

Traffic Engineering
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Lecture 32
Delay as a Performance Measure

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Recap of Lecture E.5

- Saturation flow and saturation headway
- Lost times
 - ✓ Start-up & clearance lost times
- Intervals
 - ✓ Green, red, change & clearance intervals
 - Dilemma zone
- Capacity of lane group
- Arrival type & platoon ratio

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Welcome to Module E, lecture 6. In this lecture we shall discuss about delay as a performance measure. In lecture 5, I introduced to you about the concept of saturation headway and saturation flow also the startup and clearance lost time, the total lost time, the green interval, red interval, change interval, clearance interval or the concept of dilemma zone and then also explained to you how we can calculate the capacity of a lane group. Finally, I mentioned to you about what is platoon ratio and how the platoon ratio can be used to describe different types of arrival of vehicle at signalized intersections.

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Performance Measures

- Level of Service (LOS) measures which are used to characterize the operational quality for signalized intersection or lane group are:
 - ✓ **Delay:** Delay refers to the amount of time consumed in traversing the intersection-difference between the arrival time and departure time, where these may be defined in a number different ways
 - ✓ **Queuing:** The number of vehicles forced to queue behind the stop line during red signal phase
 - ✓ **Volume to capacity ratio:** The degree to which a phase's capacity is utilized by a lane group



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Today, we shall talk about performance measures and specifically about delay as a performance measure. There are several measures which can be used to describe the level of service or to characterize the operational quality for signalized intersections. For example, one possible measure is delay, delay refers to the amount of time consumed in traversing the intersection and generally indicates the difference between the arrival time and the departure time where these may be different in a number of different ways.

So, that means, yes conceptually you know what is delay, but there are so, many ways that delay can be quantified and considered also to measure the level of service at signalized intersections. Also, the queuing as another measure the number of vehicles forced to queue behind the stock line during the red signal phase.

We will also consider volume to capacity ratio a very important measure because that is that indicates the degree to which a phase capacity is utilized by a lane group. So, different types of methods related to delay giving volume to capacity ratio, all are different possible methods to define the level of service or to characterize the operational quality of signalized intersections or lane group. Among all these measures, the most important and widely used measure is the delay.

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Delay as a Performance Measure



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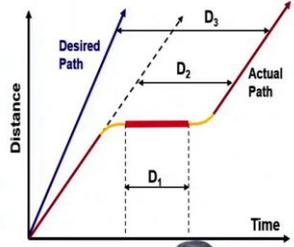
Delay as a Performance Measure

Types of Delay

Stopped-time Delay (D_1): Time for which vehicle is stopped in queue while waiting to pass through the intersection

Approach Delay (D_2): (Stopped-time delay) + time loss due to deceleration from approach speed to a stop and time loss due to acceleration back to the desired speed

Travel-time Delay (D_3): Time difference between the driver's expected travel time through the intersection and the actual time taken



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So, now in the subsequent part of this lecture, we shall discuss specifically on delay as a measure of performance. There are different types of delays for example, one is the stop delay also we can use approach delay as a measure, travel time delay is also another possibility, let us look at this plot what I have shown. It is a time distance diagram, the solid red line with a constant flow as you can follow the slide follow my cursor movement. This indicates when the vehicles are arriving and crossing the intersection in green.

So, the correspondingly this time we can consider this is basically the green time then this is amber followed by red. Now, when the green is over, amber is introduced, then the flow rate will decrease and eventually vehicle will come to stop. So, that is shown through this yellow segment and then the red phase starts so, the signal is red. So, obviously distance wise vehicles

are not moving anymore, so, vehicles are completely stopped. And that is why this solid and thick red line, horizontal red line it is parallel to time axis indicating that vehicle is stopped condition is in stopped condition.

So, when the vehicle is completely in stopped condition, this is the time difference or this is the time shown as D1 part that is the stop delay that means, time for which vehicle is stopped in queue while waiting to pass through the intersection. So, now the vehicle is in red signal so, the vehicle is waiting and this is the stop delay. Now, once the red phase is over, red indication is over then again, the vehicle starts moving, but there will be initially not immediately it will go to a steady state discharge.

Slowly the discharge will go up as that is the portion which is shown here again in through this yellow line, then you can say again the solid red line straight solid set red line as it is shown here actual path the vehicle starts moving during the next green. So, the approach delay now is actually the stop time delay that is the D1 plus time lost due to deceleration from approach speed to a stop and time lost due to acceleration back to the desired speed. What does it indicate?

