \text{ tpc}$

$Q_2 = \frac{c}{3600N} d_2 = \frac{1901}{3600 \cdot 2} \cdot 1.3 = 0.3 \text{ tpc}$

$Q_3 = 0.0$ (there is no initial queue)

$Q = Q_1 + Q_2 + Q_3 = 3.5 + 0.3 + 0.0 = 3.8 \text{ tpc}$

Direction	Lane Groups	Q ₁	d ₂ (s)	c (tpc/h)	N	Q ₂	Q ₃	Q
EB	TH	3.5	1.3	1901	2.0	0.3	0.0	3.8
	RT	2.2	9.7	278	1.0	0.7	0.0	2.9
WB	TH	6.9	17.6	642	1.0	3.1	0.0	10.0
	TH/LT	6.7	38.1	531	1.0	5.6	0.0	12.3
SB	TH/RT	5.0	28.4	422	1.0	3.3	0.0	8.3
	TH	5.5	26.7	461	1.0	3.4	0.0	8.9
	TH/LT	5.2	27.7	437	1.0	3.4	0.0	8.6



In this calculation coming back to our calculation and then obviously, total queue is Q equal to Q1 plus Q2 plus Q3. Now, in our calculation, this Q3 is 0. So, we actually omit this term or just simply put it as 0 and then I have shown you in this slide, we know the directions we know the lane group, we know the value of Q1 we know the value of d2 that delay random delay component. The capacity number of lanes. So, accordingly based on our calculation here Q2 c divided by 3600 into N into d. So, that calculation we can do we can get the value of Q2. Q3 in the present example is 0. So, the total Q will be Q1 plus Q2 plus Q3 that is the average back of Q estimate for a lane group during the analysis period.

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Step g: Compute Queue Storage Ratio (R_Q)

$$R_Q = \frac{L_h Q}{L_a}$$

$$L_h = L_{pc} (1 - 0.01 P_{HV}) + 0.01 L_{HV} P_{HV}$$

Direction	Lane Groups	P_{HV} (%)	L_h (m)	L_a (m)	Q	R_Q
EB	TH	10	8.1	60	3.8	0.52
	RT	10	8.1	60	2.9	0.39
WB	TH	10	8.1	100	10.0	0.81
	TH/LT	10	8.1	100	12.3	1.00
SB	TH/RT	10	8.1	100	8.3	0.68
	TH	10	8.1	100	8.9	0.72
	TH/LT	10	8.1	100	8.6	0.69

For EB: TH Lane Group:

$$L_h = 7.5 * (1 - 0.01 * 10) + 0.01 * 13.5 * 10 = 8.1 \text{ m}; R_Q = \frac{L_h Q}{L_a} = \frac{8.1 * 3.8}{60} = 0.52$$

L_a = available queue storage distance (m/ln),

L_h = average vehicle spacing in stationary queue (m/veh)

L_{pc} = stored passenger car length ~ 7.5 (m),

L_{HV} = stored heavy-vehicle length ~ 13.5 (m)

P_{HV} = % heavy vehicles in the corresponding movement group (%)



Now, once you have done that, we know how much will be the value of Q and we know how much is our available queue storage distance that is an input. So, we know the average available queue storage distance. So, what is then the RQ? storage ratio, my queue length is Q actual Q is lengthy is Q multiplied by Lh, what is the Lh? Lh is average vehicle spacing in stationary queue meter per vehicle, Q is number of vehicle, number of vehicle multiplied by meter per vehicle.

$$R_Q = \frac{L_h Q}{L_a}$$

$$L_h = L_{pc} (1 - 0.01 P_{HV}) + 0.01 L_{HV} P_{HV}$$

So, you know the length divided by La, La is the available queue storage distance per lane how many meters, all this per lane wise. So, this La known, La is actually an input. So, this ratio will give you the queue storage ratio. What proportion of the available queue storage distance is actually getting utilized and obviously, it should not be more than 1 then that operation existing operation if it is creating the RQ as more than 1 then it is not acceptable.

