Introduction to Transportation Engineering
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Lecture - 15
Horizontal Alignment - Part II

Horizontal alignment part II.

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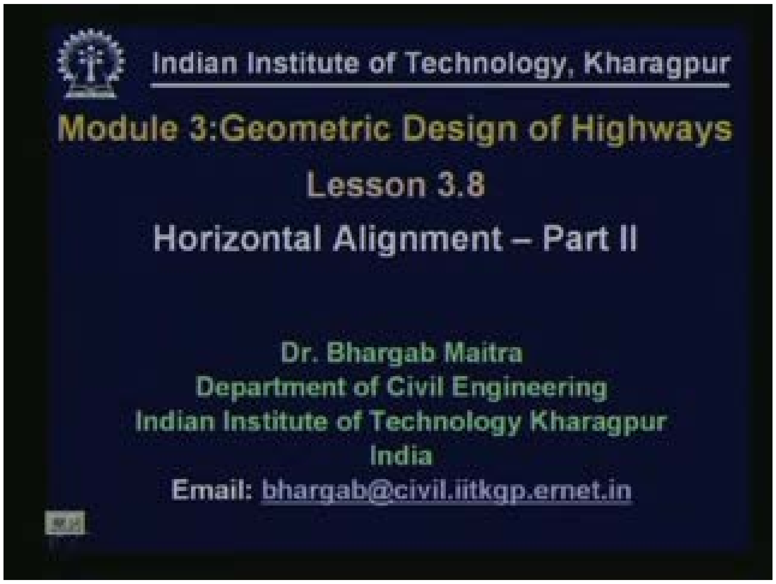

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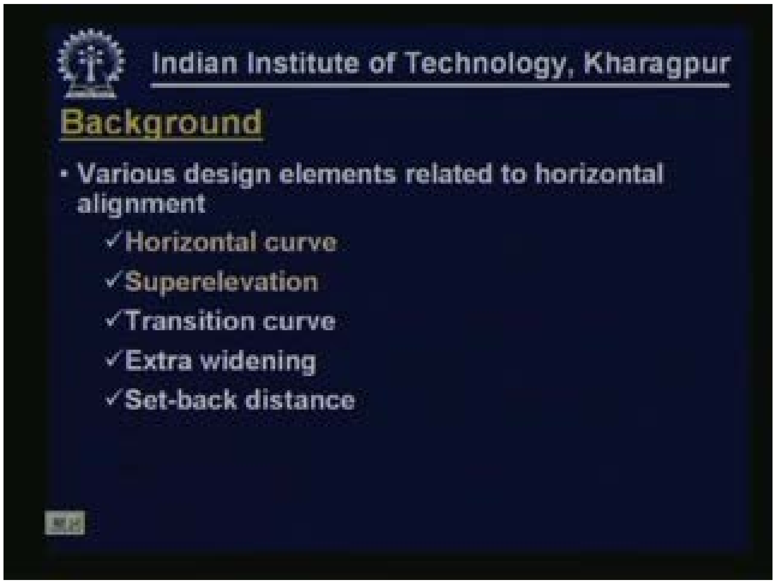

In the last lesson we discussed about various design elements related to horizontal alignment. A road can never be straight, in fact straight road is not desirable also from safety point of view and it is practically necessary to change the alignment. Now, when a road alignment is to be changed then the elements which are related to horizontal alignment include horizontal curve. When horizontal curve is there one has to think in terms of the Superelevation.

Also, it is required to provide transition curve at both ends of the horizontal curve. So there are transition curves which is another element then for various mechanical reasons, mechanical requirement, psychological requirement it is necessary to widen the portion of the road or the carriage way on curves which is known as widening of road length curves and also it is necessary to have adequate sight distance particularly when a vehicle is approaching or negotiating a horizontal curve. Thus sufficient distance towards the inner side of the curve should be free from obstruction which we call as calculation of set-back distance to make sure that required distance inside the inner side of the curve is available. So the elements what we talked about are horizontal curve, Superelevation, transition curve, extra widening and set-back distance are the five major elements related to horizontal alignment.

In the last lesson we discussed about horizontal curve and also discussed about the Superelevation particularly the need and basis for providing Superelevation.

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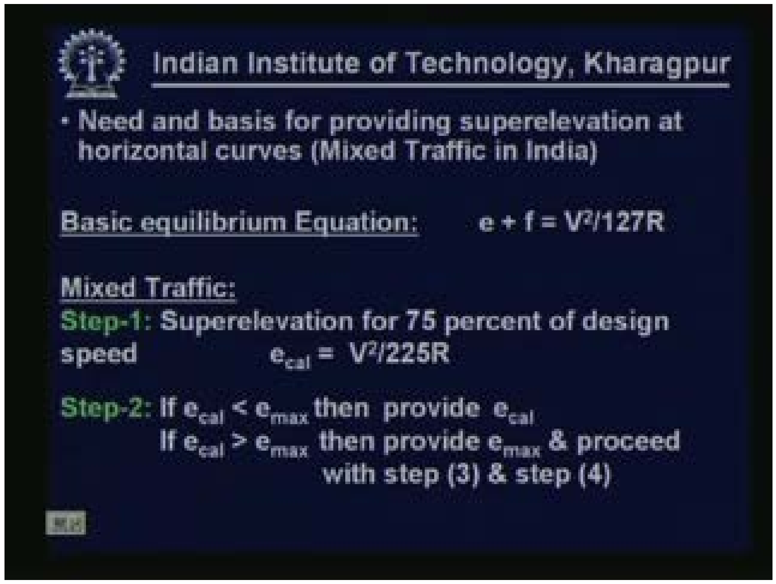

So we basically try to answer the question why it is necessary to provide Superelevation basically to counteract the centrifugal force and what is the basis for providing Superelevation at horizontal curve considering mixed traffic operation in India. We also discussed the design aspect of Superelevation particularly considering the mixed traffic operations in India.

Let us have a quick review of what we discussed in terms of the design of Superelevation particularly considering the mixed traffic operation. Basic equilibrium equation which was used is this one: e + f = V square/127R. Now here e is the Superelevation f is the coefficient of friction r what we called as sight friction factor that = V square/127R where v is the speed in kilometer per hour and r is the radius of horizontal curve in meter so this is the basic equilibrium equation. Superelevation and sight friction factor together are counteracting the centrifugal force.

In mixed traffic operation a road system is used by slow moving vehicles as well as by fast moving vehicles. Obviously when a road is designed for the design speed then the operation must be safe for any vehicle traveling at design speed. So, most of the fast moving vehicles are also expected to travel at the design speed. But for slow moving vehicles if the Superelevation is provided considering the design speed it will obviously be safe for vehicles which are moving at design speed but it will not be comfortable and in some cases it may not be even safe for slow moving vehicles which are traveling at a speed much lesser than the design speed. But the road section one way is designed for the maximum speed so it must be safe for the maximum speed where vehicles are operating at maximum speed. On the other hand, it also must be safe for movement of slow moving vehicle. So that makes the design of Superelevation in mixed traffic operation a complex task.

What is done in Indian practice?
Superelevation is designed for seventy-five percent of the design speed. Now step one is therefore Superelevation for seventy-five percent of the design speed not the complete design speed. So Superelevation is calculated neglecting sight friction, the earlier basic equation was e +

f = V square/127Rr. Now this f is made 0 initially and v is taken as seventy-five percent of the design speed that makes the equation V square/225R instead of V square/127R. So whatever e is calculated if it is less than the permissible maximum Superelevation then we provide the calculated Superelevation. That means it is safe and it is permissible. But when the Superelevation is calculated the calculated value is more than the permissible Superelevation standard or acceptable Superelevation value. In that case we can provide only Superelevation up to the maximum permissible limit but the safety of operation is to be checked, again the value of coefficient of friction or the lateral friction f. So what we do is, in that case if e cal is greater than e max then we provide e max and proceed with step 3 and step 4 which is we now calculate the value of f, how much we are depending on this f.

