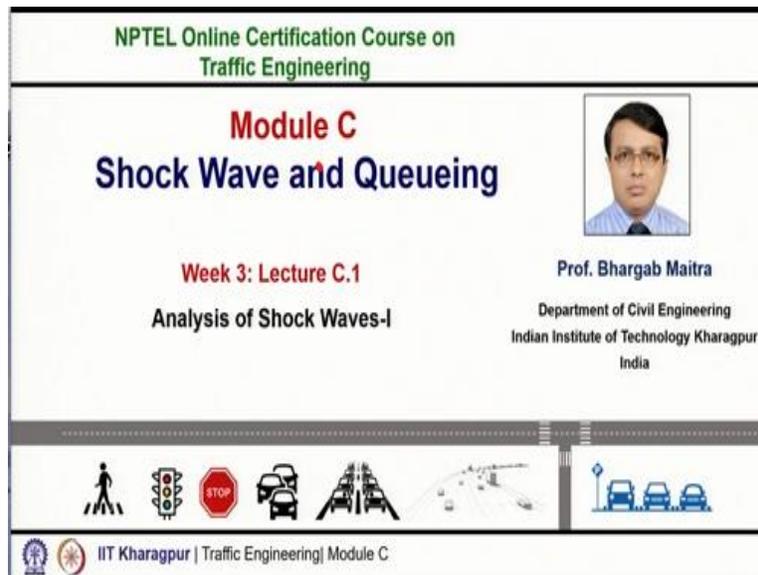**Traffic Engineering**
Professor. Bhargab Maitra
Department of Civil Engineering
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Lecture 11
Analysis of Shock Waves-I
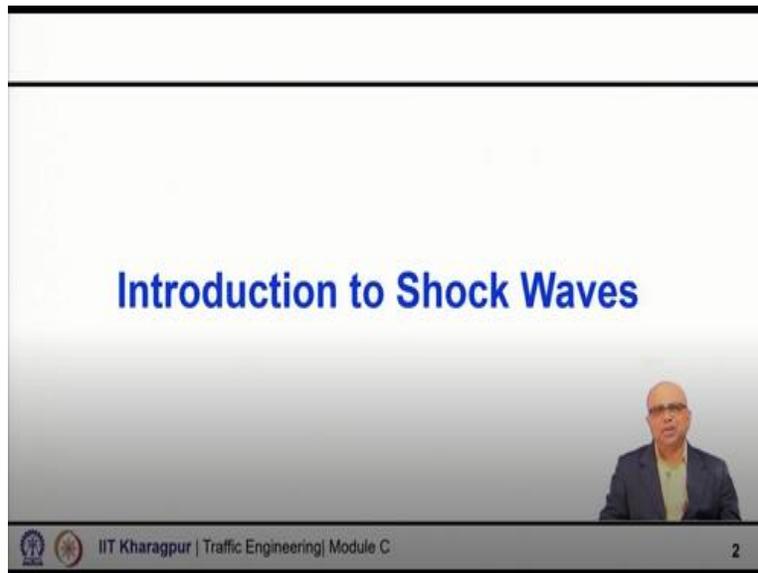
Welcome to Module C lecture 1.

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In this module we shall discuss about shockwave and queuing and this lecture will be on analysis of shockwaves.

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First, what is shockwave?

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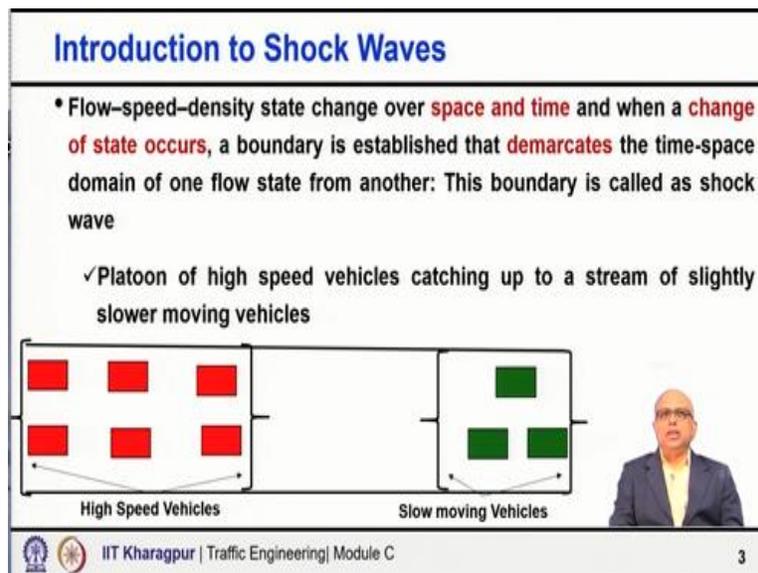
Flow speed density state change over space and time. When you travel through road due to change in roadway traffic and control conditions, the flow speed and density all these macroscopic parameters do not remain same throughout the travel stretch, it will change. Also over a period of time the travel state like the speed flow and density will change because the travel traffic volume will change and the roadway condition and the control condition also may change some time.