It indicates clearly also this yellow segment at 2 ends of red because the first user segment is what? It is time lost due to deceleration from approach speed to a stop and the other yellow segment indicates that time lost due to acceleration back to the desired speed. So, the D2 you can clearly now understand from this figure is a measure of approach delay, which includes stop delay plus time lost due to deceleration from approach speed to stop plus the time lost due to acceleration back to the desired speed.

Also, sometimes we use a term what is called travel time delay, what is travel time delay? It is the time difference between the drivers expected travel time through the intersection and the actual time taken. So, this is supposed a desired path by looking at this solid blue line and the solid red line you can clearly understand that the desired travel path, desired speed or desired travel time is better than the actual time. Desired speed is higher as compared to the actual average speed or so, and desired travel time is lower than that actual travel time. So, this is the desired path and this is the actual path of movement.

So, it is the time difference between the drivers expected travel time through the intersection and the actual time taken and the actual time taken. So, D3 is actually a measure of the travel time delay that means, you probably expect that at 40 kilometer per hour speed I can travel

through that intersection. So, how much time it takes? If I can travel at the desired speed or my expected travel time is then whatever is the corresponding time and what time is actually taking for me to clear the vehicle. It is the difference of these 2-travel time that is called as travel time delay.

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Delay as a Performance Measure

Theoretical Modelling of Delay

- Depiction of arrivals and departures at a signal allows the estimation of three critical parameters:
 - ✓ Total time that any vehicle 'i' spends waiting in the queue, $W(i)$
 - ✓ Total number of vehicles queued at any time 't', $Q(t)$
 - ✓ The aggregate delay for all vehicles passing through the signal is the area between the arrival and departure curves (vehicle x time)

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Now, coming to the theoretical modeling of delay, depiction of arrival and departure at a signal shows that you can actually estimate all the 3 critical parameters namely total time that the vehicle a particular vehicle spends waiting in the queue, the number of vehicles that are queued at any time t and also the aggregate delay of all vehicles passing through the signal. All these 3 critical parameters you can actually quantify. Let us again look at this graph this is the green time, so the vehicle is let me first tell that the blue line solid blue line as I am please follow the cursor the solid blue line is actually the arrival curve.

The red line, solid red line is actually the departure curve and the arrival rate is such that for this portion the arrival and departure is same that means whatever is vehicles are arriving all of them are able to clear the intersection that is the idea. So, arrival and departure curve is same, but this point onwards the signal becomes red ignore that startup delay, end delay, total delay ignore those for the time being because conceptually we are trying to understand a few fundamental things.

So, this point onwards arrival curve goes because vehicles arriving at a constant rate this is the cumulative vehicle arrival therefore, is increasing over time, but the cumulative departure is not happening because the signal is red, so, all vehicles are queued up and stopped. Now, when

the red is over and again the signal turns to green then the discharge is happening. So, now the departure is happening as per the capacity whatever saturation flow is there, the green time is given now, so the discharge starts happening and eventually if the demand and the arrival departure is in that way. So, then eventually let us assume that this departure curve will catch up the arrival curve.

So, whenever it catches up if in the immediate next green it catches up, then all the vehicles which were actually queued up because of the red indications all are now cleared and again the operation goes back in the green interval as it was there in earlier green interval that means the vehicles which are arriving during the green are all able to clear.

So, this is a situation where vehicles which are arriving during the green all are cleared all are able to clear the signal. Vehicles which are arriving during the red they are queued up, but eventually in the immediate next green interval all those queued up vehicles are also cleared and you come back to the original or the earlier situation.

So, you can see here the red line is again meeting the blue line and then blue line and red line are actually together in the sense. So, here now if you look at this area, which is shown as the shaded area, this indicates what? This indicates the aggregate delay of all vehicles passing through the signal is the area between the arrival and departure curve. So, that is what the area indicates the aggregate delay. The number of vehicles queued at any time t is what? This is the difference, why difference between the departure curve and arrival curve.

So, many vehicles arrived at a given time t and so many vehicles are cleared both are cumulative, because look at this y axis it is cumulative vehicle. So, many vehicles arrived at the intersection up to time t and so many vehicles actually cleared intersection as shown in the using the red line, solid red line cleared the intersection up to time t . So, how many vehicles are there in the queue, it is the difference between these 2.

Similarly, what is basically the total time that any vehicle i spends waiting in the queue. So, if you take any vehicle i what is the time the vehicle is waiting in the queue is that why it is the time wise difference between the arrival curve and the departure curve. So, we can calculate total time any vehicle i spends waiting in the queue, we can calculate the total number of vehicle queued at a given time, we can also calculate the aggregate delay.