One more calculation here is given how to calculate this Lh. Lh is the average vehicle spacing in stationary queue it depends on primarily considering car and heavy vehicle these are the 2 vehicle types considered in the highway capacity manual 2016. So, what is the proportion of heavy vehicle? So, 1 minus 0.01 into that percentage of heavy vehicle.

So, obviously, if you have 10 percent then this 1 minus 0.01 into PHV will be 0.9. So, 0.9 in that case 90 percent you have car so, 90 percent car 0.9 into Lpc, what is the storage passenger car or

stored passenger car length plus 10 percent if you have commercial vehicle or heavy vehicle, then 0.01 into that 10 percent which is 0.1 multiplied by PHV is the that PHV into 0.01 is 10 percent multiplied by the length of average length of heavy vehicle.

So, accordingly you can calculate the average vehicle spacing in the stationary queue considering the effect of car and heavy vehicle as per their at what proportion their shared, they are sharing in the share in the overall traffic stream accordingly you can calculate this one. So, here we have calculated now all the values are known I have shown you here how for the eastbound through lane group how we can calculate this value. So, we know that this average length is taken as 7.5 meter for the stored passenger car stored heavy vehicle length 13.5 meter and you have 10 percent actually this heavy vehicle.

So, 90 percent will be the cars so 7.5 into this value plus 0.1 into 13.5. So, you get that 8.1, that is why we can calculate. Now, accordingly that is the this is the Lh value. So, you can calculate Lh and once you know that, Lh value, you can calculate this Q storage ratio and in this case it will be 8.1 into 3.8 divided by 60. So, only 0.52.

So, like that you calculate for every lane group. Here interestingly you can see one value is 1 that been just where the whole queue storage distance is actually getting utilized. So, little bit higher means it will not nor be acceptable. And in fact, we should not operate with this queue storage ratio as 1 because marginal increase means it will fail in that sense.

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Operational Analysis of Signalized Intersection

Interpreting of Results

- Scenario I : X_c (intersection) ≤ 1.00 ; all lane groups $X_i \leq 1.00$
 - ✓ There are no capacity deficiencies in any lane group
- Scenario II : $X_c \leq 1.00$; some lane groups $X_i > 1.00$
 - ✓ Cycle time is generally not appropriately allocated among the phases
 - ✓ Reallocation of the cycle time should be considered, so that additional time is given to the phases serving those lane groups with $X_i > 1.00$



So, now a quick interpretation of the results, how we can interpret the results. Now, let us consider a scenario where for the overall intersection volume to capacity ratio is less than 1 and for all lane groups or every lane group X_i , i indicate say lane group for all our individual X_i also it is less than 1. There is no problem then everything is fine. The whole intersection is operating nicely, of course, we have to see if this X_i and X_c all less than 1, but it should not be too much on a lower side, that also you need to check.

But as long as it is lower than 1 and maybe 0.8, 0.9 in that range, it should be quite acceptable. So, at least the capacity wise there is no issue. So, whatever may be the X_c and X_i as long as they are all less than 1 that clearly indicates that there is no capacity deficiency in the lane group. Now, take that another scenario X_c is less than equal to 1.

So, overall intersection capacity wise it is fine, but some lane groups or for some length groups X_i is greater than 1. What does it indicate? The overall operation overall intersection looks alright it can handle but the green time distribution is not proper. Because some cases X_i greater than 1 some other cases greater than less than 1 maybe some cases significantly less than 1.

So, that indicates the green time allocation for different lane group needs to be adjusted further. So, the indication is cycle time is generally not appropriately located among the phases and therefore, reallocation of cycle time should be considered. So, that additional green time is given to the phases serving the lane groups with X_i greater than 1. So, where volume to capacity ratio for certain lane group is more than 1, we should allocate more green time there and reduce the given time for that other lane groups or other phases.