So, when a change of state occurs one traffic state to another traffic state, here I mean not that change means steady state to fourth flow condition, no. It may be all our steady state, but the speed flow and density values from one section to another section is not exactly the same. So, wherever there is a change in flow speed and density it will be called a different traffic state. So, when two such traffic states are there, there will be a boundary in between.

So, a boundary is established that demarcates the time space domain of one flow state from another and this boundary is called as the shockwaves. Examples maybe platoon of high speed vehicles catching up to a stream of slightly slower moving vehicles. Let us see here in this sketch. The red vehicles are actually high speed vehicles which are trying to catch up the slow moving vehicles which are shown as green blocks. So, the traffic state here and the traffic state which is there in this block of red vehicles are not going to be same.

So, when these vehicles are really catching up these green vehicles or the slow moving vehicles, then there will be somehow two traffic states one represented by this green vehicles eventually the red vehicles when they catch up, they will also move along with this green vehicle. So, they become like green blocks and somewhere upstream vehicles will be in operating conditions such as shown here as shown here in using the red blocks. So, two traffic state will exists.
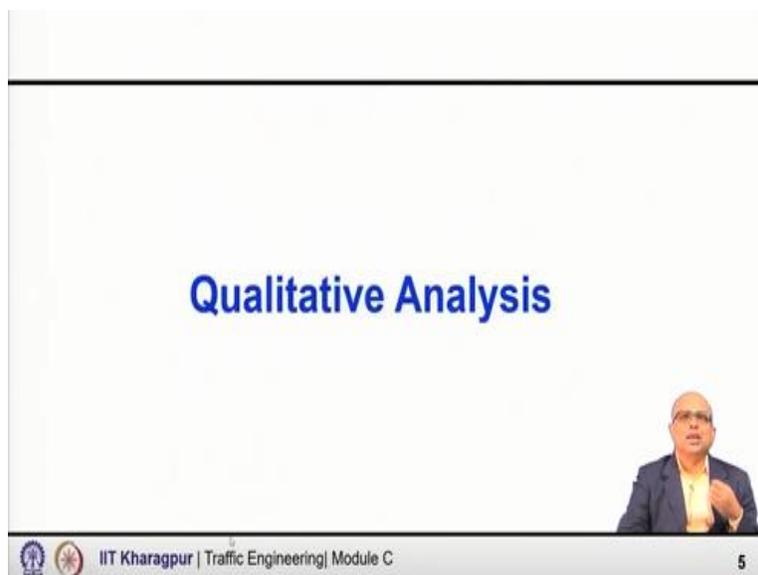
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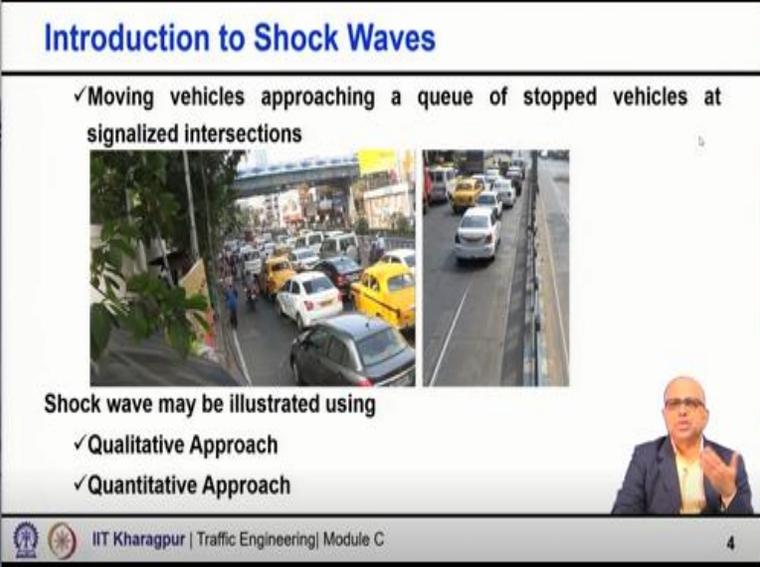
Similarly, moving vehicles approaching a queue of stopped vehicles at signalized intersections. You can see the photographs shown here vehicle are standing in a queue upstream of a signal and