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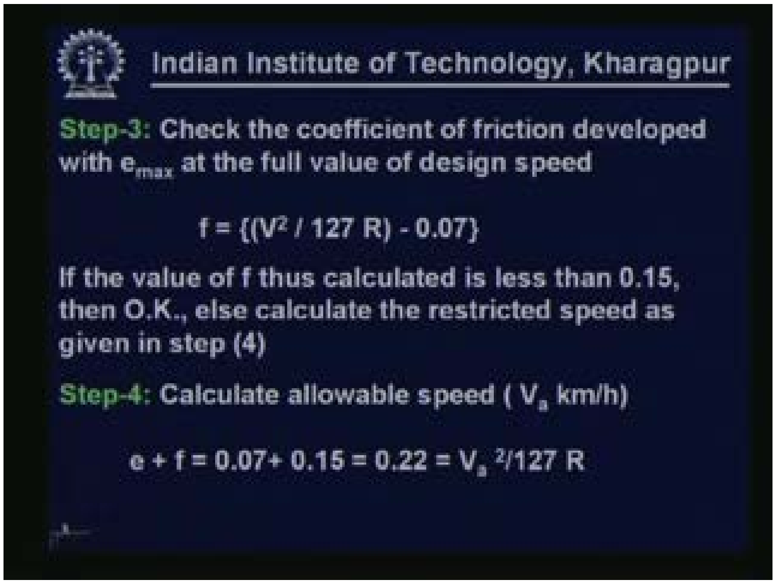

Now here we take the complete speed not seventy-five percent of the speed because ultimately e + f = V square/127R that is the basic equilibrium condition and we know that we have provided the maximum permissible value of Superelevation which is seven percent normally so we calculate the value of f. Now if this f value is less than the permissible value which is again as per the Indian practice the permissible value is 0.15 then the overall operation is safe or e + f = V square/127R this basic equilibrium considering this basic equilibrium e and f values are sufficient to counteract the centrifugal force.

If we find that f is more than the calculated value then there are two options practically. Recall the basic equation it is e + f = V square/127R. So e we know that this is the maximum e we can provide, if we know this is the maximum f that is permissible normally the value of e is 7% so 0.07 and f is 0.15. So you know this total limiting value is 0.22 if 7% is the permissible value. Then the only possibility is either to reduce this v speed limit, limit the speed or put restriction on this speed or have a better value of r a larger radius or a flatter radius. So one of these two things are to be taken up. So either provide a larger radius or calculate the speed or the restricted speed. If we calculate the restricted speed then for the given r what is the value of Va or V allowable speed that we can calculate from this basic equation.

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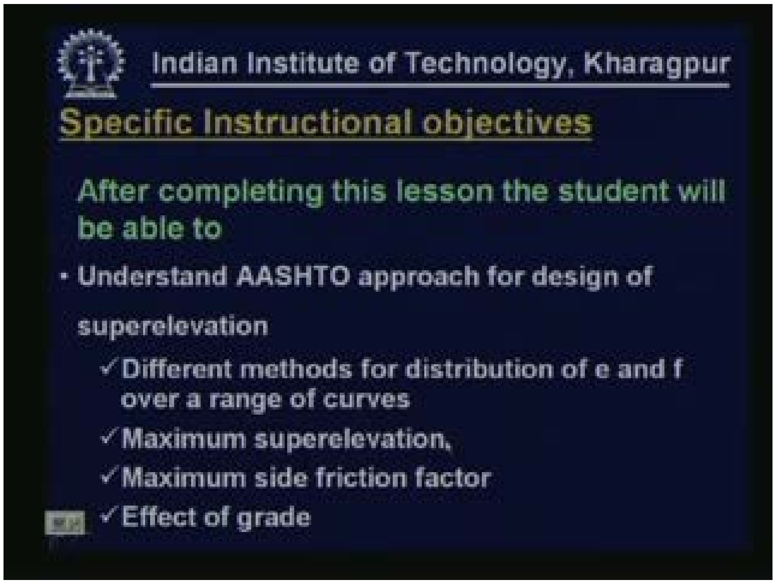

Now let us come back to today's topic. After completing this lesson the student will be able to understand AASHTO approach for design of Superelevation. So far we have discussed only about the approaches which are normally considered in India for design of Superelevation and then mixed traffic operation. So today we shall talk about the approach recommended by AASHTO so all our discussion will be around AASHTO recommendations and AASHTO approach for Superelevation design.

In particular we shall cover the following elements particularly different methods for distribution of e and f over a range of curves, how e and f are to be distributed, what are the different methods that are discussed, maximum permissible Superelevation, maximum sight friction and what is the effect of grade on Superelevation design. So these are the elements we shall discuss today.

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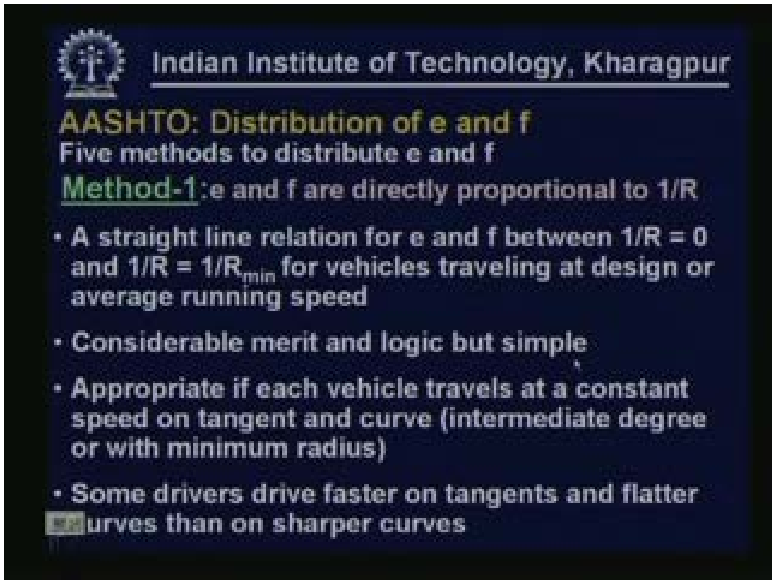

Now AASHTO recommends five different approaches or methods for distribution of e and f, e is Superelevation, f is the sight friction factor. First method it says that e and f are directly proportional to 1/R. That means it indicates basically a straight line relationship both for e Superelevation as well as f sight friction factor between 1/R = 0, 1/R = 0 is the tangent point.

2) 1/R = 1/R minimum, r minimum is the radius of the circular curve. So what is suggested as per this approach a straight line relation for e and f between 1/R = 0 and 1/R = r minimum this r minimum is nothing but the radius of the horizontal curve and initially 1/R = 0 because here the 'R' is infinity or basically it is at the tangent point. And a straight line relationship for vehicles traveling at design or average running speed carefully observe this part, this indicates the straight line relationship for e and f for vehicles which are traveling at design or average running speed.

Now this method has considerable merit and logic but yet it is a simple approach which can be used which can be adopted. This is due to the fact that actually for a tangent portion there is no centrifugal force. Now as 1/R value changes that means curvature is changing gradually the centrifugal force is introduced and it is maximum when R = R minimum or the rate R is equal to the radius of the horizontal curve. So, if we assume that speed is uniform then it is logical and it is correct also to have a linear relationship both for e and f in terms of the distribution. So it is a considerable merit and logic is there and also this is a very simple approach.

Now this method is appropriate if each vehicle travels at a constant speed on tangent and curve. Earlier also I have mentioned here that it is for vehicles traveling at design or average running speed. Now the same point is coming back here. This method is appropriate and correct if each vehicle in the traffic stream is traveling at a constant speed on tangent on curve of intermediate degree and also curve with minimum radius.

In all places each vehicle is traveling at uniform speed this is a question or here there is a question because often it is found some drivers they have a tendency to travel faster on tangent and flatter curves then the speed whatever they normally maintain on the sharper curve. That means vehicles may not travel or have a tendency not to travel uniformly at the same speed over tangent over flatter curve and also over sharper curves. That puts a question mark on this approach for distribution of e and f. Now let us see the graph.

