

Traffic Engineering
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Lecture 36
Operational Analysis of Signalized Intersection – II

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NPTEL Online Certification Course on
Traffic Engineering

Module E
Traffic Control at Intersections

Week 7: Lecture E.10
**Operational Analysis of Signalized
Intersection-II**



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Recap of Lecture E.9

Operational analysis of signalized intersection

- Step 1: Determine movement groups and lane groups
- Step 2: Determine movement group flow rate
- Step 3: Determine lane group flow rate
 - ✓ Lane group flow rate on shared-lane approaches

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Operational Analysis of Signalized Intersection

Continued.....



Welcome to module E, lecture 10. In this lecture, we shall continue our discussion about operational analysis of signalized intersection. In lecture 9, I mentioned to you about the various steps that are required to be followed to carry out a complete operational analysis and we discussed in details about step 1, 2 and 3. So, we shall continue our discussion today and we shall start with step 4.

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Operational Analysis of Signalized Intersection

Step 4. Determine Adjusted Saturation Flow Rate

- Adjusted saturation flow rate (s) is calculated as:

$$s = s_o f_w f_{HVg} f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} f_{wz} f_{ms} f_{sp}$$

s = adjusted saturation flow rate (veh/h/ln)

s_o = base saturation flow rate (pc/h/ln)

f_w = adjustment factor for lane width

f_{HVg} = adjustment factor for heavy vehicles & grade

f_p = adjustment factor for existence of a parking lane and activity adjacent to lane group

f_{bb} = adjustment factor for blocking effect of local buses that stop within intersection area



Now in step 4, we actually do the estimation of saturation flow rate. Now of course, in step 3 we have seen that we have used a saturation flow value. So, actually step 3 and step 4 will work in an iterative manner. So, every time we need to carry out the calculation in step 3, we have to actually come back to step 4 get the saturation flow values and then go back to step 3 again

to complete the calculation. So, you have seen that, I said that just assume that the saturation flow is given like this.

$$s = s_o f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} f_{wz} f_{ms} f_{sp}$$

So, where from it is coming? It is coming actually from step 4. So, there is always something called base saturation flow rate, that means it is almost we can consider some kind of idealized situation when there is no other factor present which might influence the saturation flow value, always might influence means in this case always bring down the value. So, the base saturation flow is the highest possible value under idealized condition and then we need to do a number of adjustments using appropriate factor to get the saturation value for a prevailing operating condition.

What are the adjustments? Number of adjustments, you can see that so many factors are multiplied with the base saturation flow to get the adjusted saturation flow s . What are the factors? Factors that with respect to lane width, if the standard lane width is not available. If it is much higher or lesser then some adjustment factor. Then adjustment factor with respect to heavy vehicles and great very logically you can get convinced that saturation flow will depend on the percentage of heavy vehicle and also the grade, upgrade, downgrade.

Then adjustment factor due to the existence of parking lane and activity adjacent to lane group, if there is a parking obviously the parking the vehicle will go to the parking lot, will come out from the parking lot and that will create some kind of interference to the traffic stream and therefore it will impact the saturation flow adversely.

Similarly, the bus blocking effect of local buses that stop with the intersection area. If suppose the bus is standing in the or waiting in the bus stop, then for the time the bus is waiting that time the lane is not available. So, obviously the saturation flow rate if we are calculating that will get impacted.

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Operational Analysis of Signalized Intersection

f_a = adjustment factor for area type
 f_{LU} = adjustment factor for lane utilization
 f_{LT} = adjustment factor for left-turn vehicle presence in a lane group
 f_{RT} = adjustment factor for right-turn vehicle presence in a lane group
 f_{Lpb} = pedestrian-bicycle adjustment factor for left-turn groups
 f_{Rpb} = pedestrian adjustment factor for right-turn groups
 f_{wz} = adjustment factor for work zone presence at the intersection
 f_{ms} = adjustment factor for downstream lane blockage
 f_{sp} = adjustment factor for sustained spillback



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Similarly, the type of area whether it is within the CBD area or outside the CBD area because land use and several characteristics are generally likely to be different in CBD area and outside CBD area. Then the lane utilization that I already discussed in my previous lecture, that if there are multiple lanes then shared of even through traffic, if there is a shared lane and there is a straight dedicated lane for the through movement, the traffic distribution may not be same.

Then adjustment factors also for the left hand vehicles present in a lane group. Similarly, for adjustment factors for right turn vehicle, adjustment factor for pedestrians and bicyclist. Suppose, the left turning permitted left hand, the pedestrian volumes it will impact the saturation flow rate. Pedestrian adjustment factor similarly for the right hand group. Then the presence of work zone in the intersection is part of the intersection, the construction activity or the maintenance activity is going on the whole intersection area as normally available otherwise is not available because of the construction, then that will impact.

Adjustment for downstream lane blockage, traffic is getting discharged and the entering may be in one approach. Now when the traffic is entering in one approach, if all the lanes are not available. Suppose one lane is blocked, the lane blockage may happen due to several reasons. There may be some activities like work is happening or maybe some other event is going on so the lane is blockage blocked. So, wherever the lane will be blocked that will then impact the saturation flow or the discharge. Adjustment factor also for sustained spillback, if the downstream intersection is red and because of that the vehicle is queued up.

Now how the queue? The queue has probably gone much longer and when the vehicle is getting discharged, the drivers also probably can see that there is a queue. They have to join a queue,

so naturally the way the discharge happens in normal condition will not happen now. So, all these adjustment factors are to be considered to get the saturation flow under a prevailing condition from the base saturation flow.

Now if you look at the highway capacity manual, each of these adjustment factors, how they are calculated? How in a case specific or context specific situation, how we calculate it. It is quite complex, not so easy. And anyhow when you will do it, you have to refer back to the highway capacity manual 2016 to really know how exactly step by step it is done or what equations you need to use or what table value or tabular value you need to refer. Here I will try to give you some ideas, just to help you to understand the overall process.