stop line of course, and the signal rate indication is red. So, when the signal is red vehicles are simply accumulating. So the traffic state here just upstream of the stop line and traffic state somewhere farther upstream where vehicles have not joined the queue are different.

So somewhere a border is created and will be created and upstream and downstream of that boundary the traffic state will be different. So, that boundary is again called as shockwave. Shockwaves may be illustrated using both qualitative approach and quantitative approach. First, we shall discuss about the qualitative approach and in the second lecture I shall discuss about the quantitative approach.

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Coming to the qualitative analysis.

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Qualitatively, shockwaves may be defined as the boundary, we are talking about the boundary in the time space domain there is a time dimension there is a space dimension or locational dimension that demarcates a discontinuity in the flow density condition, why discontinuity, because the upstream and downstream the flow density conditions are not exactly the same. So, there is a discontinuity.

In fact, flow and density conditions or flow density conditions if they are different, the speed environment also will be different, because as you know the speed flow and density all are related and simultaneously all these parameters will change that means. I cannot keep speed same, but change flow and density I cannot do that, if flow and density are changing, then the speed also will change.

So, qualitatively the shockwave will be defined as the boundary in the time space domain that demarcates a discontinuity in the flow density conditions. Now, this shockwaves could be stationary or moving that means this boundary which is actually demarcating the discontinuity in the flow density relationship or that boundary for which the upstream and downstream with reference to that boundary very specifically.

The flow density conditions are different that boundary may be stationary that means over a period of time that boundary is not moving forward or backward, it may be stationary or it may be moving as well. So, the shock waves could be stationary or moving. When it is stationary, it could be

frontal or rear what I mean by that, whenever a new flow condition or flow state is created. Now, over a period of time, more and more vehicles will join.

Suppose I gave you an example of these traffic signals. And vehicles are stopping. So, the moment the signal turns from green to red, maybe that is zero vehicle, we can assume that simply and over a period of time, more and more vehicles are joining. So, the new traffic state which is created as shown here, vehicles are in jam density. So, there is a front of that, which is the stop line and the rear end more and more vehicles in this case, in this particular case, as more and more vehicles are joining that demarcation point is also moving.

So, if the stationary shockwave is in the front of that new traffic state, here, the new traffic state is the queued vehicle in front of the stop line. So, the stationary, Shockwave could be in the front of that traffic state front of the queue. And it could also be in the rear of the queue. Of course, the example of what I give now, the vehicles are accumulative, accumulating and more and more vehicles joining the queue over a period of time the rear end the shockwave is not stationary.

But the front one it is stationary because you have the stop line. One side of the stop line and the other side of the stop line that traffic states are different. So, there is a shock wave there and which is stationary. So, this is an example of a frontal stationary Shockwave. But similar, another situation may emerge where such shockwave is stationary, but which is the rear one.

So, if so, then that will be called as rear stationary shockwave on the other hand, the shockwave could be moving obviously, it can move, but then it can move forward or it can move backward. How we define forward or backward, over a period of time if the shockwave is moving in the direction of the movement of vehicles, then we will call it as a forward shockwave or forward moving shockwave and with reference to the direction of the movement of vehicle, if the shockwave is moving backward then we will call it as backward moving Shockwave.

The example what I gave you just now, in the upstream of signal when the queued vehicles are getting longer queue length is getting longer because more and more vehicles are joining the queue during the red time. So, then the rear shockwave is actually a moving shockwave and it is a backward moving shockwave because the travel direction if it is towards north then the queue is getting formed and the shockwave is moving on the south direction. So, upstream it is moving upstream not downstream, so, it is backward moving.

Now, whenever shockwave is moving shockwave may be forward or backward it could be forming or it could be recovering forming means the traffic state the new traffic state which has been created is actually growing.

So, again this example what I gave you the rear front stationary rear moving shockwave backward moving shockwave and that backward moving shockwave in this case is forming shockwave because over a period of time as long as the signal is red and as long as the vehicles are more and more vehicles are joining the queue, the new traffic state which has been created that is the queued up vehicles that jammed in city condition that traffic state it is growing.