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Operational Analysis of Signalized Intersection

- Scenario III : $X_c > 1.00$; some or all $X_i > 1.00$
 - ✓ Overall signal timing and geometric design provide inadequate capacity for the given demand flows
 - ✓ Suggested improvements:
 - Changes in intersection geometry (change in number or use of lanes)
 - Increase in signal cycle length if it is determined to be too short
 - Changes in signal phase sequence or timing



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Now, another possible scenario probably the worst, could be X_c is greater than 1 and some or all X_i also greater than 1. So, you have no problem with the overall intersection capacity and a few or all individual lane group capacity. That is a real problem. So, overall signal timings and geometric design the present one the present signal timing and the present geometric design is unable to provide adequate capacity for the given demand flow.

So, you have to think something more not simply reallocation of green time to different phases or different critical lane group. You have to think something more than that, because the overall intersection capacities also not adequate. So, some of the suggested improvements may include change in intersection geometry, that means, changing the number or use of lane. So, you know that critical value for lane group it is going more than 1.

So, in that case, if you add additional lane obviously, it will benefit that will give benefit to this overall calculation of X_i . So, that is one possibility or use of lane the way the present lane is lanes are utilized for through left turning, right turning, shared, exclusive whatever the thing some further change is there. To bring down this overall X_i values lower than 1 and also the X_c less than 1.

And change of course, in signal phase sequence or timings as appropriate along with the changes in additional lane or use of lane overall changes whatever will happen. So, you have to think of

signal flow sequence or timings, all are may be changed. Signal phase sequence or timings may also be changed.

So, these are the possible scenarios and what actions if at all is required suppose first case no action everything is fine, second case, yes re-allocation of the green time, third case it is not only re-allocation of green time, but change the number of lane, use of lane, increase the cycle length if it is determined to be too short and also change the signal sequence or phase sequence or timings multiple interventions may be required.

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Operational Analysis of Signalized Intersection

Summarized Results

- Intersection as a whole operates at a high v/c ratio (0.891)
- It is recommended that capacity for all critical-lane groups be increased and that the green be reallocated to provide for balanced v/c ratios in all critical lane groups (Especially WB:TH/LT)
- R_q ratio for WB:TH/LT reaches 1.0 which with little increase in flow will result in more queued vehicles and may block other vehicles from moving forward

Direction	Lane Groups (LG)	Lane Group Flow Rate (tpc/h)	v/c Ratio	d (s)	LOS	R_q
EB	TH	1100	0.579	8.64	A	0.52
	RT	170	0.611	32.85	C	0.39
WB	TH	576	0.897	35.55	C	0.81
	TH/LT	529	0.996	57.11	E	1.00
SB	TH/RT	390	0.924	49.78	D	0.68
	TH	426	0.924	48.10	D	0.72
SB	TH/LT	404	0.924	49.08	D	0.69
	Intersection	-	-	0.891	34.9	LOS C




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Now, if I have to summarize the results, which we got based on our example problems, then what you see here all these calculations have been done earlier, but now, I am trying to relook at the results. You see the v is c ratio 0.579, 0.611 quite on the low side, but you also have values like 0.996, 0.924 quite high, acceptable not more than 1, but near 1.

So, even some slight fluctuations in the demand may cause this v by c ratio to be more than 1. Also, if you see the queue storage ratio, in all other cases it is quite acceptable, but for westbound through and left shared lane it is 1, that means a slight change in the demand for this lane group will cause your R_q the queue storage ratio to be more than 1.

So, what it is saying and if you see the overall intersection 0.891, quite happy situation in that way. Not too low, not very close to 1 it is reasonable. In an almost I will say, yes, that kind of values may be accepted quite comfortably. So, intersection as a whole operates at a high v by c ratio, not

too close to 1, not too on the lower side not like overall is 0.4, 0.5 or 0.6 not even that, but it is recommended that capacity for all critical groups be increased because you can see especially this westbound through and left.

So, that is what I have said that all lane groups should be increased and that the green be allocated to provide a more balanced v by c ratio in all the lane groups. Ideally, we do not want values to vary so much 0.579 in some case, one lane group and 0.996 in another lane group. So, it indicates some reallocation of the green time probably will benefit the operation of traffic at this signal.