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Operational Analysis of Signalized Intersection

Condition & Adjusted Saturation Flow	Omitted Terms	
General Equation $s = s_0 f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} f_{wz} f_{ms} f_{sp}$	-	f_{LU} : lane utilization f_{LT} : left-turn vehicles f_{RT} : right-turn vehicles
Protected operation (TH/LT/RT) in exclusive lanes TH: $s = s_0 f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{wz} f_{ms} f_{sp}$ LT: $s = s_0 f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{wz} f_{ms} f_{sp}$ RT: $s = s_0 f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{RT} f_{wz} f_{ms} f_{sp}$	$f_{LT}, f_{RT}, f_{Lpb}, f_{Rpb}$ f_{RT}, f_{Lpb}, f_{Rpb} f_{LT}, f_{Lpb}, f_{Rpb}	f_{Lpb} : pedestrian-bicycle adjustment (left-turn) f_{Rpb} : pedestrian adjustment (right-turn)
Protected TH operation in a single exclusive lane $s_{th} = s_0 f_w f_{HV} f_g f_p f_{bb} f_a f_{wz} f_{ms} f_{sp}$	$f_{LU}, f_{LT}, f_{RT}, f_{Lpb}, f_{Rpb}$	
Protected LT operation in a shared Lane $s_{sl} = \frac{s_{th}}{1 + P_L(E_L - 1)}$	$f_{LU}, f_{Lpb}, f_{RT}, f_{Rpb}$	
Protected RT operation in a shared Lane $s_{sr} = \frac{s_{th}}{1 + P_R(E_R - 1)}$	$f_{LU}, f_{Lpb}, f_{LT}, f_{Rpb}$	




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Now the general equation what I have mentioned earlier, I am calling it a generalized equation or the general equation because this is something which includes all the factors that are generally possible but then, there are different context and in different contexts all the factors may not be really applicable.

So, let me try to give you a little bit of understanding about various situations. So, one may be protected, another may be permitted. Then left from shared lane or exclusive lane. Like that there are different possibilities left turn and right turn. So, all cases, each of the cases or each case need to be handled separately. So, this is the generalized equation where all factors are present because that is what is possible. But if you take now protected operation, it may be through it may be left turn it may be right turn in exclusive lane. Carefully note that we are talking about exclusive lane not shared lane and then through left or right.

Now, if you consider the through then some of the factors mentioned in generalized equation will not be applicable. For example, I said fLT that is the left turning vehicle because we are calling about exclusive through lane. So, the left turning correction factor due to left turning vehicle will not be applicable. Correction factor for right turning vehicle will not be applicable correction factor for pedestrian bicycle adjustment for left turn and also for right turn will not be applicable.

So, these factors will get omitted that means they will be taken as default value as one, so I have omitted that. Now if you consider the left turn, then out of all these factors if you consider exclusive lane left turn, then obviously the right turn vehicle adjustment will not be required. Similarly, the right hand pedestrians also will not be required and since it is protected operation as well, I have written exclusive lane but also protected operation.

So, once there protected operation also the left turning pedestrian should not be a factor. So, these factors will get omitted from the generalized equation to get the protected operation left turning in exclusive lane.

Similarly, right turning in this case the if RT will be there, right turning vehicle adjustment factor will be there but the left turning vehicle factors will get omitted and as usual pedestrians for left turning and right turning both will get omitted because we are talking about the protected operation not permitted.

Now protected through operation in a single exclusive lane, single exclusive lane. So, here I have written again, how the saturation flow for the through movement can be calculated. We are talking about single exclusive line and protected through operation. So, obviously a fLU, the lane utilization will not be there. Otherwise, lane utilization will come, why the lane utilization is getting dropped? Because we are talking single exclusive lane. So, single lane utilization will not come.

Then also along with that a fLT left turning vehicles, right turning vehicles, left turning and then whatever pedestrians adjustment bicycle adjustment is required that will not be applicable right turning vehicles and with whatever adjustment is required for the presence of or movement of pedestrian bicycles those will not be required. So, these are all omitted.

Now protected left hand operation in a shared lane. Protected left hand operation in a shared lane. Earlier what I said here, left turn operation in an exclusive lane but here it is shared lane.

For the shared lane, you are already familiar to this sorts of equation. I have discussed it we have used it earlier.

Now if it is a shared lane, then whatever is the through saturation flow that will get further modified by two other factors. One is what is the proportion of left turning vehicles in the overall shared lane. How many, how much percentage of traffic is actually taking left hand and also the left hand vehicle equivalency factor because those vehicles which are taking left turn, they will not have similar effect of the vehicle which are moving through.

So, this EL equivalency for the left hand and proportion of left turning vehicle, the same exactly for protected right turn operation, these are all protected. So, the pedestrians are not coming into picture so far. So, the protected right turn operation exactly the same way, here again the through movement what is the through saturation flow then equivalency for right turn, right hand vehicle equivalency and proportion of right turning vehicle in the stream. So, that way we can calculate the saturation flow.

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Operational Analysis of Signalized Intersection

Condition & Adjusted Saturation Flow	Omitted Terms	
Permitted LT operation in exclusive lane $s_l = s_o f_w f_{HV} f_p f_{bb} f_a f_{LU} f_{LT} f_{Lpb} f_{wz} f_{ms} f_{sp}$	f_{RT}, f_{Rpb}	f_{LU} : lane utilization
Permitted LT operation in shared lane $s_{sl} = \frac{s_{lh}}{1 + P_L \left(\frac{E_L}{f_{Lpb}} - 1 \right)}$	f_{LU}, f_{RT}, f_{Rpb}	f_{LT} : left-turn vehicles f_{RT} : right-turn vehicles f_{Lpb} : pedestrian-bicycle adjustment (left-turn) f_{Rpb} : pedestrian adjustment (right-turn)
Protected-Permitted LT operation in exclusive lane During protected period: $s_{lt} = s_o f_w f_{HV} f_p f_{bb} f_a f_{LU} f_{LT} f_{wz} f_{ms} f_{sp}$ During permitted period: $s_l = s_o f_w f_{HV} f_p f_{bb} f_a f_{LU} f_{LT} f_{Lpb} f_{wz} f_{ms} f_{sp}$	f_{Lpb}, f_{RT}, f_{Rpb} f_{RT}, f_{Rpb}	




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Now coming to permitted left hand operation, once it is permitted then protected versus permitted, I say protected operation in exclusive lane and now we are saying permitted left turn in exclusive lane, what is the omission here, from the earlier one is this one, pedestrians. The pedestrians will come into picture, left turning pedestrians. So, what will get omitted is only the right turning vehicle adjustment factor and the pedestrian bicycle adjustment for the right turn lane, that will not be there but otherwise the pedestrian adjustment factor for the left turning you can see f_{Lpb} that is there.