So, the shockwave is moving backward and shockwave is actually forming this traffic state, the traffic state is growing. So, it is forming on the other hand, if shockwave is moving backward, but it is actually the queue length is decreasing or the new traffic state whatever has been created is getting diminished over time or getting reduced over time, then that will be called as recovery because over a period of time that traffic state will eventually vanish, reduce and eventually vanish.
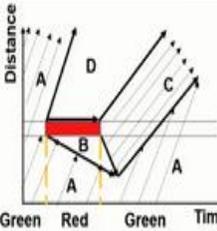
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Now, let us take some examples of different types of shockwave. We will take up two examples first one is signalized intersection as I was talking about. So, suppose the traffic is moving through a signalized intersection when the signal is green, without stopping or slowing down signal is green vehicles are arriving and they are crossing the stoplight because the signal is green and without stopping without slowing down.

So, if this is the stop line and the vehicles this is the upstream condition, this is the downstream travel condition. So, very cool sir approaching and same speed without slowing down without stopping the vehicle are passing through the signal or the stoplight. So, the traffic state in the upstream it is also A and the traffic still in the downstream traffic state in the downstream is also A.

So, since same static state, there is no question of any shockwave but then the flow state A is existing both upstream and downstream. Now, when the signal turns red from Green, now, from Green it has turned into red. So, what will happen vehicles are stopped at the stop line and the queue forms and this queue grows over time as more and more vehicles arrive and join the queue?

So, more and more vehicle will arrive and join the queue. So, now, a new traffic state is created that traffic state in the upstream of the stop line that traffic state is called B. But further upstream, the traffic state is still A, because those vehicles have not yet reached near the queue even. So, they are traveling as they were traveling earlier when the signal was green. So, now we have a new traffic state that is called D.

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Now, there will be no vehicles immediately downstream of the signal during red time. So, what I am saying this is upstream of the stop line. Now, let us think about the downstream part. Downstream either the flow state was earlier the flow state was A, but now when the signal turns into red no vehicle is getting discharged.

So, as the red time continues in new traffic state D will be created. And if we considered the no other vehicle from any other side is entering, then there will be no vehicle but that is also traffic state, zero flow, zero density. So, the traffic state in front of the stop line in new traffic state will be created that traffic state is called D.

Now, when signal turns green again after red the signal will become green again. So, now this point onwards again the signal becomes green what will happen queued vehicle will start discharging so that all vehicles which were earlier queued up will start getting discharged and a new flow state will be created let us call that flow state as C. Obviously, since now the flow will be higher, let us consider that as compared to the traffic state A because all queued vehicles are there. So at capacity or the queue discharge capacity, the discharge will happen.

So, a new traffic state will get created that will be C. Now during green time as vehicles are discharged the queue length will reduce whatever vehicles were in the queue, the traffic state be now the traffic state B slowly will get reduced because the vehicles are getting discharged from the stop line starting from the stop line. And therefore, the overall queue length will reduce.

And let us assume this is an assumption here, that all queued vehicles will be discharged completely during green time, it depends because if you take some signals during the peak hour morning peak, that demand may be so high that all vehicles may not even get discharged in one immediate green interval. But we are assuming here that the all vehicles queued up vehicle is getting discharged.

So, within this green time itself finally, this queue length will become 0 because there will be no vehicle in the queue. So, the traffic state B will eventually vanish during the immediate green and then the only traffic state A will be there. So, if you consider only these phenomena, then how many shock waves will be created? But before that, let us see how many traffic states will be there. We will have traffic state A, B, C and D. So, what I said whenever two traffic state will be there in the boundary shockwave will be created.

So, obviously, when it was initially green upstream downstream both are A then there was no shock wave, the moment the traffic state B is created because of the red, one shockwave will be created between B and D at the stop line upstream and downstream of the stop line that shock wave will be created, because two traffic state one side B and another side D. Similarly, the rear

end of the queue till that B is continuing and wherever B ends that boundary further upstream of that boundary the traffic state will be A.

So, one between A and B, that is the second one. If you consider D further downstream, somewhere the traffic condition is A, and then upstream of that A will be D during this red time. So, another shockwave will be created between A and D, two traffic state, that is the third one. Fourth, when the signal turns from green to red and the vehicles are getting discharged, then the traffic state C is created. So, there will be again one shockwave between traffic state B and traffic state C that is the fourth one.