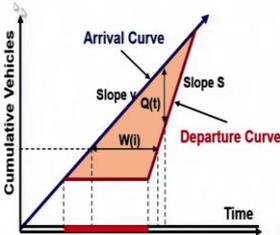
Only one condition here is as shown in the curve, vehicle which are even in the green all are able to clear. Vehicle which are arriving during the red they are all also cleared during the

immediate green and the cumulative departure curve and cumulative arrival curve they are again meeting together.

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Delay as a Performance Measure

- From the plot of vehicle arrivals in queue and departures from queue, the model closely represents **time-in-queue delay**, $W(i)$
- Basic assumptions considered for this plot
 - ✓ **Uniform vehicle arrivals:** At a completely isolated intersection, actual arrivals would be random, while inter arrival times would vary around an average rather than being constant



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Now, from the plot vehicle arrival in queue and departure from queue, the model closely represents actually time in queue delay, that is W_i that is what we can calculate. Now, there are certain basic assumptions considered for this plot. First is uniform vehicle arrival. At a completely isolated intersection, actual arrival would be random. But while inter arrival and inter arrival time would actually vary around an average rather than being constant, but what we are considering here is uniform vehicle arrival.

Always the headway between the time gap between arrival of 2 successive vehicle is constant. But what we are indicating here, in reality, it will not be constant because it will be random. And the actual arrival times would vary around an average rather than being a constant. But that is the assumption here. That is one assumption.

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Delay as a Performance Measure

- ✓ **Queue builds at a point location** (as if vehicles were stacked on top one another). In reality, as the queue grows, vehicle arrival rate at its end is the arrival rate of vehicles (at a point), plus a component representing the backward growth of queue in space

Delay Scenarios

- ✓ **Stable flow**
- ✓ **Individual cycle failures within a stable period**
- ✓ **Demand exceeds capacity for significant period**

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There is a second assumption implicitly that is queue builds at a point location as the vehicles were stacked on top of one another. But what will happen in reality? As the queue is growing vehicle arrival rate at its end, end of the queue, is the arrival rate of vehicles and that is at a point plus a component representing the backward growth of queue in space because queue is growing going back if 10 vehicles have arrived, then the queue has gone up to 10 vehicles back.

Now, coming to different delay scenarios, depending on how the arrival is happening and how the discharge can happen for a given intersection. There could be several delay scenarios based on whether it is stable flow, whether it is individual cycle failure within a stable flow or stable period or whether demand exceeds capacity for significant period. The first one is stable flow means there is no cycle failure. Every individual cycle, the arrival whatever vehicle are arriving at the intersection approach the all those vehicles can be cleared in every cycle.

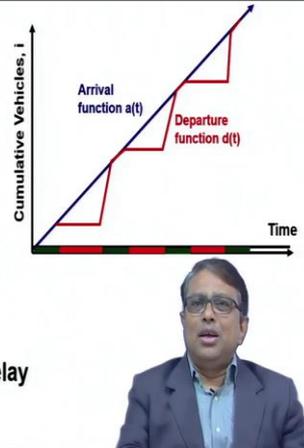
Second, it has 1 or 2 in between some individual cycle failure could be there, but within the period, which is reasonably shorter period, not just 1 cycle or 2 cycle, but also not like 6 hours or 5 hours; a shorter period. Overall it is stable. That means overall whatever vehicles are arriving at the intersection or intersection approach all can be cleared, but in between 1 or 2 individual cycle failure may be there. The third is a scenario when actually demand is significantly higher for an overall reasonable time period. I have written here a significant period so the demand exceeds capacity for significant period.

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Delay as a Performance Measure

Stable Flow

- No signal cycle failures
- During every green phase the **departure function catches up with arrival function**
- Total aggregate delay = Total of all the triangular areas between the arrival and departure curves
- This delay is often referred to as uniform delay



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So, if we want to represent stable flow, as you can see here it is red and green, red and green. So, one is the arrival function, this shows the cumulative vehicles another there is the departure function, what is really happening, arrival and departure function is same here. Once the red starts then it deviates arrival function and departure function become different vehicles are waiting, stop delay is happening and again end of the red the departure starts happen and overall arrival and departure rates are such that the within this green itself the red line is going back and meeting the blue line again.

So, in every cycle, the red line and blue line are meeting back joining back, you can see here all this small triangles which have been created due to the stopping of vehicle during the red ultimately the red line is every time joining back to the blue line that means, the cumulative discharge and cumulative arrival is equal discharge is able to pick up the cumulative arrival indeed indicating that there is no vehicle in the queue when the signal or the when the green time is, no backlog, no queue is remaining all vehicles which are arriving within a signal cycle is cleared.