Now permitted left hand operation in shared lane. This again the equation is you are familiar with this equation, shared lane again permitted left hand. How it will depend? It will depend on protected, it depends on what? For protected left hand operation we said that percentage of left turning vehicle and equivalency left turn vehicle equivalency. Now, one more additional or one more factor will come that is what? That is basically f_{Lpb} . The pedestrian bicycle adjustment.

So, pedestrian bicycle adjustment for the left turn. That will come, that will also be a relevant factor here so shared and protected and permitted the only difference is, this is protected left turn and this is permitted left turn, the only difference is the pedestrian. So, along with PL and EL, proportion of left turning vehicle and equivalency for left turn vehicle also the adjustment factor for pedestrian bicycles for the left turn.

Now protected permitted left turn operation in exclusive lane. I have also taught you that what is protected permitted operation? So, when the protected period will be there, this is given like this very similar very logical what we are omitted you can understand from the generalized equation how we are getting this one. Same way during permitted period, it will be the pedestrian volume will come into picture.

So, left turn pedestrian volume will come into picture. So, here the difference is here a f_{RT} , right turn vehicle adjustment is omitted, right turn adjustment for pedestrian vehicles is omitted and here it will be only right turn and right turn vehicle and right turn pedestrian bicycle adjustment will be omitted but permitted the f_{Lpb} , the left hand pedestrian vehicle adjustment that will be coming back. So, that makes it very clear.

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Operational Analysis of Signalized Intersection

Permitted Right-Turn Operation in Exclusive Lane

- ✓ First period of flow begins with the start of the effective green period and ends with the clearance of the opposing queue

$$s_{r1} = \frac{s_r}{\left(\frac{E_{R2}}{f_{Rpb}}\right)}$$

E_{R2} = equivalent number of through cars for a permitted right-turning vehicle when opposed by a queue on a single-lane approach

- ✓ The second period of flow begins after clearance of the opposing flow queue

$$s_r = s_p f_w f_{HV} g f_p f_{bb} f_a f_{LU} f_{Rpb} f_{wz} f_{ms} f_{sp} \quad s_p = \frac{v_o e^{-(v_o t_{cg}/3600)}}{(1 - e^{-(v_o t_{fh}/3600)})}$$

s_p = saturation flow rate of a permitted right-turn movement (veh/h/ln)

v_o = opposing demand flow rate (veh/h)

t_{cg} = critical headway = 4.5 (s)

t_{fh} = follow-up headway = 2.5 (s)



Now what is remaining is the permitted right turn operation in exclusive lane. Now here, there are two things the additional consideration between the left turning permitted and right permitted, the basic difference is left turning permitted means only the pedestrian bicycle. The turning vehicle has to yield to the pedestrians and bicycles.

So, that is the factor. Right turning case, one more thing is there the vehicle is coming from the opposite direction because you are taking right turn and the vehicle is coming, the opposing through movement.

Now when the opposing through movement happens, two possibilities are there. The first is the period begins flow begins with the start of effective green and ends with the clearance of the opposing queue because during red, the opposing queue the straight moving these vehicles were waiting in a queue. So, what happens? When the queue is there, one vehicle will come so that time what will be the opportunity for the right turn or what could be the saturation flow will be very different from the saturation flow during the subsequent period of green.

Subsequent period of green means when the flow begins or when the flow is happening after clearance of the opposing vehicle queue. So, that all the vehicles which are queued up is cleared now in the first period of the effective green then the latter period of effective green there is no queue from the opposing vehicle. So, the discharge will be different.

So, when the second period of flow begins that after clearance of the opposing flow queue, then this saturation flow may be calculated using this equation which is again logical. The only new term here is the S_p , S_p is the saturation flow rate of a permitted right turn movement. Now how you calculate the S_p , this equation is given. It is a function of opposing demand flow rate, very logical, very very logical. What is the opposing demand flow rate so it depends on the opposing demand flow rate. Also it depends on the critical headway and the follow-up headway.

So, the calculation is given here and for the first period when the flow begins with start of effective green period and continue till the clearance of the opposing queue, opposing through movement queue.

So, there will be, this S_r is going you can see here divided by again two factors are considered one is ER_2 , ER_2 is equivalent number of through cars for a permitted right turn vehicle, when opposed by a queue on a single lane approach. The one is the right turn equivalency is there but that under any condition when there is no other thing also, a straight going and a right turn vehicle the equivalence will be different but here it is ER_2 indicates that equivalency for a permitted right turn, for a permitted right turn that means opposing vehicle is considered when opposing opposed by a queue on a single lane approach.

The vehicles are in the queue for the through movement opposing through movement. So, that equivalency factor is different than the normal right turn equivalency and of course the pedestrian part will also come. It will again get impacted by the pedestrian. So, fR right turn vehicle and the pedestrian bicycle adjustment. So, that is what it is.

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Operational Analysis of Signalized Intersection

Base Saturation Flow Rate

- If metro population >250,000 : 1900 pc/h/ln
- Otherwise: 1750 pc/h/ln

Adjustment for Lane Width

Average Lane Width (ft)	Adjustment Factor f_w
<10.0 (~ 3 m)	0.96
≥10.0-12.9 (~3.0 to 3.9 m)	1.00
≥ 12.9 (~3.9 m)	1.04



Now with this, let's try to get a little bit of more understanding how we get the values. Now, for base saturation flow rate, we can normally assume it as 1900 pcu, per hour, per lane pcu or passenger car unit or passenger car equivalency equivalent whatever you say, pc passenger car per hour per lane. If the metro population is less greater than 250,000 otherwise it is 1750. So, as per highway capacity manual 2016.

Then this is the lane adjustment factor, it was actually given in feet but we have also mentioned here in meter equivalent meter or approximate what is the meter so if the lane width is in the range of 3 to 3.9 meter approximately, then it is 1, if it is lesser than then, then 0.96 and greater is 1.04.