And as I said the Rq ratio Rq value, the ratio of storage ratio it is again for westbound through and left shared lane this one you can see, here it is 1. So, westbound through and left you can see here 0.996 this v by c ratio is also critical and here the Rq value storage ratio is also 1. So, it indicates that with little increase in the flow will result in more queued vehicles and maybe block vehicles from moving forward. Because the upstream discharge also may get affected. So, it may be a real problem.

So, a reallocation of green time to make more balance in terms of the v by c ratio and more rational distribution of the queue storage ratio would actually be possible and that will benefit the operation of traffic in this intersection. But the overall utilization, overall volume to capacity ratio for the intersection should be generally acceptable.

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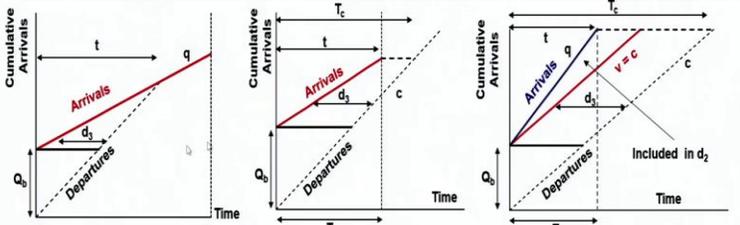
Initial Queue Delay



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Initial Queue Delay



T = analysis period, h;
 t = adjusted duration of unmet demand in the analysis period, h
 T_c = Queue clearing time (h)



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Now, coming back to a little bit more analysis and more discussion about the initial queue delay. We talked about the queues, the initial queue delay this part we have not discussed in details. So, little bit more discussion about the initial queue delay. Initial queue delay means, when we are starting our analysis or in the beginning of our analysis period, there is already a queue and that is shown here as Q_b . So, you are starting your analysis period here, here your capital T is the duration of analysis period. So, here it is 0 and here it is T if I consider this time axis of course, capital T the analysis period. So, in the beginning of analysis period only you have a value of Q_b .

So, this is the cumulative arrival. So, cumulative vehicle already Q_b number of vehicles are there, you have to take that right from the beginning from the previous analysis period. Now, although this Q_b remains same in different cases, but then the other things there are based on the arrival and based on the departure, there are 3 possible scenarios, which are shown here.

First, the simplest one and the most comfortable one, what is there? You can see the red line is showing the arrival cumulative arrival and these dotted lines showing the cumulative departure. So, obviously, since there is a Q_b number of vehicle d_3 is the delay additional delay. Because this Q_b vehicles need to be discharged.

So, when all these Q_b vehicles will get discharged after d_3 time d_3 seconds, so, d_3 is the additional delay in that case. So, d_3 is the additional delay in this case. Now, you are seeing interestingly the cumulative arrival and cumulative departure they are meeting at this point and they are meeting at this point at what time at time small t from the beginning of the analysis period, and this small t time is lesser than the analysis period capital T .

So, within the analysis period my considering the Q in the beginning my cumulative arrival Q_b plus my whatever vehicles are arriving during this analysis period of small t seconds, I am able to clear all the vehicles within small t seconds and small t is less than the overall analysis period. So, end of the analysis period what will happen? Your queue length will be 0 all vehicles got cleared.

So, you are starting with the Q in the beginning of analysis period which is Q_b . But end of the analysis period you will have 0 queue no queue. So, t is the small t is the adjusted duration of unmet demand. So, unmet demand is served entirely 100 percent within this analysis period small t which is also lesser than capital T the overall analysis period. The second one is not such a happy situation somewhat different.

Here again we start with Q_b . So, obviously, there will be delay, but the arrival and the departure rate during this analysis period is such that not they are not meeting but also not that they are simply parallel parallel mean they are not going to meet now. Or as in the case 3, this one there the gap is widening further over analysis over the analysis period. You can see here this is the arrival and this is the dotted line is the departure and the red line is shown here which is parallel to the departure.