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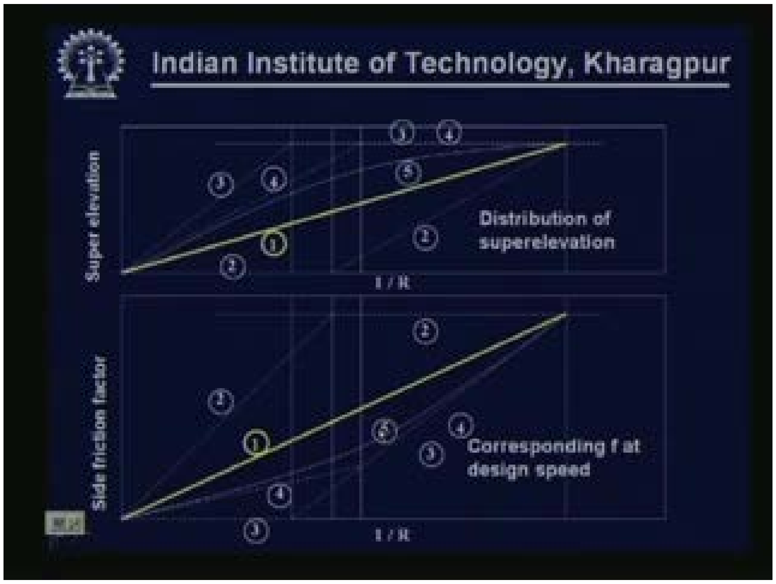

Here the distribution is shown for Superelevation and also for the corresponding sight friction. So this is the point 1/R is 0 and this is the point where 1/R is 1/R minimum or the R minimum is the radius of the circular curve. Now it indicates a straight line relationship as shown here by the yellow line for the distribution of Superelevation. A corresponding distribution of f is also shown, the sight friction factor. Again this is the point where 1/R is 0 and here this is the point where 1/R = 1/R minimum. So here also sight friction factor shows a linear distribution. That's what is approach one or method one for the distribution of e and f.

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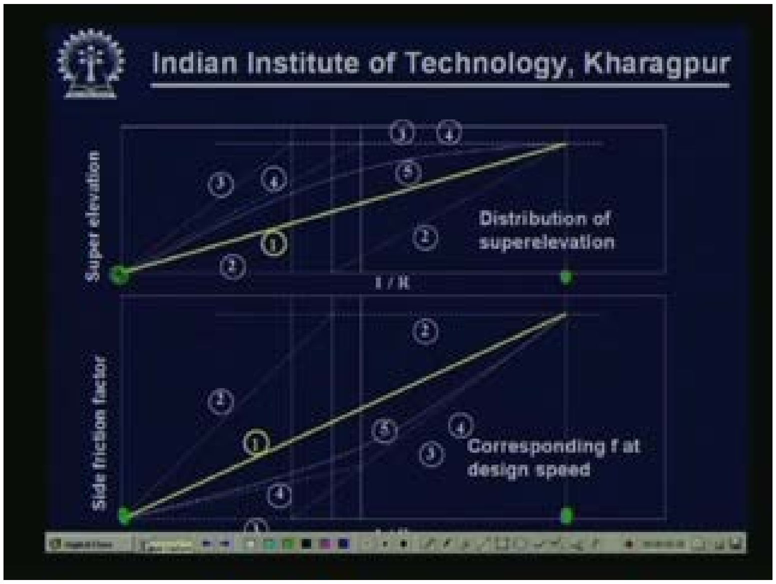

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Coming back to the second method now, according to the second method f fast reaches the maximum value that means sight friction factor is increased initially till sight friction factor reaches its maximum value. Once sight friction factor reaches its maximum value then the Superelevation is introduced and Superelevation is increased up to the maximum allowable Superelevation. So first e and no f e only {first if e) first f no e e comes only when f has reached to its maximum permissible value. So according to this approach let us see.

First f and then e are increased in inverse proportion to the radius of curvature so here because we are introducing Superelevation only when f value has reached to its maximum value. We are introducing Superelevation only when the f value has already reached to its maximum value therefore it may happen that for flatter curve because the requirement is less it may not be required even to provide any Superelevation because the sight friction factor alone may be sufficient to counteract the effect of the centrifugal force and even the f value required may not exceed the value of f max or the maximum permissible value. Therefore it may not be necessary to provide Superelevation so for flatter curves this may result into a situation where we may not require Superelevation.

Second, Superelevation when introduced increases rapidly. Why it is so?
It is because initially Superelevation is not used it is only the f value which is used so e value is used only when f is saturated. That means f has reached to its maximum value then as the curve becomes sharper the whole effect is counteracted by the Superelevation only. Therefore although initially Superelevation is not used and only the f value is used but when e is used e increases very rapidly as the curve become sharper.

This method is particularly advantageous for urban roads where frequently it is not possible to provide Superelevation because these are essentially or often low speed facility. The centrifugal force is also not may not be very high as compared to the centrifugal force whatever may be obtained on highways with much higher design speed. Therefore this method is particularly advantageous for low speed urban roads or urban street because of practical constraints. Superelevation frequently cannot be provided on such urban roads so there this method can be applied. Now let us see the distribution of e and f.

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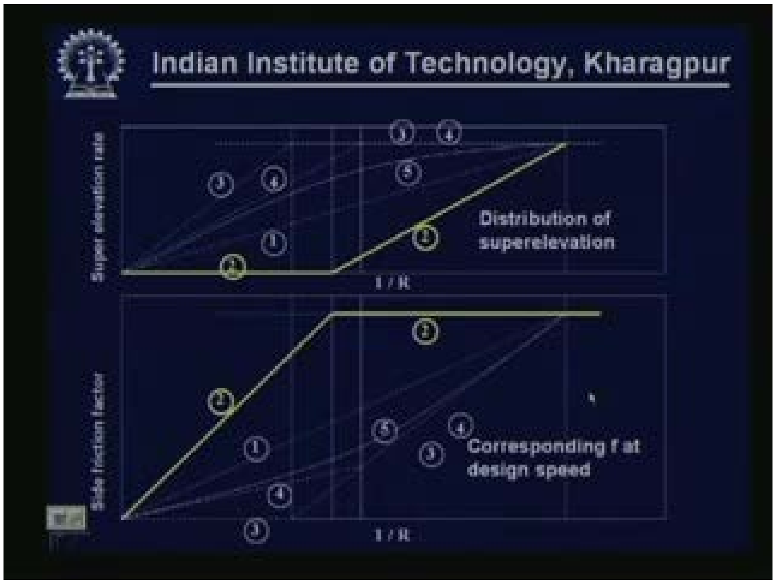

Here is the distribution of e and f as per this method 2. As I mentioned initially Superelevation is not introduced. That means only this f value is increasing. You can see this f value is increasing from 0 to its maximum value that's what is being done. Once f reaches its maximum value then it is kept constant and that point onwards the e value starts increasing.

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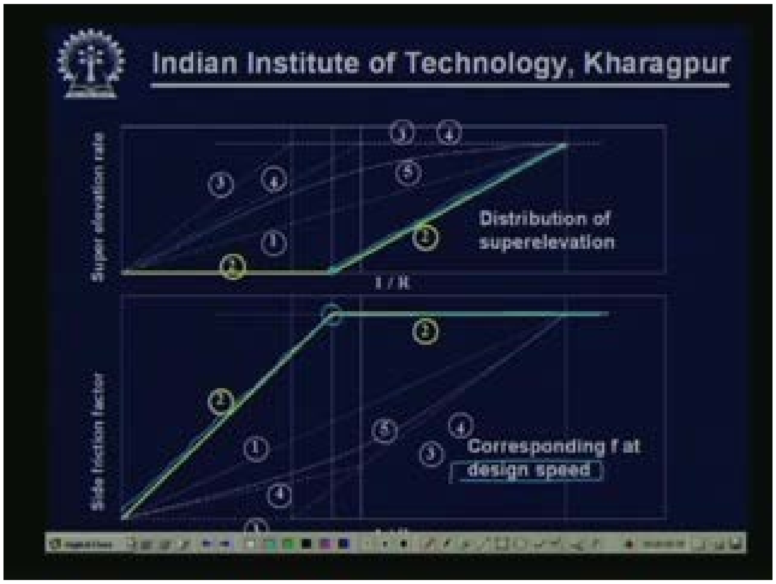

So Superelevation is introduced only when f has reached to its maximum value so this shows the distribution of Superelevation and the corresponding f remember at design speed. Now let us see the method 3 for distribution of e and f.