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Operational Analysis of Signalized Intersection

Adjustment Factors for Heavy Vehicles & Grade, Bus Blockage & Parking

Factor	Formula	Description
Heavy Vehicles & Grade	If grade (-) is downhill: $f_{HVG} = \frac{100 - 0.79P_{HV} - 2.07P_g}{100}$ If grade (+) is level or uphill: $f_{HVG} = \frac{100 - 0.78P_{HV} - 0.31P_g^2}{100}$	P_{HV} = Percent of heavy vehicles in the movement group P_g = Approach grade for the corresponding movement group (%)
Bus Blockage	$f_{bb} = \frac{N - \frac{14.4N_b}{3600}}{N} \geq 0.050$	N = Number of lanes in lane group (ln), N_b = Bus stopping rate on the subject approach (buses/h).
Parking	$f_p = \frac{N - 0.1 - \frac{18N_m}{3600}}{N} \geq 0.050$ $f_p = 1.0$ for no parking	N = Number of lanes in lane group (ln), N_m = Number of parking maneuvers/h



Now this is table, I am showing or in this slide I am showing adjustment factors for three things, heavy vehicles, heavy vehicles and grade together, then bus blockage and parking. So, actually for four things but then heavy vehicles and grade are combined because the grade also will impact the heavy vehicles. So, heavy vehicles and grade are combined, then the bus blockage, then the parking. Now heavy vehicles and grade obviously the factor depends on the percentage of heavy vehicle and what is the grade.

Now there are two formulas which are given here one is for the downhill, negative grade and one is for the uphill, approach the positive grade. So, grade what is the grade? Positive or negative, if it is negative or downhill, we will use the first equation. If it is positive, we will go for the with that plus value will go to the second equation and then percentage of heavy vehicle and what is the grade?

Now bus blockage, what is bus blockage? Bus will stop in the normally the curb side lane, the outer lane. Now whenever bus is stopping, then that time the discharge is getting affected. So, how much time actually the bus is occupying? Now, if that can be estimated, then we know how much time that lane is available for through movement. So, this equation is given you can say capital N minus $14.4 N_b$ by 3600, the whole thing divided by N.

Now, it is almost like if one bus is actually stopping, then the impact is, you can consider like 14.4 seconds. So, if there are N_b number of buses in an hour, then N_b into 14.4 seconds is actually that lane is not available. So, that out of 3600 seconds in an hour? So, it is n minus this divided by n. So, what will happen, if suppose the $14.4 N_b$ becomes actually 3600, just theoretically I am saying, that always there is a bus, that means the whole lane is not available. So, what you have actually, it is not N number of lane but it is N minus 1. That is an extreme situation but it helps you to understand this equation.

In the similar way, the parking, every parking manoeuvre will have some interference. Sometime in terms of time, a few seconds 18 seconds you can consider that it is affecting the movement. So, you cannot have the normal movement. So, 18 into N_m , number of parking manoeuvre divided by 3600, so N minus 0.1 minus this by N. So, approximately, you know this are basically logical equations.

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Operational Analysis of Signalized Intersection

Adjustment for Area Type, Left & Right turns, Work Zone, Lane Blockage & Spillback

Factor	Formula	Description
Type of Area	$f_a = 0.9$ for CBDs $f_a = 1.0$ for all other cases	-
Left Turns	$f_{LT} = \frac{1}{E_L} \geq 0.05$	E_L = Equivalent number of through cars for a protected left-turning vehicle (= 1.18)
Right Turns	$f_{RT} = \frac{1}{E_R} \geq 0.05$	E_R = Equivalent number of through cars for a protected right-turning vehicle (= 1.05)
Work Zone Presence	If no work zone is present $f_{wz} = 1.0$	Refer to HCM
Downstream Lane Blockage	If no downstream lane blockage is present $f_{ms} = 1.0$	Refer to HCM
Sustained Spillback	If no spillback occurs $f_{sp} = 1.0$	Refer to HCM



Now, next is adjustment for area type, left and right turn, work zone, lane blockage and spill back. Now in this case, type of the area if it is CBD you take 0.9 for all other areas 1, this is the left turn, left turn is equivalent number of through curves in a protected left turning vehicle. So, one by EL equivalency for the left turn, right turn again one by ER, similar way and this I am not going to discuss in details that if there is work zone, then how to do the adjustment factor. How to calculate it.

Similarly, the downstream lane blockage or if there is sustained spill back then how to do the correction factors. How to calculate this corresponding factors. So, please refer to HCM for knowing these things because within the limited time I will not be able to discuss everything. So, if no work zone is present, if no downstream land blockage is present, if no car spillback occurs, then in each case the corresponding factors will be one. If nothing is present that is not a factor then it is 1. So, always otherwise there will be a value less than one and you can refer to this.

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Operational Analysis of Signalized Intersection

Adjustment for Lane Utilization

- The lane utilization adjustment factor is calculated as

$$f_{LU} = \frac{v_g}{v_{g1}N}$$

v_g = demand flow rate for the lane group, veh/h,

v_{g1} = demand flow rate for the single lane with the highest volume, veh/h/ln

N = number of lanes in the lane group

Movement Group	No. of lanes in Movement group	Traffic in Most Heavily travelled Lane	f_{LU}
Exclusive Through	1	100.0	1.000
	2	52.5	0.952
	3	36.7	0.908
Exclusive Right Turn	1	100	1.000
	2	51.5	0.971
Exclusive Left Turn	1	100	1.000
	2	56.5	0.885



Now the next part is adjustment for lane utilization. This you know, you have understood it earlier also. I discussed it, but here the equation is slightly different. What is it doing, the lane utilization adjustment factor, if it is demand flow rate for the lane group V_g , that means total demand for the lane group divided by demand flow rate for the single lane with the highest volume. Single lane in that lane group, multiple lanes are there.

So, the lane which is having the highest demand flow rate, multiplied by the number of lanes. So, it is very similar in terms of its calculation is very similar to the calculation of like peak hour factor. What we do, hourly flow rate divided by peak 15 minute flow rate. So, peak 15 minute flow rate multiplied by 4.

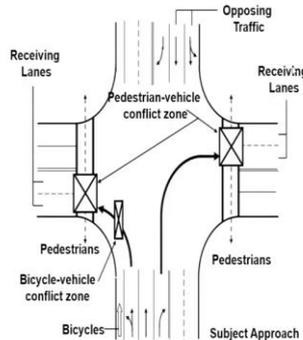
So, similarly here that 4 is not that 4 is for 15 minute to 60 minute conversion but here similar kind of thing we are saying the total flow divided by the lane which is taking the maximum flow rate multiplied by number of lanes. So, somewhat like the peak hour factor calculation, so this table gives you that for exclusive through, for exclusive right turn, for exclusive left hand then depending on the number of lanes in the lane group. Now always if it is one lane, then it is factor is always one there is no question of utilization or sharing but more than one, how we take it. So, that you can take the value from the table, but conceptually you can calculate it also or you can otherwise also calculate it based on this equation.