So, there is no signal cycle failure during every green phase, the departure function catches up with the arrival function that is what I have shown here, the arrival function is shown in the blue line the departure function is shown in the red line. So, the red line is catching up the blue line and total aggregate delay in this case is total of all the triangular areas between the arrival and departure curves.

Every cycle what is the delay, in that cycle area of the triangle, next cycle again area of the triangle. So, if you consider the time period, then what is the total delay? Sum of all these triangle areas, so, this delay is often referred to as uniform delay, why because we are assuming the vehicle is arriving at a uniform rate. And second one which is underlying thing that departure and arrival is such that there are all vehicles which are arriving during the green are able to clear the intersection vehicles which are arriving in the red all are also cleared immediately in the next green. So, there is no residual queue or no backlog.

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Delay as a Performance Measure

Individual Cycle Failures

- Individual cycle failures within the period occurs (**Overall period of analysis is stable**)
- At the end of time period, departure function catches up with arrival function
- Second delay component, in addition to uniform delay, which known as **overflow delay** is the area between the arrival function and the line representing the intersection capacity

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Second, look at this it is quite interesting. There are individual cycle failures. So, again the solid blue line and solid red line same meaning as I have shown in the previous slide. Here, eventually the red and the blue line are catching up, it is catching up at this point, it is catching up again at this point, catching up here at this point. So, overall if you see overall during this period, the cumulative arrival and cumulative departure is same. That means overall all the vehicles which are arriving in the intersection are able to clear the intersection, but not every individual cycle it is happening.

So, for example, you can see here the vehicles are waiting in the red and then cleared but all the vehicles could not be cleared here. So, the red line could not go and touch the blue line it remained somewhere here. Next again, it could not touch it remained here it did not touch really the blue line, so, that means did not touch means. All the vehicles which are accumulated during red could not be cleared along with whatever new vehicles are arriving during that green all could not be cleared.

So, whenever it is catching up means what, in one cycle, it is catching up, catching up means what, whatever vehicles who are waiting during the red and whatever vehicles which have arrived now during the green all could be cleared during this green time. That is why the cumulative arrival and cumulative departure could catch up. But here in individual cycle some of the individual cycle, there is a failure that means not that all the vehicles which were there in the queue or which arrived even during the green, next green could be cleared in the same green interval.

So, individual cycle failure within the period occur. So, overall period of analysis is stable because eventually overall analysis it is catching up at the end of time period departure function catches up with arrival function, second delay component in addition to uniform delay, which is known as overflow delay, overflow means when even in individual cycle the demand is more than the capacity that is why the overflow is happening. Overflow delay is the area between the arrival function and the line representing the intersection capacity.

So, the solid blue line is actually the actual arrival and the dotted blue line is what, as if the arrival if it would have followed that dotted line then there would not have been any overflow delay or even individual cycle failure that line we are saying is capacity function that means, that rate of uniform arrival could have been handled by this intersection without even a single cycle failure. So, now the overflow delay how we can measure? It is the area between the arrival function that is the solid blue line and the line representing the intersection capacity that dotted blue line.

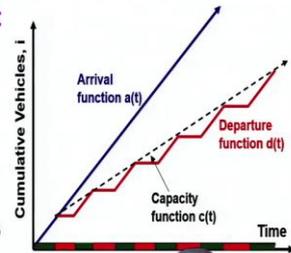
So, we can calculate the area between this capacity function and the departure function that gives us like the previous case the delay plus there is an additional component because of individual cycle failure that is coming as the area between the arrival function and the line representing the intersection capacity. So, the total area you will get and that will be the total delay.

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Delay as a Performance Measure

Demand Exceeds Capacity for Significant Period

- Demand exceeds capacity (Worst case)
- Every green interval fails
- The residual or unserved queue of vehicles continues to grow throughout the analysis period
- The overflow delay component grows over time, quickly dwarfing the uniform delay component



Now, this is another extreme case, where you can see that demand exceeds capacity for significant period. It is not catching up finally, the solid red and solid blue line and not really meeting and not catching up. So, substantially higher arrival demand as compared to the capacity or whatever could be discharged or handled. So, demand exceed capacity clearly is the worst case, every green interval fails the residual or unserved queue of vehicles continued to grow throughout the analysis period and the overflow delay component grows over time quickly dwarfing the uniform delay component.