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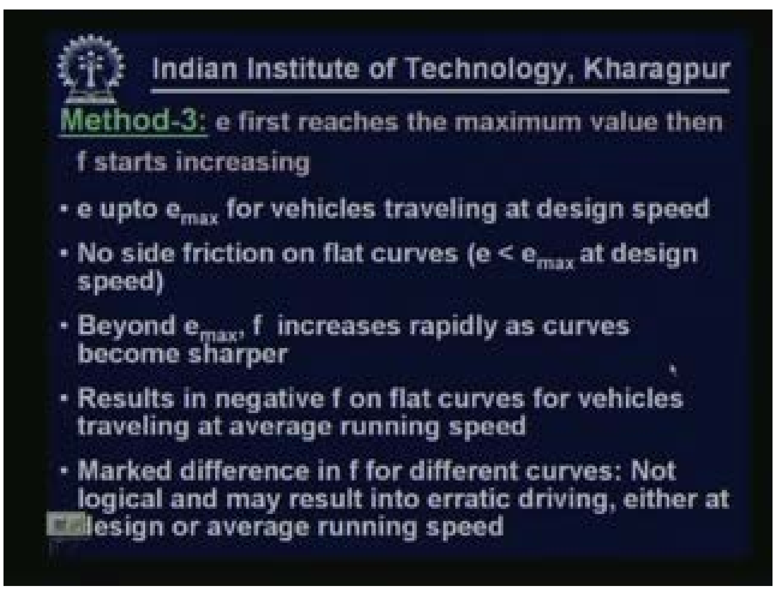

In this method it is the reverse. Now what we have discussed for method 2?
In method three initially e is introduced or that means only Superelevation is introduced. Thus Superelevation is introduced in the beginning and it is only the Superelevation what is used till Superelevation reaches its maximum permissible value. That means it is only e till the e value reaches to its maximum. Once e reaches to its maximum then only f is used or f is introduced and

then f is also increased as the curve becomes sharper. That means let us see here in this case e is introduced up to e max for vehicles struggling at design speed.

Again carefully observe that it is with respect to design speed and no sight friction is used for flatter curves. For the same reason as we have discussed for method 2 because if it is a flatter curve only Superelevation may be adequate to counteract the effect of the centrifugal force and the required Superelevation may not cross the limiting value of the Superelevation so e may be well within the limit of e max maximum Superelevation. And as long as e is within the limit of e max f is not introduced because f is introduced only when e is not able to counteract that centrifugal force. That means it is necessary to go beyond the maximum Superelevation limit. Therefore if it is for flatter curve it may not be necessary to go up to the use of coefficient of friction so it may happen that there is no sight friction on flat curves because e may be lesser than e max at design speed. Again carefully observe with respect to design speed.

Now beyond e max f is increased and it is increased rapidly as curves become sharper. Why it increases rapidly?
Again it is for the same reason because up to e max f is not used and whenever f is used that point onwards e remains at a level of e max so there is practically no additional contribution now rather from the Superelevation. So as the curve becomes sharper the whole effect is counteracted by the sight friction factor f. Therefore f initially although is not used but whenever it is used for sharper curves it increases very rapidly.

Also understand clearly that we are talking about this distribution with respect to design speed. Now, if vehicles do not travel at design speed, suppose vehicles are traveling at a speed lesser than the design speed in that case we have provided Superelevation corresponding to the design speed. So, for vehicles which are not traveling at design speed or rather they are traveling at a speed lesser than the design speed if you now think of that equilibrium equation e + f = V square/127R the basic equilibrium equation we have for the operating V, 'e' is operating, V is lesser than the design speed but 'e' is provided with respect to the design speed. That means we are essentially considering a negative value of the coefficient of friction for vehicles which are not traveling at design speed.

Let us see this equilibrium equation again. What I was mentioning this is e + f = V square/127Ror V square/Gr this is the basic equilibrium. So essentially what it indicates is that we have provided e value corresponding to the design speed. Now, if the vehicle is not traveling at design speed then V square/127R this value will be lesser as compared to a situation where the vehicle is traveling at design speed. So if vehicles are not traveling at design speed this V square/127R value is lesser but we have provided 'e' with respect to the design speed. That means 'e' value is higher. So this immediately indicates that a negative value of f is assumed and this will be there only for the flatter curves where vehicles are traveling at average running speed and not at design speed. This mark difference in f at different curves, flatter curves, tangent portion, and sharper curves so that particular aspect that is this mark difference in f for different curves is not logical and may result into erratic driving either at design or average running speed. That is what the disadvantage is with method 3?

Now let us see how the distribution looks like.

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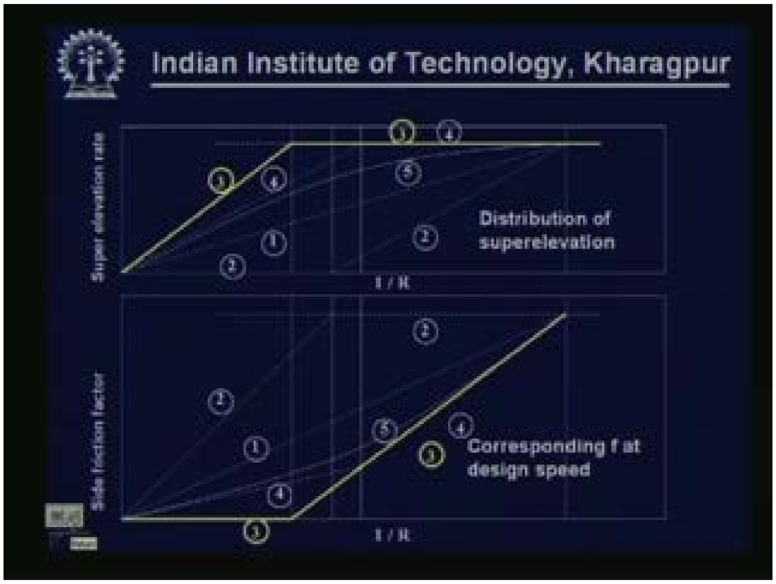

This is the distribution as indicated here. You can see initially if f = 0 and 'e' is only increased, only 'e' is increased up to a value where up to a value of e max till that time this f value remains 0. After that one 'e' remains constant and = e max and as 1/R changes it goes here up to 1/R minimum both for distribution of Superelevation and distribution of sight friction factor, then as this changes now this f value increases rapidly. But what I was indicating is that, observe that this is the corresponding distribution of f at design speed and not at average running speed.

If we take the average running speed then for method 3 it will show altogether a different distribution because the f value may be or will be negative. Instead of remaining 0 if you take the corresponding f at average running speed then f value will actually go down or it will take a negative trend. Now let us see method 4.

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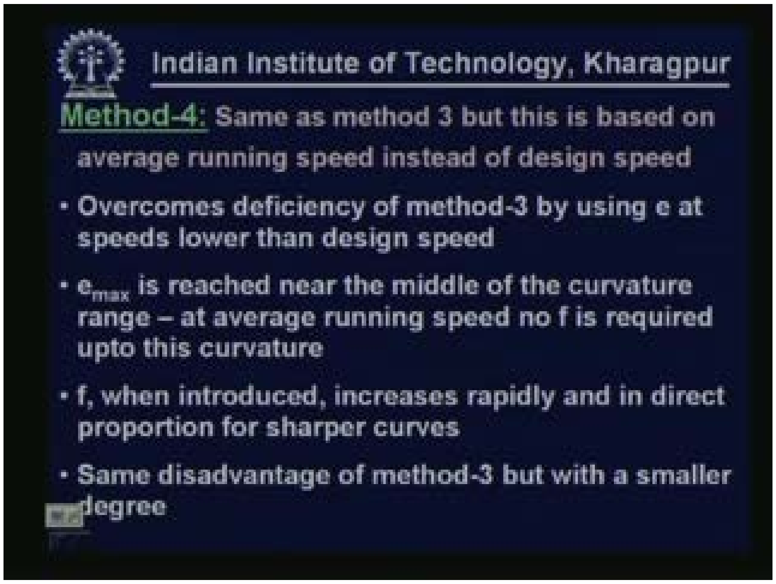

Method 4 is same as method 3 but this is based on average running speed instead of the design speed. So this is similar to method 3 but in method 3 a major problem was Superelevation was designed considering the design speed which was a problem because vehicles which are traveling at average running speed lesser than the design speed for them f value was going in the negative range just to make that equilibrium or keep that equilibrium equation. So here instead of method 4 idea is instead of using the average design speed actually average running speed is used. Now this overcomes the deficiency of method 3 by using 'e' at speeds lower than the design speed.