So, here in this case, the arrival line actually is on the left side of this red line, which is v is equal c and here the arrival although have shown it using the red line, but this arrival line is somewhere like on the right side of the line where arrival is equal to the departure. So, exactly not parallel. So, if you take the width of or the length of this line, this solid line and the length of this dotted line, both are horizontal lines, the dotted line length is lesser than the length of the solid line that means what will happen your arrival whatever is your arrival rate, your departure rate is higher than that, in this case also departure was higher.

But the difference was such that the arrival and departure rates were such that that the departure cumulative departure curve could catch up with the cumulative arrival within the analysis period, but here no within the analysis period, the cumulative departure car should not catch up with the cumulative arrival curve. Considering the also the Q , which is which were there in the beginning.

So, what will happen in this case after the analysis period, it will not be 0 like the first case, but it will be not same as Q_b or will not even increase further it will be something lesser than Q_b , because during this whole analysis period capital T the number of queued vehicles the number will get reduced. All these vehicles, so, whatever will arrive the rate is such that suppose there is so, it is the gap is getting reduced in this case.

Now, go to this extreme situation where the arrival rate during this whole analysis period T is higher and significantly higher. So, forget about this Q_b with this arrival rate itself the all the vehicles which are arriving during this analysis period cannot be cleared because it is even at higher rate than the departure arrival rate is even higher than departure.

So, here there will be two effect the Q_b will be there, that length will be there plus due to oversaturation during this analysis period, there will be additional Q . So, first case Q_b after the analysis period becomes 0. Second case Q_b does not become 0, but get reduced end of the analysis period and Q_3 is the worst it will be Q_b plus something, what is this plus value, is this one after this analysis period. So, the end of this analysis period whatever Q you will get that queue length will be higher than Q_b in this case. Here during the after this analysis period, your queue length will be lesser than Q_b but not 0, in this case it will be 0.

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Initial Queue Delay

$$d_3 = \frac{3600}{vT} \left(t \frac{Q_b + Q_e - Q_{eo}}{2} + \frac{Q_e^2 - Q_{eo}^2}{2c} - \frac{Q_b^2}{2c} \right)$$

$Q_e = Q_b + t(v - c)$

- If $v \geq c$

$$t = T \quad \& \quad Q_{eo} = T(v - c)$$
- If $v < c$,

$$t = Q_b / (c - v) \leq T \quad \& \quad Q_{eo} = 0.0$$

Q_b = Initial queue at start of analysis period T, veh; Q_e = queue at the end of the analysis period (veh), Q_{eo} = queue at the end of the analysis period, when $v > c$

Initial Queue Delay with Increasing Queue

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Operational Analysis of Signalized Intersection

Step e: Compute the Third-Term Back-of-Queue Size (Q_3)

- Accounts for the additional queuing that occurs during the analysis period because of an initial queue
- This queue is a result of unmet demand in the previous time period

$$Q_3 = \frac{1}{NT} \left(t \frac{Q_b + Q_e + Q_{eo}}{2} \right)$$

$$Q_e = Q_b + t(v - c)$$

If $v < c$, then $Q_{eo} = 0.0$ veh & $t = Q_b / (c - v) \leq T$

t = duration of unmet demand in the analysis period (h),
 T = analysis period duration (h),
 Q_b = initial queue at the start of the analysis period (veh),
 Q_e = queue at the end of the analysis period (veh), and
 Q_{eo} = queue at the end of the analysis period when $v \geq c$ and $Q_b = 0.0$ (veh)

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Now, with this we can calculate what is the d_3 , there is a formula is the quadratic equation you can use this formula to get the value of d_3 and in this case Q_e I have mentioned it earlier is Q_b plus t into v minus c , I have explained that if it is v minus v is less than c then t will be can be calculated like this and if that t is less than capital T that is small t is less than capital T then you use this small t in this equation here Q_e equal to Q_b plus t into v minus c .

$$d_3 = \frac{3600}{vT} \left(t \frac{Q_b + Q_e - Q_{eo}}{2} + \frac{Q_e^2 - Q_{eo}^2}{2c} - \frac{Q_b^2}{2c} \right)$$

If this t becomes more than capital T then you assume this small t as value equal to capital T then put it there. So, what will happen in that case v less than c . So, c is higher. So, this will become negative that means Q_b minus in the overall analysis period capital T how much is the difference between v and c . So, essentially if you take minus it will be then c minus v . So, the Q_b equal to Q_e will be Q_b minus something, Q length will get reduced. What will happen if v is greater than c ?