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Operational Analysis of Signalized Intersection

Pedestrian Adjustment Factors

Step A: Determine Pedestrian Flow Rate During Service



$$v_{pedg} = v_{ped} \frac{C}{g_{ped}} \leq 5000$$

v_{pedg} = pedestrian flow rate during the pedestrian service time (ped/h)

v_{ped} = pedestrian volume (ped/h)

g_{ped} = pedestrian service time (can be assumed to equal the effective green time for the phase)



Now going back to our own example problem which we started in the last week, in the last lecture rather not last week in this week itself the last lecture. So, we continue with that, here we have to also do, I am sorry this is not that example problem but now we are talking about pedestrian adjustment factor, I am sorry. So, pedestrian adjustment factor, so this we discussed about the lane utilization.

So, now come to the pedestrian adjustment factor. Now pedestrian adjustment factor, suppose what is happening, here the left turn here this you know vehicles are taking right turn, here also vehicle may take left turn. So, the pedestrian movements are there. Now the pedestrian along with bicycle also could be there but we are neglecting the bicycle movement for the discussion at present. So, what we are saying here, pedestrian flow rate during service, what is the service? Service mean when actually the pedestrian signal is green.

So, what is then that pedestrian flow rate during the pedestrian service time or when the pedestrian signal is green. Very simple what it is happening? If the V_{ped} , is the pedestrian volume generally at what rate pedestrians are arriving that is V_{ped} . So, how many pedestrians are arriving during a cycle time C , V_{ped} multiplied by C in some form, taking care of the units that many pedestrians are there but they are crossing when? They are crossing during the green time given for pedestrians so all those pedestrians are actually crossing during the green time for pedestrians.

So, when the pedestrian green is there what is then the pedestrian flow rate? So, obviously V_{ped} into C is equal to V_{pedg} when it is green time multiplied by pedestrian green time effective green time. So, you can get then V_{pedg} that means then what is the pedestrian flow rate during the pedestrian service time.

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Operational Analysis of Signalized Intersection

Step B: Determine Average Pedestrian Occupancy

$$OCC_{pedg} = \frac{v_{pedg}}{2000} \quad (v_{pedg} < 1000 \text{ peds/h})$$

$$OCC_{pedg} = 0.4 + \frac{v_{pedg}}{10000} \leq 0.90 \quad (1000 < v_{pedg} < 5000)$$

OCC_{pedg} = Average pedestrian occupancy

Step C: Determine Relevant Conflict Zone Occupancy,

OCC_r

$$OCC_r = \frac{g_{ped}}{g} OCC_{pedg} \text{ (for no bicycle interference)}$$



Next stepwise approach again not so simple. Now determine the average pedestrian occupancy, now that is the pedestrian flow rate during the service time or during the pedestrian green time and now we want to calculate the occupancy. There are two formulas which are given one for pedestrian volumes if it is less than thousand and another case it is more than thousand and less than 5000 in that range. So, you get the average pedestrian occupancy.

Now, once we have got that we need to calculate relevant conflict zone occupancy. What is the conflict zone occupancy? Is g_{ped} pedestrian what is the effective green time for pedestrian divided by what is the green time overall green time effective green time into this average pedestrian occupancy. Now obviously this equation is given considering there is no bicycle interference as I said that, I did not consider bicycle effect when I am explaining the equations.

(Refer Slide Time: 33:46)

Operational Analysis of Signalized Intersection

Step D: Determine Unoccupied Time, A_{pbT}

If number of cross-street receiving lanes = the number of turn lanes,

$$A_{pbT} = 1 - OCC_r$$

If number of cross-street receiving lanes > number of turn lanes

$$A_{pbT} = 1 - 0.6 OCC_r$$

LT Adjustment factor: $f_{Lpb} = A_{pbT}$

RT Adjustment factor: $f_{Rpb} = A_{pbT}$



Then determine then, unoccupied time. So, what is then unoccupied time? The number of cross street receiving lane, if it is equal to number of turn lane, then it is 1 minus OCCr, OCCr is what? This relevant conflict zone occupancy. Now, understand that if the entire green for this lane group movement, whatever is the green given for a movement and where pedestrian interference is happening. If the pedestrian green is also for the entire period, then OCC pedg, average pedestrian occupancy and conflict zone occupancy will be same.

They will only be different suppose the green is for 40 seconds but the pedestrian green conflicting one, pedestrian green is for 30 seconds, then in that case conflict zone occupancy will be different from average pedestrian occupancy because not the full green, entire green which is available for that lane group, they have to face pedestrian interference but if it is gped equal to g, then the for the entire green they have to face the pedestrian interference.

So, depending on that unoccupied time that means when there is no pedestrian interference. So, this will only have some positive value if the gped is lesser than g. Then only OCCr will be less than OCC pedg. So, 1 minus this value sense wise and if it is number of turn lane, so you can get this.

Now, if there are number of cross street receiving lane is greater than number of lanes, then what will happen? Number of turn lanes may be one but number of cross street receiving that lane is more than that or it is two and there it is more than that. So, number of cross street receiving the lane is higher. So, traffic will get distributed to more number of lanes when they are entering in the receiving lanes.

So, in that case it will not be 1 minus OCCr but 1 minus 0.6 OCCr, that is what is assumed or suggested by highway capacity manual. There is a logic for everything. Now how, I cannot explain here, why the value is 0.6 exactly, but there is a logic for everything. Why this consideration is there? Similarly, you can see here left turn adjustment factor, now it will be f_{Lpb} will be then this A_{pbT} similar will be the right turn adjustment factor.