When the vehicles are getting discharged in traffic states C, then further upstream further downstream the traffic state is D. So, again there will be line where one side downstream will be D upstream will be C. So, one more shockwave will be created between traffic state C and traffic state D, that is the fifth one.

And then eventually when traffic state B will vanish as per our assumption here, then vehicles will be moving with a traffic state A and eventually joint traffic state C. So, there will be again in line one side upstream of that line will be traffic states A downstream C so, there will be one more shockwave between A and C. So, altogether 6 shockwaves will be created.

Qualitative Analysis

- At the stop line during red phase, a frontal stationary shock wave is created between flow state B and D
  - ✓ Stationary means the location of shockwave is fixed: At stop line
  - ✓ Frontal refers to the formation of shock wave at the downstream/ front edge of the congested region (queued vehicles)
- During red phase, a backward forming shock wave is created between flow state A and B
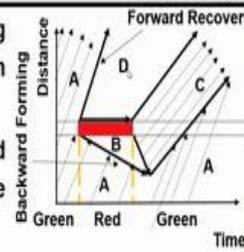
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So, as I have told at the stoplight during red face a frontal stationary shockwave is created just at the stop line between flow state B and flow state D, this is stationary, why we are stationary, as the location of shock wave is fixed stop line is there vehicles do not move. So, that stop line itself is the shockwave in a way and that shockwave does not move forward or backward it is stationary because it is at the stop line. Frontal means why frontal as they are told frontal refers to the formation of Shockwave at the downstream or front edge of the congested region.

So, as more and more vehicles are joining that traffic state is extending further upstream. So, whatever has been created at the stop line is the front one. So, that is why it is called frontal stationary. During red phase also, a backward forming shockwave is created between traffic flow states A and B. So, more and more vehicles are joining and further upstream the traffic condition is still A so one shockwave between A and B but that is moving in which direction moving in the backward direction opposite to the direction of movement of vehicles right over time. So, it is backward and since that queued vehicle that new traffic state B is growing over time, so it is actually forming shockwave.
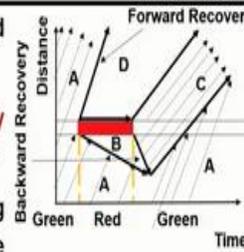
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So, second one we say backward because queues are propagating upstream over time that is in the opposite direction of traffic forming refers to the increase in congested region as more and more vehicles join the back end of the queue. At red time, a forward recovery shockwave is formed between A and D, why recovery? Because A is more congested condition as compared to D. So, these are better condition we are recovering. So, a recovery shockwave and it is forward. Why?

Because this shockwave is moving when the during the red time that shockwave A and D traffic states created by these two traffic states C and D is actually moving forward. So, it is forward, but it is also a recovery shockwave right at red time forward recovery shockwave is formed between traffic state or flow steady and D, forward means, as I have said earlier the shockwave is propagating in the direction of traffic flow vehicles in the flow state are moving away further and further over time during this red period.

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And why recovery because the decrease of congested portion by dissipating vehicles or dissipation of vehicles as I say the D is a better state then A, so, where A is become D is becoming more or appear pushing away the, the traffic state A.

Now, when signal turns green a backward recovery shockwave is formed between traffic state B and C that shockwave is shown here it through this line and why we are calling it backward because it means this backward means that this shockwave is propagating upstream as vehicles discharged from the head of the queue as vehicle getting start getting discharged, the traffic state is changing from B to C.

And the traffic state B from the front it is actually moving further upstream because more and more vehicle starts moving following this traffic state C and why it is recovery, because this traffic state all the queued vehicles which actually formed this traffic state B is now getting reduced over time. As the green time continues, the queue length is reducing queue length is reducing and eventually as per our assumptions the whole traffic state we will vanish.

Why it is vanishing because of this backward recovery shockwave that backward recovery shockwave is actually finally helping us to remove this congested state traffic state B that is why it is recovery because recovery refers to dissipation of queues.