Further addition. So, whenever there is an oversaturation, then this small t will be equal to capital T , and what will be your Q_{e0} ? Q_{e0} will be t this equation small t gets replaced by capital T into v minus c . So, that will be the value of Q_0 and what is Q_0 , I have told you earlier, let me go back again and tell you, what is what is Q_{e0} ? It is the queue at the end of analysis period when v is greater than equal to c and Q_e is Q at the end of the analysis period. So, coming back what we can see now, we know conceptually the possibilities how to calculate also the formula is also known, the equations are given. So, it is a simple calculation now.

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Initial Queue Delay

- What would happen if the demand flow rate for the WB TH/LT lane group ($c = 531$ tpc/h) was actually 551 tpc/h instead of 529 tpc/h?
- Let's assume this condition exists for four consecutive 15-minute analysis periods
- There is no initial queue at the beginning of the first 15-minute interval
- Since $v > c$, there will be a queue at the end of the first 15-minute interval, and therefore a queue at the beginning of the second 15-minute interval (and the third and the fourth)



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So, let us consider whatever we have taken the worst that westbound through and left lane group. There the capacity is 531 tpc per hour and our actual demand flow rate was 529. So, it was almost like 1, 0.996 or something we got. Now, suppose instead of 529 if it would have been 551, Then what will happen, capacity is 531 actual demand flow rate is 551 and if we consider four

consecutive 15 minutes analysis periods separate one 15 minute then 15 minutes again 15 minutes and the fourth 15 minute.

So, if we consider four consecutive 15 minute or 0.25-hour analysis period, then what will happen? There will not be any queue initial queue in the beginning of first 15-minute interval. But then since v is greater than c there will be queued at the end of the first 15-minute interval and therefore, at the beginning of the second 15-minute interval and eventually in the beginning of third 15 minute or fourth 15-minute interval, there will always be Q_v value, what will be the calculation in that case?

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Initial Queue Delay

Analysis Period	t (h)	v (tpc/h)	c (tpc/h)	Q_b	Q_e	Q_{eo}	d_s (s)
1	0.25	551	531	0	5	5	0.0
2	0.25	551	531	5	10	5	33.9
3	0.25	551	531	10	15	5	67.8
4	0.25	551	531	15	20	5	101.7

$Q_e = Q_b + t(v - c)$

If $v \geq c$

$t = T$

$Q_{eo} = T(v - c)$

- The length of the queue is 20 tpc/lm at the end of the fourth period
- This may be a concern if the next upstream signal is close enough that queue would negatively vehicles attempting to leave the upstream signal

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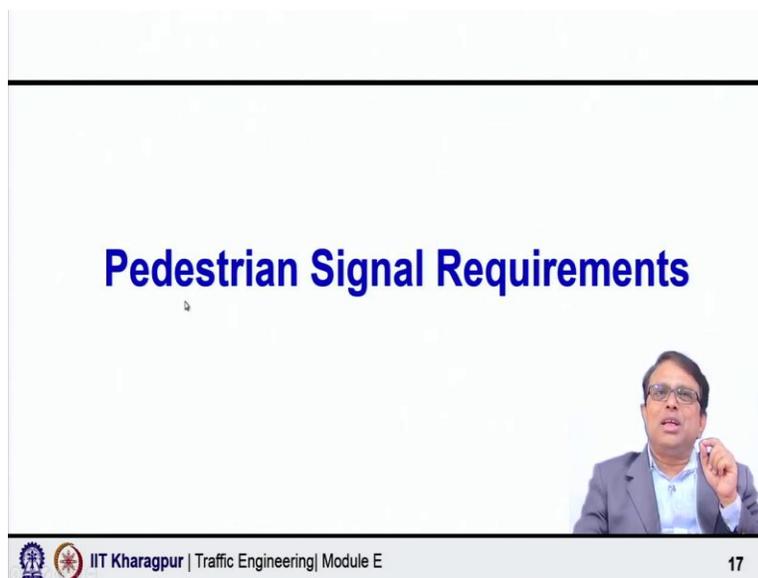
So, we are considering a every time four consecutive analysis period each of 15 minute or 0.25 hour and this is all 551. We have assumed that I say that what will happen if instead of 529 if the actual demand flow rate is 551. So, in that case what will happen this v is 551 capacity is 531. In the beginning of your analysis period you have 0 but then Q_{e0} as far as the calculation, you will be 5 and, then Q_e will be what? Q_b plus Q_{e0} . So, total will be 5.