Obviously if instead of design speed the running speed is used then for running speed maximum Superelevation will reach later near the middle of the curvature range. If V is the design speed then quickly this e max will reach because of the higher value of the speed. But instead if the average running speed is used then e max will reach later or in the middle of the curvature range. And at average running speed no 'f' is required up to this curvature because it is similar to method 3 unless and until 'e' reaches to its maximum value we are not using the value of 'f. so till 'e' reaches to e max f is not required or no f is required up to that curvature.

Like method 3 if f when introduced increases rapidly and in direct proportion for sharper curves reason is again simple because initially f is not used but when f is used corresponding to the running speed the whole effect is taken by the value of f so f increases very rapidly for sharper curves. Essentially this method or method 4 has the same disadvantages of method 3 but with smaller degree because the Superelevation here is calculated not based on the design speed rather based on the average running speed. Although the problems are similar it makes the problem with this smaller degree but it has essentially the same disadvantages.

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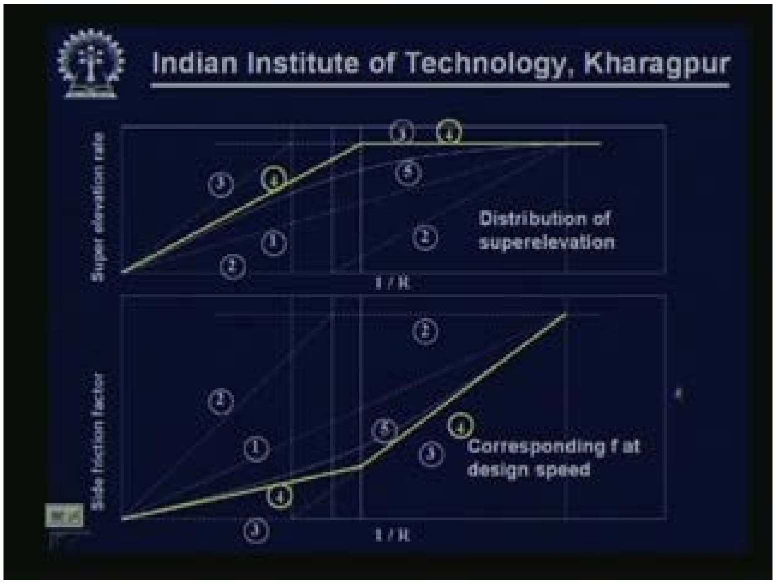

Now let us see the last method for distribution of e and f. This is method 4. So according to method 4 let us see the distribution how it looks like. Here one can see that ‘e’ is initially introduced, ‘e’ is initially increased till it reaches maximum then only f is introduced but that distribution of f is with respect to the average running speed. So now if we plot the distribution of f considering the design speed then f shows an increase. But actually if we consider the corresponding f at average running speed then the f distribution will be like this, it will not change, it will be like this and then it will increase rapidly to reach to this point. But this yellow line shows the corresponding distribution of f at design speed that's why it is indicating a value of f even in this range also when the Superelevation is increasing from 0 to its maximum value. So here Superelevation is 0 to its maximum value but here when the Superelevation is provided if we see the distribution of f corresponding to the average running speed then it will be 0 but here the yellow line shows the corresponding distribution of f at design speed not at average running speed. If you take the average running speed it will be like this as indicated by the green line.

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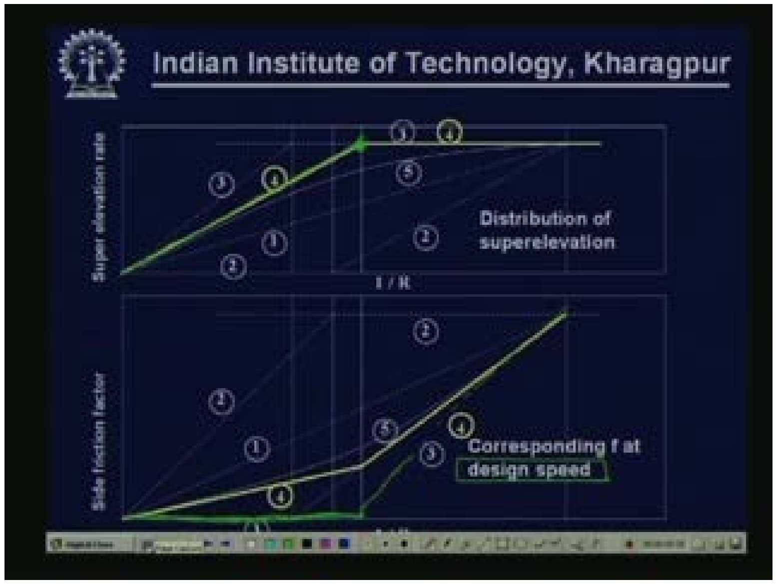

Now let us see the last method or method 5.

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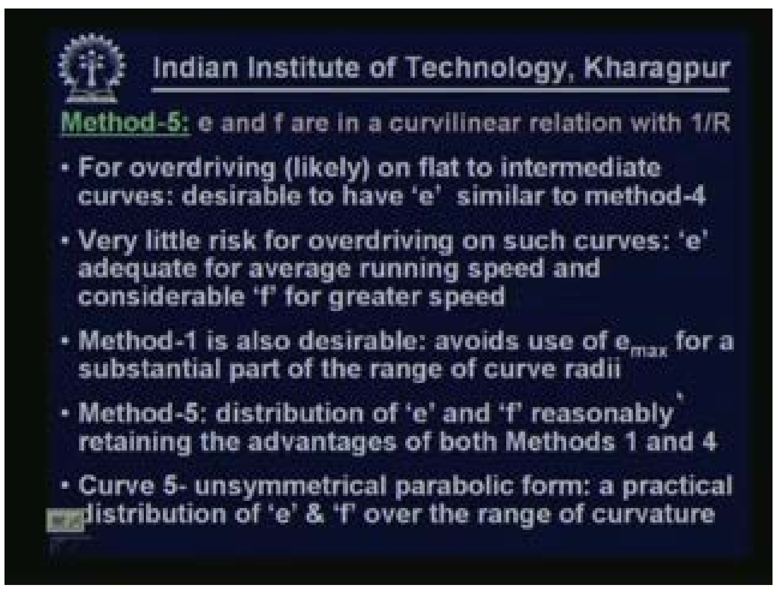

In this method e and f are in a curvilinear relation with 1/R. This is quite interesting trying to take advantage of or the good thing of the earlier approaches and then suggesting another alternative method. The drivers have a tendency for overdriving on flat to intermediate curves. This I have indicated earlier also when I was talking about approach 1 that drivers do not travel essentially at uniform speed rather some drivers may have a tendency for overdriving on flat to intermediate curves. So, if we consider that particular aspect then it is desirable to have 'e' which is similar to method 4. Why?

It is because ultimately there is very little risk for overdriving on such curves. The reasons are simple because we have 'e' which is adequate for average running speed and vehicles which will even run faster or at greater speed for them considerable amount of 'f' is also available. Therefore altogether there is very little risk for overdriving.

Let us try to understand this part once again. For vehicles which are overdriving on flat to intermediate curves it is desirable to have a distribution similar to method 4 because there is very little risk for overriding on such curves. Why?
It is because 'e' is adequate or Superelevation available is adequate for average running speed not the design speed again. And for vehicles which are traveling at greater speed than the average running speed for them also considerable amount of 'f' is available. So it is desirable to have an approach like method 4 a distribution like method 4.

But method 1 is also advantageous, why?
It is because method one avoids use of e max for a substantial part of the range of curve radii, e does not become e max so quickly. Therefore method 5 actually takes advantage of both method 1 and method 4. Therefore it suggests a distribution of e and f reasonably retaining the advantages of both the methods 1 and method 5. Curve 5 we get unsymmetrical parabolic form which is a practical distribution of e and f over the range of curvature.