So, uniform delay component now becomes small. The major component of the delay is the overflow delay. First case, no overflow delay, it is only uniform delay, the second little bit of overflow delay. And here predominantly it is overflow delay. Uniform delay component is small. That is kind of failure that shows that signal is not able to. Eventually you may ask say sir, what does it mean, it will it be like this. No, the demand arrival function sometimes will again become different the demand will come down.

So, maybe in the peak hour you are not able to clear in 1 cycle or 2 cycle here long queue everything is going well, but eventually the peak hour will go the demand will come down at some point in time so it will meet. But it is over a longer period significantly reasonably significant a longer period that demand actually exceeds the capacity not like 1 or 2 individuals cycle.

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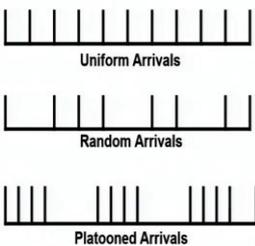
Delay as a Performance Measure

Components of Delay

Uniform Delay: Based on assumption of uniform arrivals and stable flow with **no individual cycle failure**

Random Delay: The additional delay because flow is **randomly distributed** rather than uniform at isolated intersections

Overflow Delay: The additional delay that occurs when the **capacity** of an individual phase or series of phases is **less than the demand** or arrival flow rate



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Now, as you can understand there are different components of delay therefore, one is the uniform delay assuming that uniform arrival and stable flow with no individual cycle failure. So, the vehicles are arriving following this pattern, uniform arrival first vehicle to second vehicle, second to third, third to fourth, fourth to fifth, the time gap is exactly same. It is not a realistic assumption, but that is what is the assumption with that and no individual cycle failure whatever delay you are getting, we call it as uniform delay, what is then the random delay?

Random delay is the additional delay because the flow is randomly distributed rather than uniform at isolated intersection. So, we assume that it is uniform arrival, it is not a uniform arrival, it is following a distribution rather it is a random arrival. So, there will be a little bit additional component of delay, additional delay, because the arrival is not actually uniform, but random.

Third, there is overflow delay that means, the additional delay that occurs when the capacity of individual cycle fails or series of phases is less than the demand or arrival flow rate. What is said has this scenario and also the previous scenario, this is the individual cycle failure case and this is the cycle failure case for a significantly longer period multiple cycles are failing.

So, uniform delay, random delay, uniform delay is with the assumption of uniform arrival and no individual cycle failures. So, no overflow delay in this case, random delay is only further adjustment considering that arrival is not uniform. And whenever, either for individual cycles or over a significant period of time the demand exceeds the capacity, then the overflow delay will come.

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Delay as a Performance Measure

Delay Models

Webster's Uniform Delay Model

$$UD_{Agg} = 0.5RV \quad \& \quad UD = \frac{0.5C[1-(g/C)]^2}{1-(g/C)X}$$

UD_{Agg} = aggregate uniform delay, veh-s;
 R = length of red phase, s;
 V = total vehicles in queue, veh;
 UD = Average uniform delay per vehicles, s/veh;
 C = cycle length, s; g = effective green time, s;
 v = arrival flow rate, veh/h; c = capacity of intersection approach, veh/h; X = v/c ratio or degree of saturation;

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Now, there are several delay models, one very famous and well accepted well known model is the Webster uniform delay model. And the aggregate delay in this case can be calculated simply as the area of the curve. So, 0.5 into R, R is this base into V, V is this height. So, simply the area and the average delay per vehicle can be calculated using this formula as shown in the slide.

$$UD_{Agg} = 0.5RV$$

$$UD = \frac{0.5C[1-(g/C)]^2}{1-(g/C)X}$$

You will know here g is the effective green time, c is the capacity or the g is the effective green time, C is the cycle length, so g by c ratio means it is that effective green to cycle time and then also the vehicle arrival flow rate everything is considered here you can see it here. So, this is the uniform delay part this is the uniform delay model as I go back uniform arrival low individual cycle failure then you can use this formula to calculate that delay.

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Delay as a Performance Measure

Random Delay Model

$$RD = \frac{X^2}{[2v(1 - X)]}$$

RD = Average random delay per vehicles, s/veh;
X = v/c ratio or degree of saturation;
v = arrival flow rate, veh/h;
c = capacity of intersection approach, veh/h

- This formulation somewhat **overestimates delay**
- Webster proposed that total delay (sum of UD + RD) be estimated as: **D = 0.90 (UD+ RD)**



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Now, there is also another model, which is for the calculation of random delay. Now, this random delay, why is random delay I have explained it because the arrival is not uniform. So, there will be additional delay. So, that component of delay you can calculate using this formula. Carefully observed that there is the term in the denominator 1 minus X what is X? X is the v by c ratio or degree of saturation, I mentioned about degree of saturation earlier. So, what it indicates that the degree of saturation is 1, the delay random delay will be infinity as per the model, it is not very realistic.