(Refer Slide Time: 37:08)

Operational Analysis of Signalized Intersection

Problem:

3@ 3.75 m

1100
170

200 900 120

Crosswalk 1

Underpass for pedestrians

Crosswalk 2

2@ 3.6 m

2 m

2@ 3.6 m

5@ 3.4 m

25 buses/h

Non-CBD location

930
175

Assume the given through and turning volumes are adjusted for PHF
Analysis Period: 0.25 h

Phase Diagram

(A1) G =10s, y=2s, ar= 2s

(A2) G =22s, y=2s, ar= 2s

(B) G =16s, y=2s, ar= 2s

Assume lost time/phase: 4 s

Crosswalks 1 and 2 sees 85 peds/h and used during phase A2

Pedestrian underpasses are provided under EB and WB approaches

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Operational Analysis of Signalized Intersection

Input data elements:

Direction	EB		WB		SB		
	TH	RT	LT	TH	LT	RT	
Demand flow rate (veh/h)	1100	170	175	930	120	900	200
Initial queue (veh)	0	0	0	0	0	0	0
P_{HV} (%)	10		10		10		
Platoon Ratio	1	1	1	1	1	1	1
Bay length (m)	60	60	100	100	100	100	100
Approach grade (%)	0		0		2		
Approach Speed (km/h)	45		45		45		
Analysis period duration (h)	0.25		0.25		0.25		

Bay length: Length available behind the stop line for the vehicle queue built up during the red time at an approach

Assume the given through and turning volumes are adjusted for PHF

1100
170

200 900 120

930
175

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Now coming back to the problem, our own problem you remember that the phase A1, A2 and b, the green times are 10 second, 22 second, 16 second, yellow already times are given, lost time force again, cross walk and 2 sees 85 pedestrian per hour in phase 2. So, with all these now we try to do, we are just establishing the data here. So, demand flow rate, the same data was given in the earlier lecture also when I discussed lecture 9, I used the same example

problems. So, with all these data, I have now the bay length and everything is available approach speed, all the data is available.

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Operational Analysis of Signalized Intersection

Consider EB:TH Input Data: Slide 16, 17

$$s = s_o f_w f_{HVg} f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} f_{wz} f_{ms} f_{sp}$$

$$s = s_o f_w f_{HVg} f_{bb} f_a f_{LU}$$

$$s = 1900 * 1 * 0.922 * 0.950 * 1 * 0.952 = 1584 \text{ tpc/h}$$

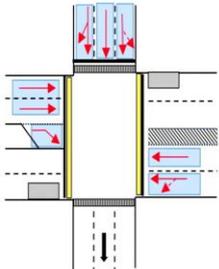
$f_w = 1$ (lane width 3.4 m i.e. between 3.0 to 3.9 m) (Slide 9)

$$f_{HVg} = \frac{100 - 0.78 P_{HV} - 0.31 P_g^2}{100} = \frac{100 - 0.78 * 10 - 0.31 * 0}{100} = 0.922$$

$$f_{bb} = \frac{N - \frac{14.4 N_b}{3600}}{N} = \frac{2 - \frac{14.4 * 25}{3600}}{2} = 0.950$$

$f_a = 1$ (Non-CBD location) (Slide 11)

$f_{LU} = 0.952$ (Exclusive through movement & number lanes = 2) (Slide 12)






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Now with this, let me try to show you the calculation, how we consider then the east bound through traffic. This is the east bound, the east bound through traffic. How we can calculate the saturation flow? It is considered exclusive lane, so the general formula is this but then some of these terms will not be applicable because there is no interference with the pedestrian, there is no left turning or right turning vehicles here. So, many of these factors will be omitted. So, effectively these factors will be there.

Now, f_w is 1, what is f_w ? Because we have lane width 3.4 meter we have said and as per the table if you go to slide 9 we have mentioned that if it is 3 to 3.9, then the adjustment factor is 1, so we take it as 1. Then if f_{HVg} 0.922. How we are getting? We are calculating here, this is the formula and we have 10 percent heavy vehicle. So, put it as 10 percent and grade is 0, it is level. So, that is 0 so you get f_{HVg} as 0.922. And the next correction is, f_{bb} , bus stop yes, there is a bus stop here and we have seen that there are 25 buses per hour.

So, N minus 14.4 into 25 divided by 3600 and here is two number of lanes. Here, 2 minus this all together you get 0.950. And, since it is a non-CBD location, so area adjustment factor we take as one, you may refer to slide 11, we have said there non CBD one and CBD how much? 0.9 or 95, I also forgot. Yes, 0.9 for CBD. But here it is outside CBD, non-CBD location, you can see here it is in non-CBD location. So, that is why the value is taken as 1. So, f_{LU} is 0.952 because it is exclusive through movement and there are two number of lanes, you can similarly go back to slide 12 and see how we have calculating.

(Refer Slide Time: 40:53)

Operational Analysis of Signalized Intersection

Consider WB: LT/TH Input Data: Slide 16, 17

$f_{l_{pb}}$: Pedestrians cross the minor street (NS Street) during phase A2, with a green time: $(22 + 4 - 4) = 22$ s

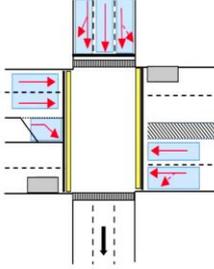
Step A: $v_{pedg} = v_{ped} \frac{C}{g_{ped}} = 85 * \left(\frac{60}{22}\right) = 231$ peds/h

Step B: $OCC_{pedg} = \frac{v_{pedg}}{2000} = \frac{231}{2000} = 0.115$

Step C: $OCC_r = \frac{g_{ped}}{g} OCC_{pedg} = 0.115$

Step D: $A_{pbT} = 1 - 0.6OCC_r = 1 - 0.6 * 0.115 = 0.931$

$f_{l_{pb}}(WB LT/TH) = 0.931$






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Now, for the east bound. Similarly, we have to do the calculation for the west bound through and L left. Westbound through L left, now here the f_{Lpb} pedestrian is important will be a consideration because this is permitted movement left turning one. So, pedestrian cross minus streets, north south street. It is crossing in phase A2 with a green time of how much? We have calculate it as 22 seconds. You know that cycle time is given, the yellow time, the already time, the lost time all are given. So, you can calculate it, you know this calculation.

Now, we are going to step A, B, C and D, one after another. So, what is V_{pedg} ? Simply apply this equation, 85 pedestrians per hour multiplied by cycle time is 60, green time is 22. So, you get this flow rate during green what is the, when pedestrian green is there what is the flow rate? The flow rate is equivalent, flow rate is 231 pedestrians per hour, obviously higher. Higher than 85 why higher? Higher is the overall cycle how many are coming, what is the rate? Now all are to be, all are getting discharged ideally in the pedestrian green time. So, what is the flow rate there? That flow rate is 231.