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Now when signal turns green a forward forming shockwave is formed also between traffic state D and C it is forward and why it is forming because C is more congested condition than D and that is why it is forming and why it is forward moving because as vehicles are moving with traffic states C this demarcation point between C and D traffic states C and D is actually moving away from the stop line and in the direction of the movement of vehicle so it is forward moving and forming.
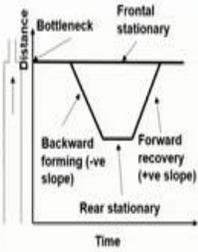
So, after the dissipation of queue, forward forming shockwave is also formed between traffic flow state A and C as you can see, and this is also forward moving because over a period of time that demarcation line between A and C is moving forward in the direction of the movement. And it is also a new traffic state is there C as compared to A.

Now let us take another example to further understand the how the shockwaves are created. Because of the various phenomena, one phenomena was stopping of vehicles at the signal because of the red time or red indication and then again getting discharged vehicle are getting discharged during that green time. So here, another example lane drop at bridge let us consider a three lane highway meets a bridge of capacity two lanes.

So, this is the three lane highway here the capacities three lane and then here is a narrow bridge that bridge is having capacity of two lane. So, what we are saying, let us consider that the demand pattern varies over time low what is usual as well, low in the morning, early morning, the demand is very low high during the peak and then once the peak period or peak hour is over again reduced to a low flow afterwards. So, there is two traffic state because one is with three lane capacity and other with two lane capacity.

So, obviously, the even if the demand is lower than the capacity of this narrow bridge still the traffic states will be different. So, let us consider flow state A on two lane bridge and flow state B on this three lane road portion. Now, be careful when the demand is equal to capacity of bridge then a frontal stationary wave is created at the bottleneck A and B my demand is exactly equal to the capacity of this two lane section or two lane bridge.

So, all the flow is actually passing there is no accumulation, but the flow density speed all three parameters are not same maybe the flow is same, but the speed and density is not going to be same

because the two sections will operate under two different two conditions. One is operating near capacity, another is operating at two-third of its capacity.

So, obviously, the speed and density is not same, but eventually the flow is same because flow is lower than the capacity of this bottleneck or two lane bridge. So, the flow is same, but the speed and density is not same, they are not same speed and density are not same. So, one traffic state A and that is B. And a frontal stationary shockwave will be created at the junction of this two lane and three lane that line but that will not move forward or backward because just a stationary Shockwave.
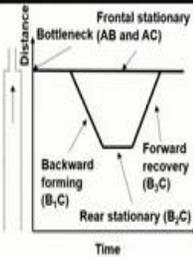
But then now, the demand is increased further because morning it is reaching towards the peak. So, when the demand exceeds the capacity of bridge, then what will happen, only the capacity portion that much capacity demand or demand equivalent to the capacity of the two lane bridge that can be served the remaining traffic will get accumulated? So, it is no more just a frontal stationary shockwave that will be a frontal stationary shockwave but vehicle accumulation.

Also will happen because previously all the demand was passing through now all the demand cannot pass through this section of two lane bridge. So, vehicle accumulation will happen. So, a new traffic state will get created, let us call that traffic flow state as C. So, now we have A, we have B and in between we also have now C when the demand exceeds capacity.

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So the, what will happen when the demand is more or arrival flow rate is more than the capacity of the two Lane Bridge, then there will be a traffic state B but let us call that traffic state as B1. Because that traffic state when demand was lower, we called it at B but now that B is different. So, let us call this B as B1. So, there will be a frontal stationary shockwave which will be created by two traffic states one is A and C that will be there at this junction.

And of course this A traffic state also may be slightly different from what we called it as A earlier, maybe slightly different. But let us call it as A generally for simplicity. Let us not make it more complicated. So, let us call it A but then it was only B but now in between a C state and the demand is more than the capacity of this two lane bridge. So, that B traffic state we are calling it as B1.

So, there will be one frontal stationary shockwave between A and C sees the newly congested condition created upstream of this bottleneck because the all the demand could not pass through these two lane capacity bridge. So, one frontal stationary A and C and another backward forming shockwave created by two traffic states one is B1 and another is C simply the B is now called B1 because the demand is different.

So, the traffic state is different that is all earlier we said the demand was lower than the capacity of the bridge, but now, the demand is more than the capacity of the bridge. So, just to distinguish that, we call it as B1 and this, what is happening the traffic state C is growing as long as the demand is higher, as long as they are arrival demand is higher than the capacity of this two Lane Bridge the traffic state C will grow.

So, the shockwave is moving backward opposite to the direction of the movement of vehicles and it is forming because the traffic state C is growing when the demand again reduced to reduces to the capacity of the bridge. Suppose, after some time the arrival demand or the flow rate is reduced and becomes exactly equal to the capacity of the, of the narrow bridge.