$$RD = \frac{X^2}{[2v(1 - X)]}$$

Now, this formula somewhat overestimates the delay. So, Webster proposed that the total delay, total delay will be how much? Uniform delay plus random delay, random delay is only because of that reason, that arrival is not uniform, it is random. So, uniform delay plus random delay together will be the total delay. And what Webster said that let it be 0.9 of that sum or summation of delays because otherwise it little bit overestimates the delay. So, let us take 0.9 into UD plus RD.

$$D = 0.90 (UD+ RD)$$

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Delay as a Performance Measure

Overflow Delay Model

$$OD = \frac{T(X-1)}{2}$$

where,

- OD = Average overflow delay per vehicles, s/veh;
- X = v/c ratio;
- v = arrival flow rate, veh/h;
- c = capacity of intersection approach, veh/h
- T= analysis period, h



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Now, there is also an overflow delay model, which is like T into X minus 1 by 2, T is the over the analysis period, X is actually capital X is the volume to capacity ratio and remaining terms are similar.

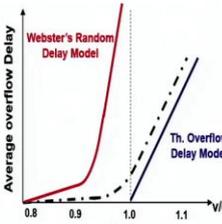
$$OD = \frac{T(X-1)}{2}$$

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Delay as a Performance Measure

Inconsistencies in Random & Overflow Delay Models

- **Inconsistency occurs** in both random and overflow delay when the **v/c ratio is around 1.0**
- With v/c ratio < 1.0, there is no overflow delay. As per model, **random delay increases asymptotically** to an infinite value as **v/c ratio approaches 1.0**
- When v/c ratio =1.0, the overflow delay is zero and as v/c increases further, the overflow delay increases uniformly (as per model)
- Neither model is accurate when the v/c ratio is around 1.0 – the delay does not become infinity with v/c =1.0



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Now, what you find there is some level of inconsistency in the random delay and overflow delay model, what are the inconsistencies? Now, these inconsistencies actually are there in both models, when the volume to capacity ratio is around 1 here X is around 1 here also X is around 1 why we are saying that there is some kind of inconsistency because we with v by c ratio than

1 there is no overflow delay and as per model the random delay increases asymptotically to an infinite value as v by c approaches to unity.

You can see this model as v by c increasing X is increasing the random delay is increasing drastically and when the X is 1 random delay is infinity. So, that is why we say that when v by c ratio is less than 1 there is no overflow delay in this case overflow is not there, because the v by c ratio is less than 1. So, there is no question of overflow delay generally, but as far as the model the random delay increases asymptotically to an infinite value as the v by c ratio approaches to 1 it is going to be almost infinite.

When v by c ratio is 1 the overflow delay is theoretically 0. And as v by c increases further, the overflow delay increases uniformly this is again as per the overflow delay model. So, if you take up this model that is what is you get. More than one it increases linearly almost uniformly it is increasing. So, the neither model is accurate when the v by c ratio is around 1 because the delay does not become infinity when the v by c is 1 if you take the random delay model it says the delay will be infinity when the v by c is 1 that is unrealistic.

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Delay as a Performance Measure

- There is **no true overflow with $v/c=1.0$** but individual cycle failure do occur due to random arrivals. The overflow delay of zero is also unrealistic
- The **additional delay** of individual cycle failures due to **randomness of arrival is not considered** in the overflow model
- **Uniform delay** is a sufficient predictive tool when **v/c ratio ≤ 0.85** . **Simple overflow delay model** (when added to uniform delay) is a reasonable predictor **when v/c ratio is ≥ 1.15**
- Model developed by **Akcelik** is commonly used to bridge this gap (**$0.85 < v/c < 1.15$**)



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Similarly, there is no true overflow delay with v by c ratio as 1, but individual cycle failure do occur due to random arrivals, because the uniform arrival if you would consider then there is no cycle failure. But even if when v by c is 1, cycle failure does occur due to random arrivals, individual cycle failure, so, over the period is still stable. So, the overflow delay is of 0 is also unrealistic. The actual problem is the additional delay of individual cycle failure due to randomness of arrival is not considered in the overflow model.

So, uniform delay is a sufficient that what is found from experiences or applications that uniform delay is a sufficient predictive tool when the v by c ratio is less than or up to 0.85 because the uniform delay component to random delay component will be very insignificant. So, it gives fairly good result, uniform delay. Simply overflow delay model with when added to uniform delay, because overflow delay component gives only the additional delay due to overflow.