Similarly, you calculate that OCC_{pedg} in this case, it is 231 divided by 2000 using the simple formula as I have shown here 2 or 3 slides back, here yes, it is less than 1000 pedestrian so this equation is governing. Then we have to calculate OCC_r , it is g_{ped} divided by g into OCC_{pedg} , I have all discussed this one. So, you calculate that OCC_{pedg} and also the step C, and now you can say one minus this is the A_{pbT} . So, that comes 0.931. So, that is the calculation. So, f_{Lpb} is 0.931 that is the one.

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Operational Analysis of Signalized Intersection

Direction	Lane Group	Number of Lanes	s_0	f_w	f_{HVg}	f_p	f_{hb}	f_a	f_{LU}	f_{LT}	f_{RT}	f_{Lpb}	f_{Rpb}	f_{wz}	f_{ms}	f_{sp}	s
EB	TH	2	1900	1	0.922	1	0.950	1	0.952	1	1	1	1	1	1	1	1584
	RT	1	1900	1	0.922	1	1	1	1	1	0.952	1	1	1	1	1	1668
WB	TH	1	1900	1	0.922	1	1	1	1	1	1	1	1	1	1	1	1752
	TH/LT	1	1900	1	0.922	1	0.900	1	1	0.847	1	0.931	1	1	1	1	X
SB	TH/RT	1	1900	1	0.910	1	1	1	1	1	0.952	1	1	1	1	1	X
	TH	1	1900	1	0.910	1	1	1	1	1	1	1	1	1	1	1	1728
	TH/LT	1	1900	1	0.910	1	1	1	1	0.847	1	1	1	1	1	1	X

Note: X= Saturation flow cannot be calculated directly for shared lane group. These are calculated in conjunction with step 3 in iterative manner

- Saturation flow for SB Shared Lanes

(Protected Right-Turn Operation): $s_{sr} = \frac{s_{th}}{1+P_R(E_R-1)}$

(Protected Left-Turn Operation): $s_{sl} = \frac{s_{th}}{1+P_L(E_L-1)}$




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Now, I take you to this mother table where I can show then for eastbound, westbound and south bound each approach for each lane group what are the corresponding adjustment factor values you can check it, you can do the calculation on your own based on this understanding and I have shown you how you are actually calculating the saturation flow.

Now while for east bound, I have shown through and right, given the value, westbound through I have given the value, south bound also through I have given the value. But for the shared lane, I have not given the value written as x. Why? What is the reason? You know the reason, this value will also depend on proportion of left turn and right turn.

So, every iteration when you are doing the calculation in step 3, every iteration your proportion of left turn, right turn as applicable for an approach. Say for southbound shared lane both left turn and right turn will be there but for through lane, for west bound it will be only the left turn.

So, it depends on the PR. So, what was doing? Every time you do the calculation in step 3, you are actually, you know what is the PR or PL corresponding PL, you come back here put that PR or PL value, then you get a saturation flow rate for the shared lane protected right turn operation, protected left turn operation and then you actually go back to step 3 and calculate the flow, link flow. So, this is the formula that is to be used so I cannot write a value here because it will depend on what is the value of PR, this PR will and PL will control.

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Operational Analysis of Signalized Intersection

$s_{th} = s_o f_{w} f_{HVg} f_{p} f_{bb} f_{a} f_{wz} f_{ms} f_{sp}$

For SB: TH/LT and TH/RT Lane Groups

$s_{th} = s_o f_{HVg} = 1900 * 0.910 = 1728 \text{ pc/h}$

$s_{sr} = \frac{1728}{1+0(1.05-1)} = 1728 \text{ tpc/h}$ $s_{sl} = \frac{1728}{1+0(1.18-1)} = 1728 \text{ tpc/h}$

For WB: TH/LT Lane Group

$s_{th} = s_o f_{HVg} f_{bb} = 1900 * 0.922 * 0.900 = 1577 \text{ pc/h}$

$s_{sl} = \frac{s_{th}}{1+P_L \left(\frac{E_L}{I_{tpb}} - 1 \right)} = \frac{1577}{1+0 \left(\frac{1.18}{0.931} - 1 \right)} = 1577 \text{ tpc/h}$

Note: $P_L=0$ and $P_R=0$ are taken from iteration 1 of Step 3 (previous lecture) and corresponding shared lane saturated flow rates are obtained. These shared sat. flow rates serve as a further input in Step 3 for iterative procedure to obtain lane group flow rates

Input Data: Slide 16, 17




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So, here I have shown the calculation here for our case, south bound through left and through line right lane groups. Now through value is 1728, it is fixed for a given context. Now, first iteration, where it started? Recall our discussion about in step 3 in the previous lecture, we started with 0 percentage of left turn and 0 percentage of right turn. So, initially to start with, so there with 0, you put the value here as 0. So, you get this value 1728 in both cases.

For west bound, southbound we did not do the calculation but mentioned it that always in the first case we assume that proportion of left turn and right turn in the shared line is zero. Now for west bound a similar calculation is done, you get 1577 and you recall, if you recall there also we use the value 1577 where it came, where from it came, it is all through this calculation which is and steps what I have discussed in today's lecture and because the PL is 0 to s through and Ssl because the PL is 0 therefore the s through Ssl left turning is same.

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Operational Analysis of Signalized Intersection

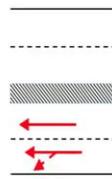
For WB Approach (TH + LT) Shared Lane (Details in previous lecture)

Input data:

V_{lt}	V_{th}	N_{sl}	N_t	E_L	f_{Lpb}	S_{th}
175	930	1	1	1.18	0.931	1577

Initial Estimate:

V_{app}	V_{sl}	$V_{sl,lt}$
552	552	0



Iterative calculations for obtaining saturation flow and lane group flow rate:

Iteration	V_t	P_L	S_{sl}	S_t	y	V_{sl}	$V_{sl,lt}$
1	378	0	1577	1577	0.2949	465	175
2	640	0.3763	1432	1577	0.3672	526	175
3	579	0.3327	1448	1577	0.3654	529	175
4	576	0.3309	1448	1577	0.3653	529	175
5	576	0.3308	1448	1577	0.3653	529	175





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So, here I have shown the calculation brought back those values as well, how we got it. So, you can say, every case the through is same but every iteration how the shared lane, left turning how the saturation flow value is getting calculated depending on the percentage of left turning vehicle and eventually that is giving you all the final flow, V_{sl} , $V_{sl,lt}$, that value you are getting. And we stopped after 5 iteration because it converged, there is no change. Recall again connect it to my previous lecture, lecture 9 and step 3.