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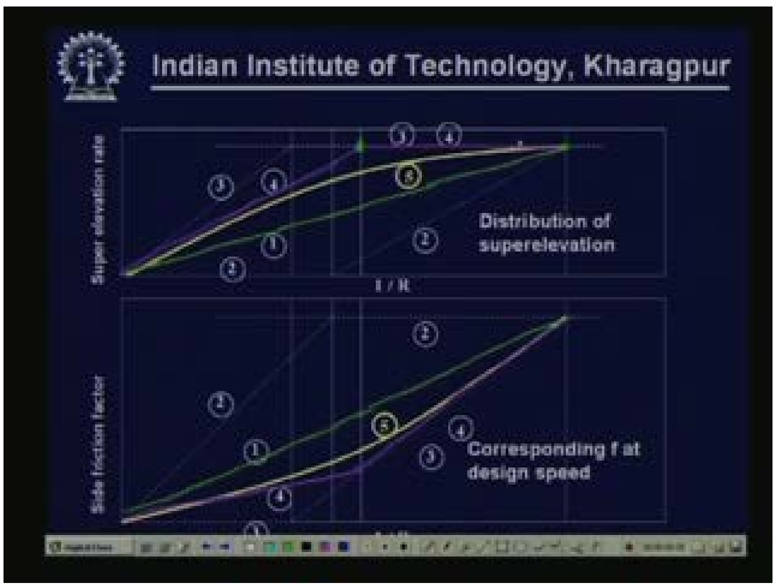

Observe carefully, this was method 4 and green line shows method 1. Now what is used is method 5 is trying to take advantage of both approaches 4 and approach 1. Shape-wise it is similar to method 4 but e max in method 4 reaches very earlier this point but in method 5 e max is reached not so quickly. That is what is the advantage taken from method 1 but it is distributed and the basic approach is that both e and f are available for faster moving vehicle as well as vehicles which are traveling at design speed and vehicles which are traveling at running speed slightly lesser than the design speed, so for both of them this becomes appropriate. That is what is shown in method 4 what we got for method 1 by the green line and the yellow line shows curvilinear distribution both for Superelevation and the corresponding sight friction. So altogether, each method has its own advantages and disadvantages. That is why all five methods are indicated but method 5 appears to be most suitable and practical out of all the methods. But each method has its own advantages and associated disadvantages.

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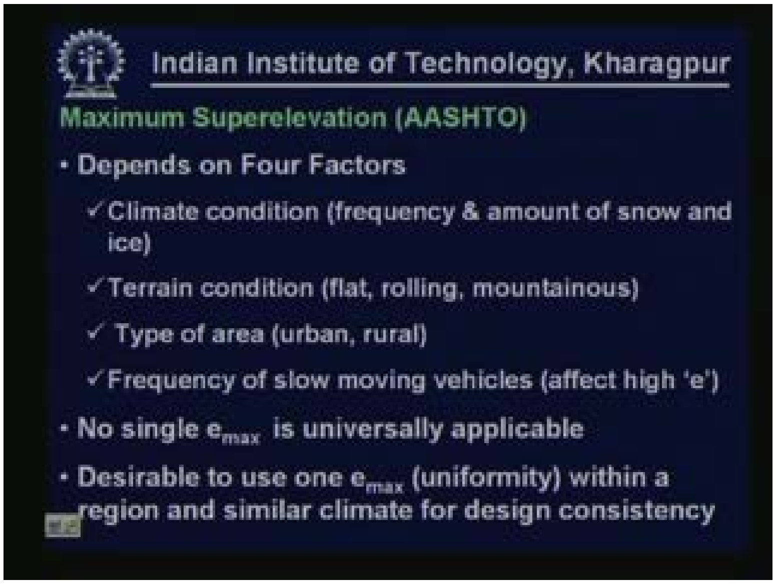

Now let us see, we have discussed the distribution every time we have mentioned that e reaches to its maximum value f reaches to its maximum value. That shows there is a limiting value for e and for f. Let us discuss now what the maximum Superelevation rate is as indicated in AASHTO.

Superelevation basically depends on, maximum Superelevation rate depends on four factors; climatic condition, essentially frequency and amount of snow and ice is not a very relevant factor in Indian context of course but this is one factor which controls the maximum Superelevation rate, then terrain condition what is the type of terrain because requirement will be different we may have to compromise depending on the terrain so flat rolling mountainous terrain, type of the area whether the road is located in urban area or in rural area because altogether they indicate different operating environment, speeds are also lower so providing Superelevation may be practically difficult in some cases in urban areas.

Therefore it depends in the type of area and most importantly it depends on the frequency of slow moving vehicle because slow moving vehicle affect providing high Superelevation value. Because for high speed vehicles providing higher Superelevation value may be okay but it depends if the slow moving vehicles are there therefore providing high Superelevation value may be problematic for slow moving vehicle. Therefore it shows that no single e max is actually applicable. Therefore it is desirable to use different e max value. But considering the design consistency aspect it is desirable to one e max or the maximum permissible value at least within this region and similar climatic condition. Therefore five different e max values are suggested 4 to 12%, 12% is the practical maximum value where snow and ice do not exist, 10% is the highest Superelevation rate that is commonly used, 8% indicates the maximum practicable limit where snow and ice are factors, also for gravel roads these are used, and where traffic condition and extensive marginal development acts to restrict the top speeds a Superelevation of maximum value of 4 to 6 percent is used.

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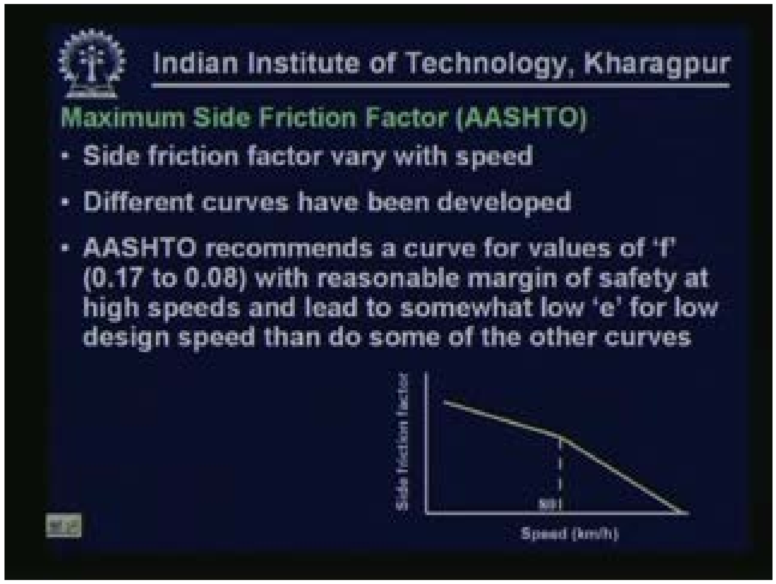

Now the side friction factor also there is a limit because every time we were talking about that f max so side friction varies with speed. Different researchers and organizations they have also developed different curves. But AASHTO recommends curves which is very similar to the curve shown here by yellow line.

Coefficient of the sight friction factor value ranges from 0.17 to 0.08 depending on the speed and essentially this curve has two different slopes, up to 80 Km one slope and then beyond 80 there is another slope, value is about 80 Km/h and the coefficient of friction value is around 1.14. So this curve provides reasonable margin of safety at high speed and leads to somewhat low value for low design speed than some other curves. As I have indicated that several other curves are also available.