So, the random component will be there. Now, the overflow delay model when added to uniform delay is a reasonable predictor when the v by c ratio is greater than 1.15. So, in between portion is really a problem that cannot be captured well with this model both are unrealistic. So, the model developed by Akcelik is commonly used to bridge this gap for particularly for the range of volume to capacity ratios saturation degree of saturation, 0.85 to 1.15.

If I go back and show you can see here is a dotted line. So, this is as per Webster, the random delay model infinity when it is 1 and when it is 1 the overflow delay model theoretical overflow delay model again shows 0, but it is none of these are true. So, you can see actually it combines and the dotted line tries to predict something more realistic than these 2 models. So, that said is say the model developed by Akcelik is commonly used to bridge this gap.

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Delay as a Performance Measure

$$OD = \frac{cT}{4} \left[(X-1) + \sqrt{(X-1)^2 + \frac{12(X-X_0)}{cT}} \right]$$

$$X_0 = 0.67 + \left(\frac{sg}{600} \right)$$

OD = 0.0 s/veh for $X \leq X_0$

where,

- T = analysis period, h;
- X = v/c ratio;
- c = capacity, veh/h;
- s = saturation flow rate, veh/s;
- g = effective green time, s




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Now, this is the model that is given by Akcelik and I need not explain this model again. So, you can see that I have given it here.

$$OD = \frac{cT}{4} \left[(X - 1) + \sqrt{(X - 1)^2 + \frac{12(X - X_o)}{cT}} \right]$$

$$X_o = 0.67 + \left(\frac{sg}{600} \right)$$

OD = 0.0 s/veh for $X \leq X_o$

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Delay as a Performance Measure

Example: An intersection approach has an approach flow rate of 1100 veh/h, a saturation flow rate of 2,900 veh/h, a cycle length of 90 s, and a g/C ratio of 0.60. What average delay per vehicle is expected under these conditions?

Solution: Capacity for the intersection approach

$$c_i = s_i \frac{g_i}{C} = 2900 * (0.60) = 1740 \text{ veh/h}$$

$$v/c \text{ ratio} = X = 1100/1740 = 0.632 \text{ (Relatively low value)}$$

The uniform delay equation may be applied directly. There is little random delay at such a v/c ratio and no overflow delay to consider




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Let us take an example, that an intersection approach as an approach flow rate of 1100 vehicles per hour is saturation flow rate up 2900 vehicles per hour, cycle length 90 second and g by C ratio 0.6, what is the average delay per vehicle expected? Now obviously, you can calculate the capacity, saturation flow into effective green time by cycle time. So, 1740 v by c ratio you can say 0.632, so 0.6 it is relatively low value as they say that up to 0.85, the uniform delay model is quite good. So, we apply simple uniform delay model and no need to consider overflow delay or random delay.

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Delay as a Performance Measure

$$UD = \frac{0.5c[1-(\theta/c)]^2}{1-(\theta/c)X} = \frac{0.5 \cdot 90[1-(0.60)]^2}{1-(0.6) \cdot 0.632} = 11.6 \text{ s/veh}$$

Example: How would the above result change, if the demand flow rate increases to 1700 veh/h?

Solution: v/c ratio changes to 1700/1740 = 0.977

- This is in the difficult range of 0.85-1.15 for which neither the simple random flow model nor the simple overflow delay model are accurate



So, you simply calculate it using Webster uniform delay model and you calculate the it is 11.6 seconds per vehicle. Now, how would the above result change if the demand flow rate increases to 1700 vehicle? Now, in that case, the only change will be the v by c ratio. So, v by c ratio will be now 0.977 very high. So, it is a problematic range neither the random delay model nor the overflow model as given earlier can work. So, this is the difficult range for which neither the simple random flow model not the simple overflow model are accurate.

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Delay as a Performance Measure

Total delay, however, includes both uniform delay and overflow delay

$$UD = \frac{0.5c[1-(\theta/c)]^2}{1-(\theta/c)X} = \frac{0.5 \cdot 90[1-(0.60)]^2}{1-(0.6) \cdot 0.977} = 17.4 \text{ s/veh}$$

Using Akcelik's overflow delay model (Assume T = 1 h)

$$OD = \frac{1740 \cdot 1}{4} \left[(0.977 - 1) + \sqrt{(0.977 - 1)^2 + \frac{12(0.977 - 0.7425)}{1740 \cdot 1}} \right] = 10.5 \text{ s/veh}$$

$$X_0 = 0.67 + \left(\frac{sg}{600} \right) = 0.67 + \left(\frac{2900 - 0.6 \cdot 90}{3600 \cdot 600} \right) = 0.7425$$

Total delay (d) = 17.4 + 10.5 = 27.9 s/veh



So, what we will do? This is the case where we should use actually Akcelik's model. So, the Akcelik's model is applied you can see the detailed calculation method and accordingly the delay is calculated.