Now, this 5 will be actually Q_b for the next analysis period. Again, you calculate what will be the Q_{e0} in this case. It will be 5 and as I said this Q_{e0} says when v is greater than c and with Q_b equal to 0 does not mean that it will be only applicable when Q_b equal to 0. This tells you that assuming that Q_b if as 0 that means Q_b effect is not included in the calculation of Q_{e0} that is the meaning.

So, what will be the actual Q_e ? Then it will be Q_b plus Q_{e0} . So, you get 10. Now, 10 will come here again you will find Q_{e0} is 5. So, what will we Q_e ? Q_e will be Q_{e0} because it is e_0 Q_{e0} calculation we are not adding this Q_b . So, actual Q at the end of analysis period will be whatever was the Q_b plus because this is oversaturation. What is the additional Q during this analysis period due to her saturation?

So, the total Q will be Q_e at the end of analysis period will be Q_b plus Q_{e0} . So, you can see here if there is a little bit of increase, then there will be 20 vehicles tpc per lane at the end of the fourth period. So, this may be a concern because then your queue storage ratio will be higher and higher and depending on the situation, it may even block the upstream signal or even if it does not block it will influence the operation of upstream signal very significantly.

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The slide features a white background with a thin black horizontal line near the top. The title "Pedestrian Signal Requirements" is centered in a bold, blue font. In the bottom right corner, there is a small inset video of a man with glasses, wearing a grey suit jacket over a light blue shirt, gesturing with his right hand. At the bottom of the slide, there is a footer bar containing the IIT Kharagpur logo, the text "IIT Kharagpur | Traffic Engineering | Module E", and the page number "17".

Pedestrian Signal Requirements

- Two pedestrian considerations:

- ✓ First: The time a pedestrian needs to perceive the signal indication and traverse the crosswalk

$$G_{p,min} = t_{pr} + \left(\frac{L_{cc}}{S_p} \right) - y - ar$$

$G_{p,min}$ = minimum green interval duration (s)

t_{pr} = pedestrian perception of signal indication and curb departure time = 7.0 (s)

L_{cc} = curb-to-curb crossing distance (ft)

S_p = pedestrian walking speed (ft/s)



So, before we close last part is basically the pedestrian delay or signal requirement not pedestrian delay, but last part is pedestrian signal requirement. So, far in all our calculation planning level analysis, operational level analysis, we have not considered or discussed this part. Since this is operational analysis, let us touch this part also very simple.

If there is an existing in if in existing intersection, if an it if in an existing intersection, there is a requirement and you have given already the pedestrian green because pedestrians want to move and that is the facility you want them to use at grade facility with the signal control for pedestrians, then, how we judge whether the green time given is adequate or not.

There are 2 considerations one, the first 1 the time a pedestrian need to perceive the signal indication and traverse the crosswalk. They have to cross the road. So, what is that length? So, here you can see this is the minimum time required we are not considering the pedestrian volume where suppose one person, but that 1 person has to cross the road safely.