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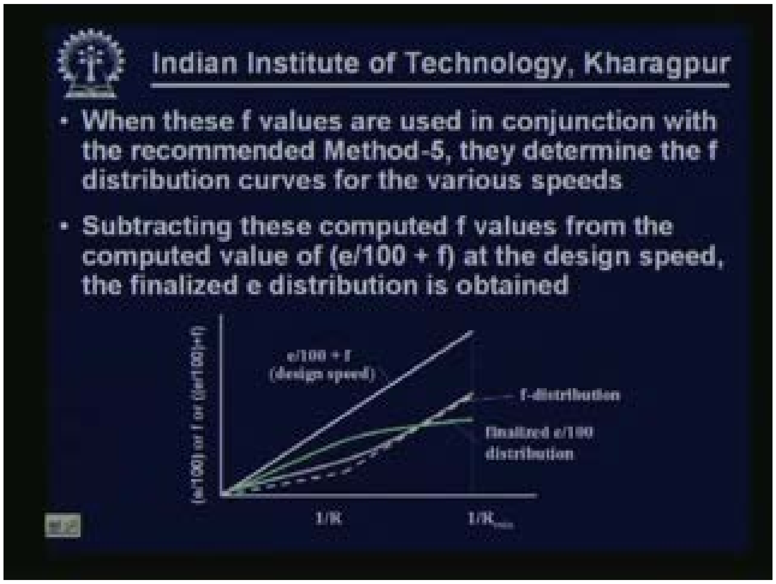

When these f values are used in conjunction with the recommended method 5 they determine the f distribution so we get f distribution as shown here. So this is the f distribution line that is shown here. Now, subtracting these computed f values from the computed e/100 + f here e is expressed in percentage that's why it is e/100 + f so we know what is total e/100 + f for design speed. Now subtracting these computed f values from the computed value of e + f that gives us the finalized distribution of e/100 as shown by the green line here and that is how we obtain the finalized distribution of ‘e’.

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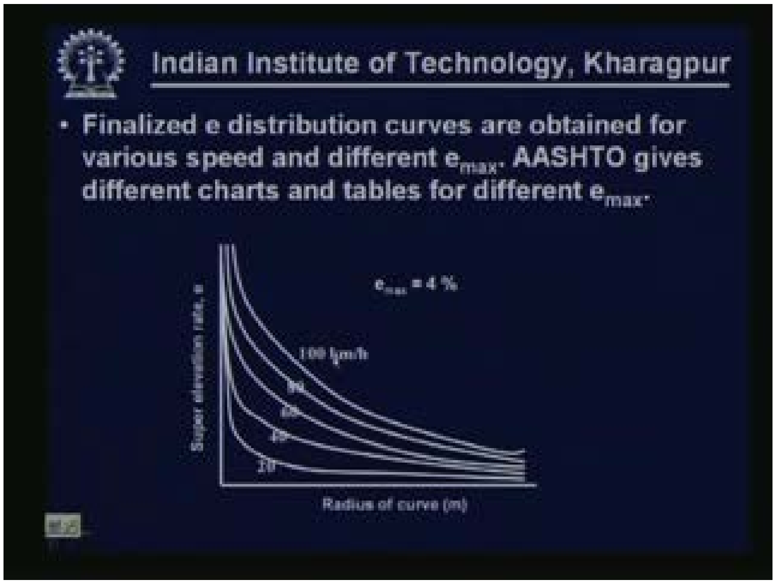

Now this e max varies from 4% to 6 to 8, 10 goes up to 12. Therefore for different e max AASHTO gives different curves. This x value indicates radius of curve in meter and y the Superelevation rate and obviously the Superelevation will be function of the speed. Hence, for different speed different lines are indicated and like this different curves are there for different e max values 4%, 6%, 8, 10 and goes up to 12%. Therefore these figures and tables are also available.

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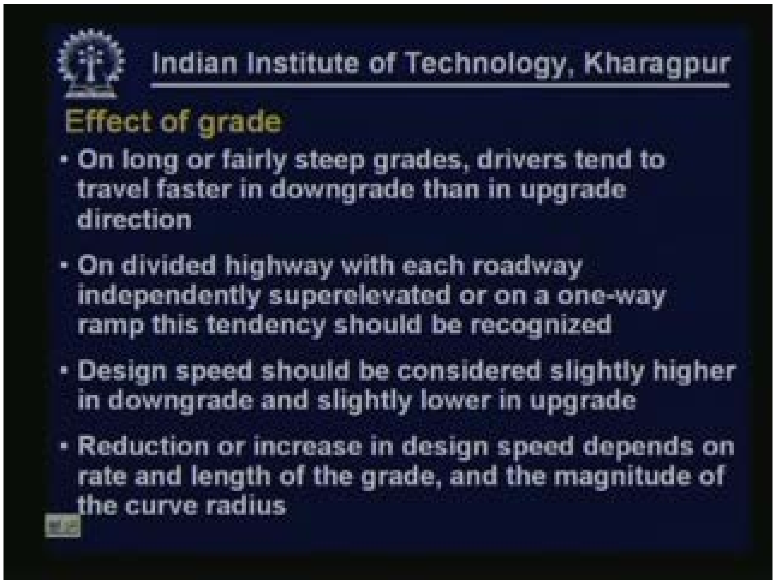

What is the effect of grade does it really affect?
Practically on long and fairly steep grades drivers tend to drive faster in down grade than in up grade direction and for finer design this effect can be taken into consideration particularly on divided highway with each roadway independently superelevated or on one-way ramp that may be there. Therefore design speed may be assumed slightly higher for down grade and slightly lower for upgrade and accordingly this can be done.

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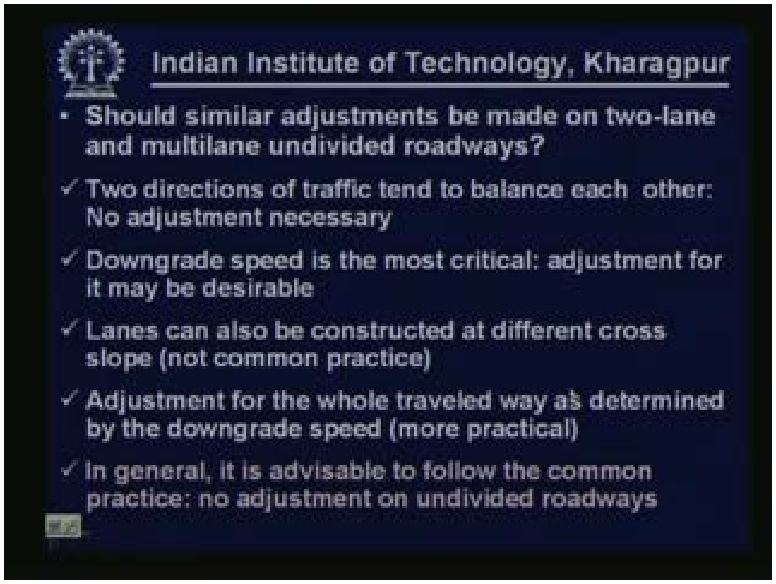

For undivided road normally it is not advisable to have different Superelevation design rather no adjustment is required.

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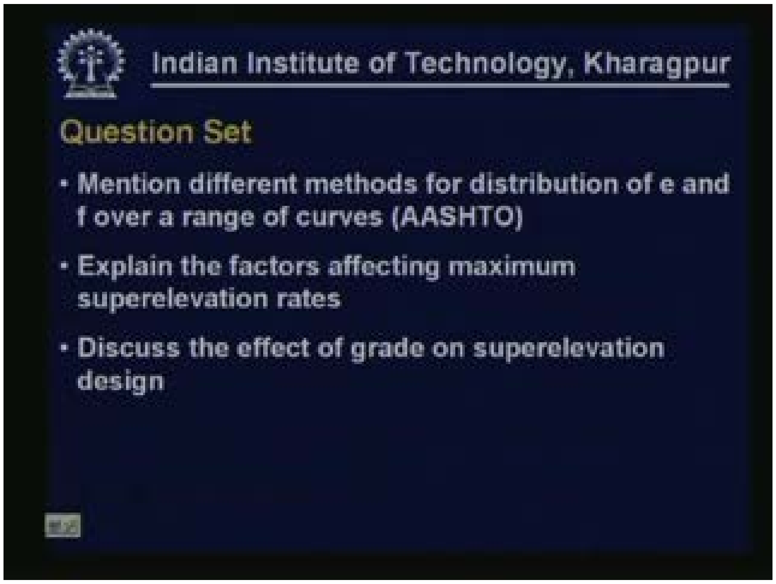

Try to answer these questions:
Mention different methods for distribution of e and f over a range of curves.
Explain the factors affecting maximum Superelevation rates and discuss the effect of grade on Superelevation design.