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Delay as a Performance Measure

Control Delay

- It represents the **average delay experienced by all the vehicles** that arrive during the analysis period
- It includes any delay incurred by the vehicles that are still in queue after the analysis period ends

The control delay (d) for a given lane group is computed by following equation,

$$d = d_1 + d_2 + d_3$$

d_1 =Uniform Delay; d_2 =Incremental delay; d_3 = Initial queue delay



Now, there is also one more concept one more very important concept is the control delay. Now, control delay represent the average delay experienced by all the vehicles that arrived during the analysis period. And it includes any delay incurred by vehicle that are still in the queue after the analysis period, because you were doing considering all the vehicles for the analysis period. So, even the analysis period is over, but if all the some of the vehicle have still not cleared the intersection the delay is still happening. So, you have to continue the analysis that way beyond the analysis period.

So, that is what you see it represent average delay experienced by all vehicle that arrives during the analysis period, but all vehicles may not be able to clear the intersection during this analysis period, but I want delay for all those vehicles which have arrived during the analysis period.

So, I have to include analysis or continue the analysis continue the measurements whatever you say, the delay which will be incurred vehicles that are still in queue after the analysis period ends, because they have not cleared the intersection. The control delay for a given lane group can be computed using 3 component d_1 , d_2 , d_3 , d_1 is the uniform delay, d_2 is the incremental delay and d_3 is the initial queue delay.

$$d = d_1 + d_2 + d_3$$

d_1 =Uniform Delay; d_2 =Incremental delay; d_3 = Initial queue delay

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Delay as a Performance Measure

- Incremental delay (d_2) consists of two delay components
 - ✓ **Overflow delay** (due to the effect of **random, cycle-by-cycle fluctuations** in demand that occasionally exceed capacity)
 - ✓ Delay due to **sustained oversaturation** during the analysis period (when aggregate demand during the analysis period exceeds aggregate capacity)
- Initial queue delay (d_3) accounts for the additional **delay incurred due to an initial queue**. This queue is a result of unmet demand in the previous time period
- Control delay as per HCM 2016 will be discussed further in future lectures



Now, the incremental delay, first part is straightforward uniform delay, the incremental delay actually consists of 2 delay components, one is the overflow delay, that is due to the effect of random cycle by cycle fluctuation in demand that occasionally exceeds capacity. Go back to this scenario somewhat similar to this we are seeing that kind of individual cycle failure sometimes it is happening.

So, that condition also can be taken care and also, the second one is delay due to sustained over saturation during the analysis period, where actually the overflow is there for a significant period of time overflow delays that over a longer period of time also the demand is much higher than what probably can be discharged through that intersection approach.

Third, d_3 is the initial queue delay that accounts for additional delay incurred due to an initial queue and this queue is a result of unmet demand in the previous time period overflow is there. So, it is the delay vehicles which could not be cleared that is the queue is the result of unmet demand in the previous analysis period. Now, we shall I shall come back to you with a lot more discussion about the control delay in subsequent lectures. So, this is very important, we just introduced you to this concept of control delay at this stage.

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Delay as a Performance Measure

Control Delay

- It represents the **average delay experienced by all the vehicles** that arrive during the analysis period
- It includes any delay incurred by the vehicles that are still in queue after the analysis period ends

The control delay (d) for a given lane group is computed by following equation,

$$d = d_1 + d_2 + d_3$$

d_1 =Uniform Delay; d_2 =Incremental delay; d_3 = Initial queue delay



And telling that there are 3 components of control delay, one is uniform delay component, incremental delay component and initial queue delay.

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Summary

- Performance measures
 - ✓ Delay, volume to capacity ratio, queueing
- Delay as performance measure
 - ✓ Stopped-time delay, approach delay, travel-time delay
 - ✓ Delay scenarios
 - ✓ Theoretical modelling of delay
 - ✓ Inconsistencies in random and overflow delay models



So, with this we close, so what we discussed today is about initially various performance measures that delay volume to capacity ratio and queueing. Then subsequently discussed about stop time, approach time, travel time delay, also various delay scenarios, theoretical modeling, also discussed about the inconsistency in then the random and overflow delay model and how this can be overcome by the Akcelik's model. So, with this I close this session. Thank you so much.