So, the step 3 table also I have brought it here in a meaningful form, so that the whole thing is available to you and these are the volumes, these are the corresponding saturation flow and this is the value of PL and this is the corresponding value of y.

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Operational Analysis of Signalized Intersection

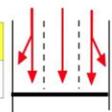
TH/LT and TH/RT Shared Lane Groups (Details in previous lecture)

Input data:

N_{sl}	N_t	N_{sr}	V_{lt}	V_{th}	V_{rt}	E_R	E_L	S_{th}
1	1	1	120	900	200	1.05	1.18	1728

Initial Estimate:

V_{app}	V_{sl}	$V_{sl,lt}$	V_{sr}	$V_{sr,rt}$
406.7	406.7	0	406.7	0



Iterative calculations for obtaining saturation flow and lane group flow rate:

Iteration	V_t	P_L	P_R	S_{sl}	S_t	S_{sr}	y	V_{sl}	$V_{sl,lt}$	V_{sr}	$V_{sr,rt}$
1	87	0	0	1728	1728	1728	0.174	300	120	300	200
2	620	0.400	0.667	1612	1728	1543	0.250	403	120	385	200
3	432	0.298	0.519	1640	1728	1581	0.247	404	120	390	200
4	426	0.297	0.513	1641	1728	1582	0.246	404	120	390	200
5	426	0.297	0.513	1641	1728	1582	0.246	404	120	390	200





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The same calculation I have shown now for the shared lane group through left and for the southbound approach, what are the input data, what are the initial estimates then and then here also again what is the PL and PR, initially it is 0. So, then all the three values are same but as in subsequent iteration PL and PR values are changing, similarly the Ssl shared lane left and shared length right Ssr the values are also changing, higher the proportion lower is the value.

And accordingly, the V_{sl} , V_{slt} , V_{sr} , $V_{sr rt}$. All the values are getting calculated and finally this when there is a convergence there is nothing much is changing then we are stopping. So, it is actually step 3 and step 4 are working together in an iterative form. You are in step 3 but then you need the saturation flow, you know what is the percentage of left turn, percentage of right turn now you go back and also for the through, through of course you do not have to go back again and again, but first time you have to get the values from step 4 only.

And step 4, you have to come back again and again as the percentage is changing, so the saturation flow for the shared lane, shared left, shared right for each of the approach and each context you have to come back and calculate from step 4. Once you have taken the saturation flow value from step 4, you will again go back to step 3 and finish the remaining calculation to get all these volume values.

(Refer Slide Time: 50:29)

Operational Analysis of Signalized Intersection

Lane Group Flow Rate & Adjusted Saturation Flow

Direction	Lane Groups (LG)	Lane Group Flow Rate (pc/h)	Adjusted Saturation Flow (pc/h)
EB	LG 1: Exclusive TH	1100	1584
	LG 2: Exclusive RT	170	1668
WB	LG 1: Exclusive TH	576	1752
	LG 2: TH + LT	529	1448
SB	LG 1: TH/RT	390	1582
	LG 2: Exclusive TH	426	1728
	LG 3: TH/LT	404	1641




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So, finally you get all this, what different direction, different lane group and what are the lane group flow rate and the saturation flow values both are summarized in this table and the red values are something which we could not get directly. So, following all these procedures we are finally getting it.

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Operational Analysis of Signalized Intersection

Step 5: Determine Proportion Arriving During Green

- Arrival Type 3: $R_p = 1.0$ and Cycle Length = 60 s
- Proportion arriving during green: $P = R_p \left(\frac{g}{C} \right)$





Direction	Lane Groups (LG)	Phase	Green time (G)	Change interval (y)	Clearance interval (ar)	Lost Time	Effective Green time (g)	P
EB	TH	A + B	36	2	2	4	36	0.600
	RT	A	10	2	2	4	10	0.167
WB	TH	B	22	2	2	4	22	0.367
	TH/LT	B	22	2	2	4	22	0.367
SB	TH/RT	C	16	2	2	4	16	0.267
	TH/LT	C	16	2	2	4	16	0.267

Note: All times are given in seconds




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Now, the last slide probably here is determination of proportion of vehicle arriving during green, this will be required subsequently for our calculation of control delay. So, we know the platoon ratio, let us take arrival time as three and platoon ratio as one, cycle length is already given 60 seconds based on this example problem and input.

So, what we do here, we know the direction, we know the lane group, we know the phase how it is operating, what is the green time, what is the change interval, clearance interval, lost time. So, you can easily get the effective green time. Once you get the effective green time, effective green time by cycle into the R_p , platoon ratio. So, you get the value of P, proportion of vehicle arrive at during green time. I think I will stop here.

(Refer Slide Time: 51:50)

Summary

Operational analysis of signalized intersection

- Step 4: Determine adjusted saturation flow rate
 - ✓ Saturation flow (exclusive lanes in protected mode)
 - Adjustments corresponding to lane width, heavy vehicles & grade, parking activity, bus blockage, area type, lane utilization, left-turn & right-turn vehicles, pedestrian-bicycle interference, work zone, downstream lane blockage, sustained spillback
 - ✓ Saturation flow (shared lanes in protected/ permitted mode)
- Step 5: Determine proportion arriving during green




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So, what we discussed basically about the step 4, majority of the time we spent how to calculate the saturation flow. First for the exclusive lane in protected mode and then how interestingly it can be done for the shared lane in protected or permitted mode and how step 3 and step 4 are working together.

Step 3 we are going to, step 4 coming back to step 3 finishing the thing going deciding whether you need to go for the next iteration then again you are coming to step three essentially at certain stage, referring back to again step 4 because your PL and PR proportion of left turning and right turning vehicles are changing, get the saturation flow value from step 4 going back there and the whole work is done together.

And finally, I have shown you how to determine the arrival proportion of vehicle arrival during the green time. So, with this I close this lecture. We shall continue again because we could go up to step 5 and we shall continue. Thank you so much.