So what will happen, In that case, as many vehicles are now joining the queue, that many vehicles more or less is getting discharged also from this three lane section to this two lane section. So, what will happen? The rear or which was the backward forming shockwave. Now, when the demand is equal to the capacity of the bridge, when the demand comes down the rear shockwave will be a stationary shock wave.

So, it will be rare stationary shockwave. But since again the demand is different traffic state is no more D1 it is a different one lower volume is coming. So, we call it as B2. So, this is the stationary Shockwave. So, initially it was the backward forming shockwave. This is the distance and time so, it was moving like this. Now, it is stationary. Now, suppose imagine peak hour is over. So, further the demand gets reduced.

Now, the demand reduces further and goes below the capacity of this two lane bridge. So, what will happen from the front that discharge will be more or less equal to the capacity of the two lane bridge? Of course, the queue discharge is slightly lower than the capacity but that we are ignoring for the purpose of this discussion, we are assuming that the discharge will happen at the rate of the two lane capacity. So, the discharge is at two lane capacity arrival demand is less than two lane capacity.

So, what will happen the queue portion this new traffic state C which was created that will get reduced and what will happen there will be still a frontal stationary AC that will remain in all cases all the when the it is greater than or equal to or less than all cases the frontal stationary will remain.

But the back end, Now that rare stationary will no more be the stationary shockwave but it will be forward recovery shockwave because if it continues to happen like that for some more time, the queue will get reduced slowly and eventually this traffic states C will vanish because of this forward recovery Shockwave. In this case, the back end is moving forward. The back end is moving forward. So, it is actually forward recovery Shockwave.
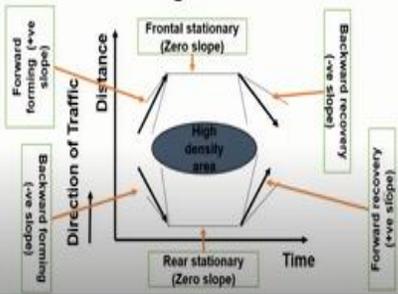
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So, with all this if I now come to the classification of shockwaves then there could be six types stationary, moving stationary could be frontal stationary, rear stationary moving could be forward forming, forward recovery, backward forming backward recovery. So, two stationary and four moving, two stationeries are frontal stationary, rear stationary moving or could be forming or recovery.

So, frontal forming, frontal or forward forming forward recovery or backward forming or backward recovery. So, all these I have shown here this is my frontal stationary, this is my rear

stationary, this is the forward forming shockwave This is my backward forming shockwave. This is the forward recovery shockwave and this is the backward recovery Shockwave.

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So, quickly to sum up, forward stationary shockwave form that the bottleneck locations as I have told you earlier formed because of the reduced capacity caused by accident or incident or road construction or maintenance activities frontal means it is front or downstream edge of the congested region and the term stationary we are saying because the shockwave is fixed by location it does not move and example.

Example 1; the shockwave created by traffic state B and D, I gave it in that example, the first example signalized intersection and also example two this example, Lane drop at bridge in this case the shockwave which was created due to traffic state AB or AC frontal stationary.
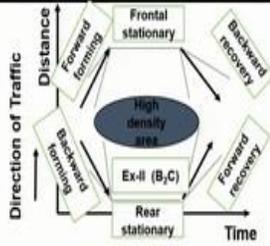
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Similarly, rear stationary it may be encountered when the arriving traffic demand is equal to the flow in the congested region for some period of time rear, how it is rear, because it is at the rare end of the congested region example. Example 2; B to C when the arrival flow rate is exactly same as the discharge or the capacity of this two Lane Bridge already queued have formed because the demand was initially higher.

But then, for some period of time demand is actually arrival flow rate is same as the discharge flow rate from the front. So, no grow queue is not growing queue is also not reducing same. So, that is the example B to C in example 2. Forward forming shockwave the term forward implies that the shockwave moves in the same direction as traffic with the positive slope indicated here with the positive slope.
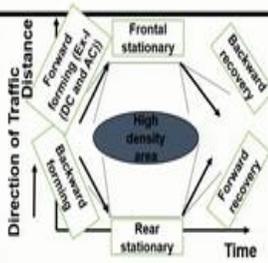
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And forming means over time the congestion is gradually extending to sections further and further downstream. Example is the traffic signal. Example shockwave formed by traffic state D and C and also shockwave formed by traffic state A and C. Backward forming shockwave it must always be present if congestion occurs and indicates the area in the time spent domain where excess demands are being stored.