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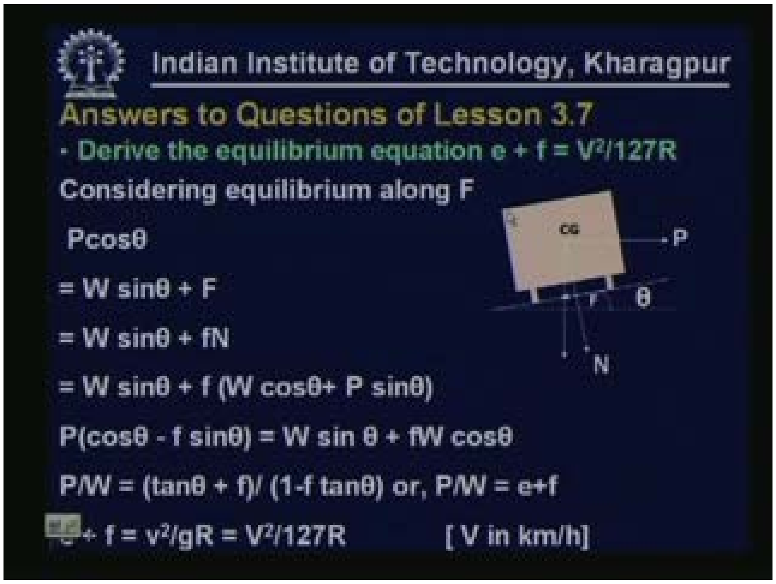

Now let us try to answer these questions which are raised earlier. Derive the equilibrium equation, the same sketch I have discussed in the last lesson also.

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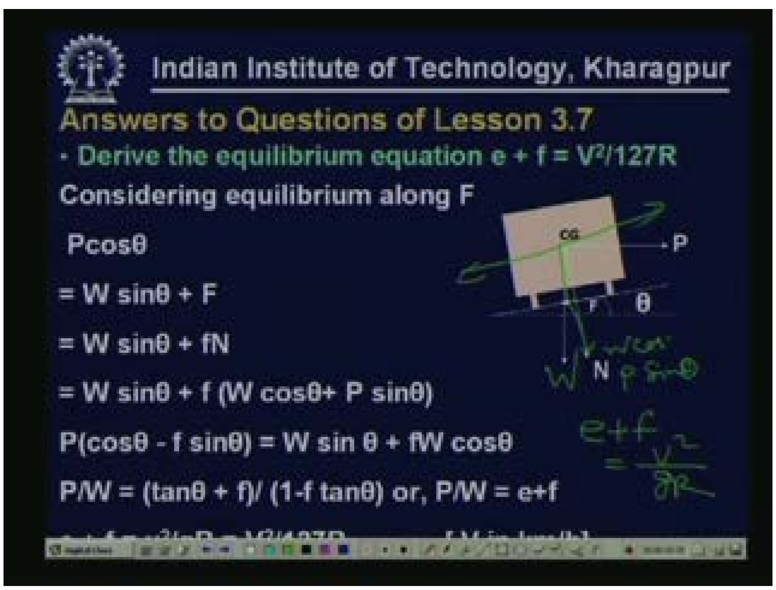

You can take the components P cos theta. Similarly if this is W this is W sin theta this is again W cos theta and component of P in the perpendicular direction is again P sin theta. So then take the equilibrium e cos theta and try to balance it. Finally one can get this equation e + f = V square/Gr if we put the value of V in kilometer per hour and put the value of G then this becomes V square/127R.

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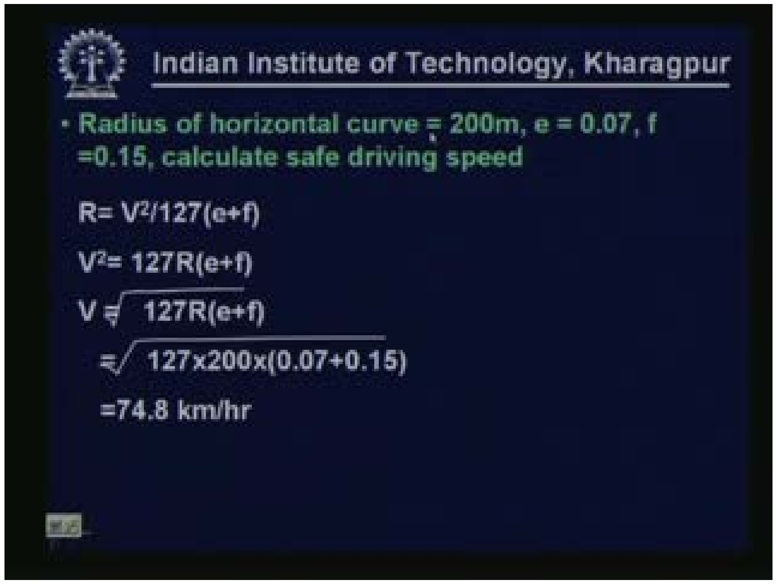

Find out the radius of curve where radius of curve is 200 m is 7% and if it is 0.15 what is the safe driving speed. Again basically the same equilibrium e + f = V square/127R. Put all the values of e f and r and get the value of V.

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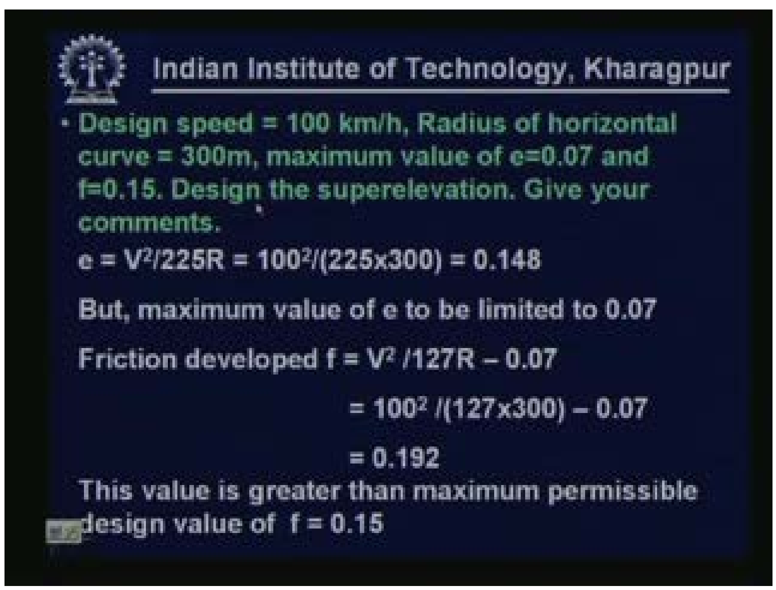

Next was design speed is 100 Km/h, all these things are given so we design Superelevation considering V square/225R. Calculated Superelevation becomes 0.148 more than 7% check for f, the f value is also more than permissible value of 0.15 so we actually go or recommend the speed restriction, the restricted speed we calculate by taking the permissible e, permissible f and again using the same equilibrium equation e + f = V square/127R.

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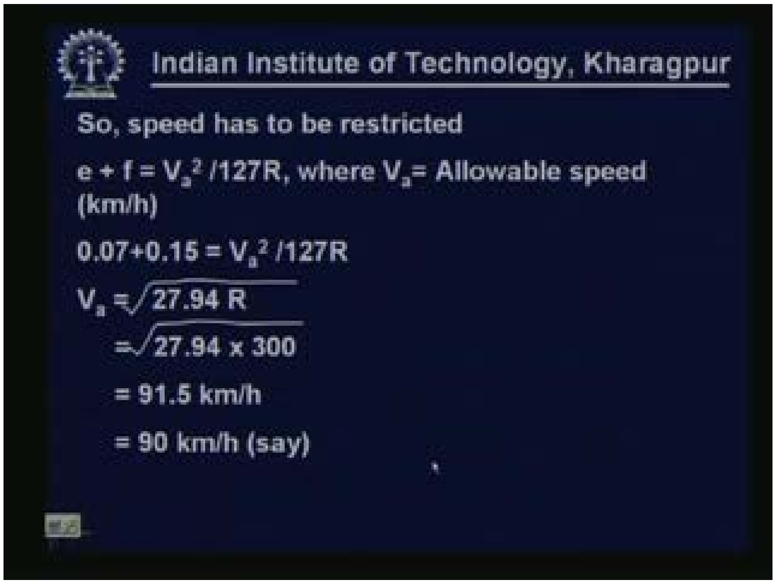

Here the restricted speed is around 90 Km/h. Thank you.