So, what is that minimum time required that is one criteria. So, $G_{p, min}$ is actually t_{pr} it is perception reaction as we normally use for vehicular traffic for pedestrian traffic also there is a perception reaction. So, pedestrian perception of signal indication and car departure time and this is taken a 7 seconds and this is taken as 7 seconds as per highway capacity manual 2016.

$$G_{p,min} = t_{pr} + \left(\frac{L_{cc}}{S_p} \right) - y - ar$$

Of course, this value could be even lower could also be higher depending on the context, what is the type of pedestrian and you know different other conditions plus. So, this is the time anyhow required plus pedestrian has to cross. So, what is the value of Lcc? Lcc is nothing but curb to curb crossing distance divided by what is the speed pedestrian walking speed.

So, Lcc by Sp minus yellow time or amber time minus the all-red time. Because we are doing this minus y minus ar, because we are talking about the minimum required time, obviously, ideally it should be little higher. So, this is the one component or one criteria that we need to check. So, our available green time must satisfy this criterion.

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Pedestrian Signal Requirements

✓ **Second: The time required to serve pedestrian demand**

$$G_p = 3.2 + \left(\frac{L_{cc}}{S_p}\right) + \left(2.7 * \frac{N_{ped}}{W_E}\right) \text{ for } W_E = \text{width of crosswalk} > 10 \text{ ft (3 m)}$$

$$G_p = 3.2 + \left(\frac{L_{cc}}{S_p}\right) + (0.27 * N_{ped}) \text{ for } W_E \leq 10 \text{ ft (3 m)}$$

$$N_{ped} = \frac{v_{ped,i} * C}{3600}$$

N_{ped} = number of pedestrians crossing during an interval, ped/cycle
 W_E = effective width of crosswalk (ft),
 $v_{ped,i}$ = pedestrian flow rate in the subject crossing for travel direction
i (ped/h)



Second based on the volume of pedestrians and also how much width we are providing. This is the width of the zebra crossing where people are crossing actually the road. So, if it is greater than 3 meters, then it is 3.2, 3.2 here again is the perception reaction part which was taken here as 7 seconds or could be higher could be lower. What was the tpr? In the second criteria it is taken as 3.2 seconds plus as usual Lcc curb to curb distance divided by the pedestrian walking speed, whatever you take plus, now the number of pedestrians in Nped divided by WE and this formula is valid equation is valid when the width of the crosswalk is greater than 3 meters into 2.7.

$$G_p = 3.2 + \left(\frac{L_{cc}}{S_p}\right) + \left(2.7 * \frac{N_{ped}}{W_E}\right) \text{ for } W_E = \text{width of crosswalk} > 10 \text{ ft (3 m)}$$

$$G_p = 3.2 + \left(\frac{L_{cc}}{S_p}\right) + (0.27 * N_{ped}) \text{ for } W_E \leq 10 \text{ ft (3 m)}$$

$$N_{ped} = \frac{v_{ped,i}}{3600} * C$$

So, per feet or per meter, whatever we take per feet, then multiplied by 2.7. If the width of the crosswalk is less than equal to 3 meter, then more or less the same equation except that this divided by WE that we are not doing. So, it is 0.27 instead of 2.7, there is a difference that way. So, 3.2 remains same. Lcc by Sp it remains same and here it was 2.7 into Nped divided by WE here we are taking 2.7 instead of that we are taking 0.27 into Nped. So, that is the equation, how we can get the Nped? Nped is the number of pedestrian crossing during an interval that is a particular cycle.

So, how many pedestrians are being processed or need to be handled per cycle? How you get that? How much pedestrians are crossing the road, what is the hourly flow rate divided by 3600 multiplied by the cycle time. So, that many pedestrian have to cross this particular place or for this particular travel direction in every cycle. So, that is the way do it.

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Summary

Operational analysis of signalized intersection

- **Step 9: Determine queue storage ratio**
- **Interpreting of results**
- **Initial queue delay**
- **Pedestrian signal requirements**




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So, if I have to summarize I will say today, we discussed about how to determine the queue storage ratio, how to interpret the results, further understanding possible scenarios and how to calculate the initial queue delay. And also little bit mentioned to you briefly about the pedestrian signal requirements, how the existing operation existing signal, the given green time for the pedestrians,

how that can be judged, adequacy of that can be judged. So, with this I close this week 2 also and thank you so much.