Again, the term backwards means the over time the shockwave is moving backward or upstream or in the opposite direction of the traffic indicated here with negative slope in this distance time distance domain.

Example signalized intersection that example shockwave AB which is created by traffic state A and traffic state B. And in the second example, that lane drop example it is B_1C. Forward recovery shockwave it occurs when there has been congestion but demands are decreasing below the bottleneck capacity as I mentioned in example two and length of the congestion is getting reduced the time space domain to the left of the shockwave has higher density and to the right densities levels are lower.
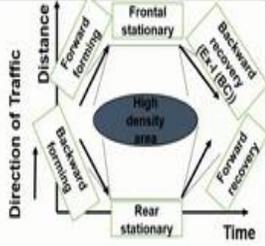
If you consider time spaced domain that what is arriving and meeting what and how the shockwave is created you will be able to match it example is first case signalized intersection case it is shockwave created by traffic state A and traffic state D. In example 2; the lane drop example, it is shockwave B_3C created by traffic state B_3 and traffic state C.

Backward recovery shockwave it is encountered when the congestion has occurred, but then due to increased bottleneck capacity; the discharge rate exceeds the flow rate within the congested region. So, that term recovery implies that over time the free flow conditions are extending further and further upstream from the previous bottleneck condition free flow or the less congested condition, that is what we mean.

The congested region is to the left of the shockwave and free flow condition or to the right if you consider the time space or time distance diagram or domain. Example, in the first case signalized intersection shockwave created by traffic still B and C.

Classification of Shockwaves

Attributes of different Shockwaves			
Types of shockwaves	Location of Generation	Demand vs Capacity	Direction of shockwave
Frontal Stationary	Bottleneck location	Demand exceeds capacity	Stationary
Rear Stationary	Rear end of the congested region	Demand is equal to the flow congested region	Stationary
Forward Forming			Moves in the same direction as traffic
Forward Recovery		Demands are decreasing bottleneck capacity	
Backward Forming		Excess demand are being stored	Moves in the opposite direction as traffic
Backward Recovery		Discharge rate exceeds flow rate	

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Finally, I tried to summarize this using this simple table type of shock wave frontal stationary where it is generally created at bottleneck location when? When the demand exceeds capacity and normally this is stationary, rear stationary is created at the rear end of the congested region, when it is created when the demand is equal to the flow of the congested region. So, this is also stationary, forward moving, forward recovery, backward forming and backward recovery like that I have said under what demand capacity condition can create and what will be the direction of movement of the shockwave.

Summary

- Qualitative approach
  - ✓ Shockwave at signalized intersection
  - ✓ Shockwave at lane drop location
- Shock wave classification
  - ✓ Frontal Stationary and Rear Stationary
  - ✓ Forward Forming and Backward Forming
  - ✓ Forward Recovery and Backward Recovery

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So, with this I have to summarize I will say that there are both qualitative and quantitative approaches which are used for analysis of Shockwave. Today's class I discussed about qualitative approach give you two example, creation of shockwaves due to this signalized intersection operation signal green then red coming back to green, what and how the traffic states are changing and how shock waves are critic and also give you an example of the lane drop location and even at the lane drop location how the different kinds of shockwaves are expected to be created over a period of time as the traffic state is moving from lower demand to going to higher and further coming down to lower.

Then the classification of the shockwave as I say stationary shockwaves or moving shockwave stationary means with reference to time shockwave is neither moving forward or backward. So, that is called stationary, but it could be the frontal if it is in the front of that congested condition or it could be rear stationary, when it is rear? When is at the rear end of the congested condition on the new flow state that has been new traffic state that has been created.

Moving, it could be forward moving or backward moving, forward with reference to the direction of the movement of vehicle it is moving in the same direction shockwave is moving in the same direction then it is for forward moving and if the shockwave is moving in the opposite direction of the movement of the vehicles, then it is backward.

So it could be forward or backward but it also could be forming or recovery. So, there congested or the new traffic state which was created temporarily due to this kind of imbalance or some interventions. If it is growing, then it is forming if the shockwave is actually moving and enhancing or augmenting that traffic state, then it is forming and if it is actually helping you to slowly bring down the, that traffic state and eventually the new traffic state which was created will vanish, then it is called recovery. Thank you so much.