Analysis and Design of Bituminous Pavements

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Lecture -16

Traffic Analysis - ESAL using VDF

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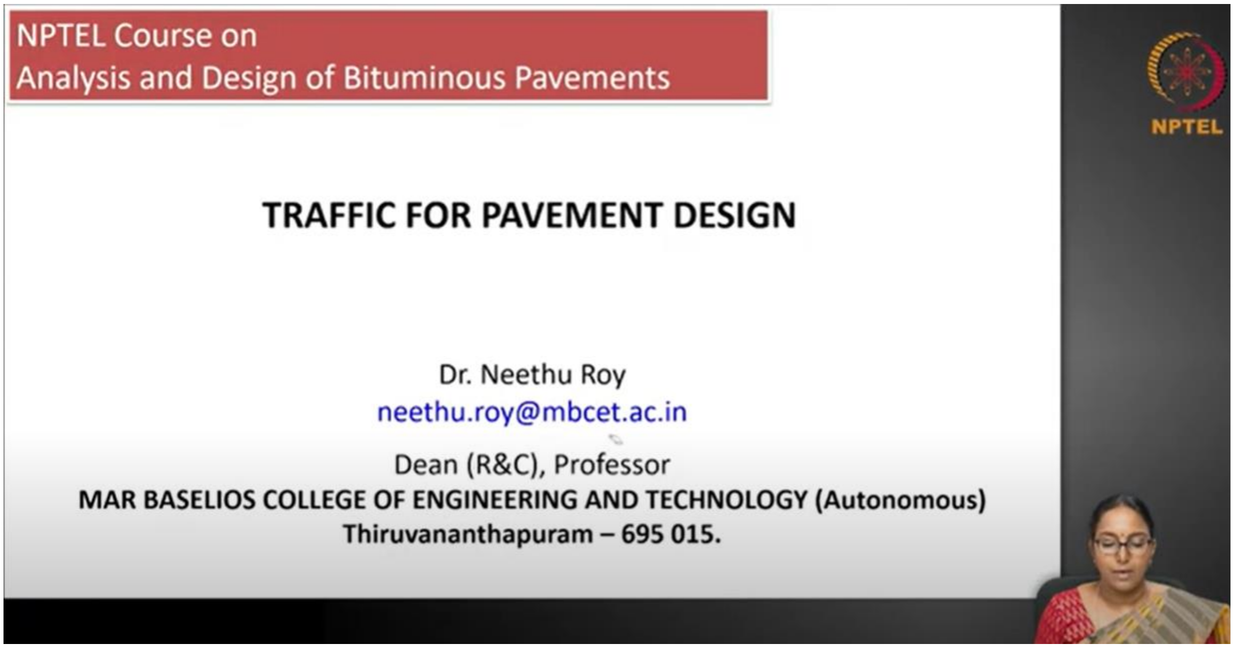

Hello everyone, we will continue our discussion on Analysis of Traffic for Bituminous Pavement Design.

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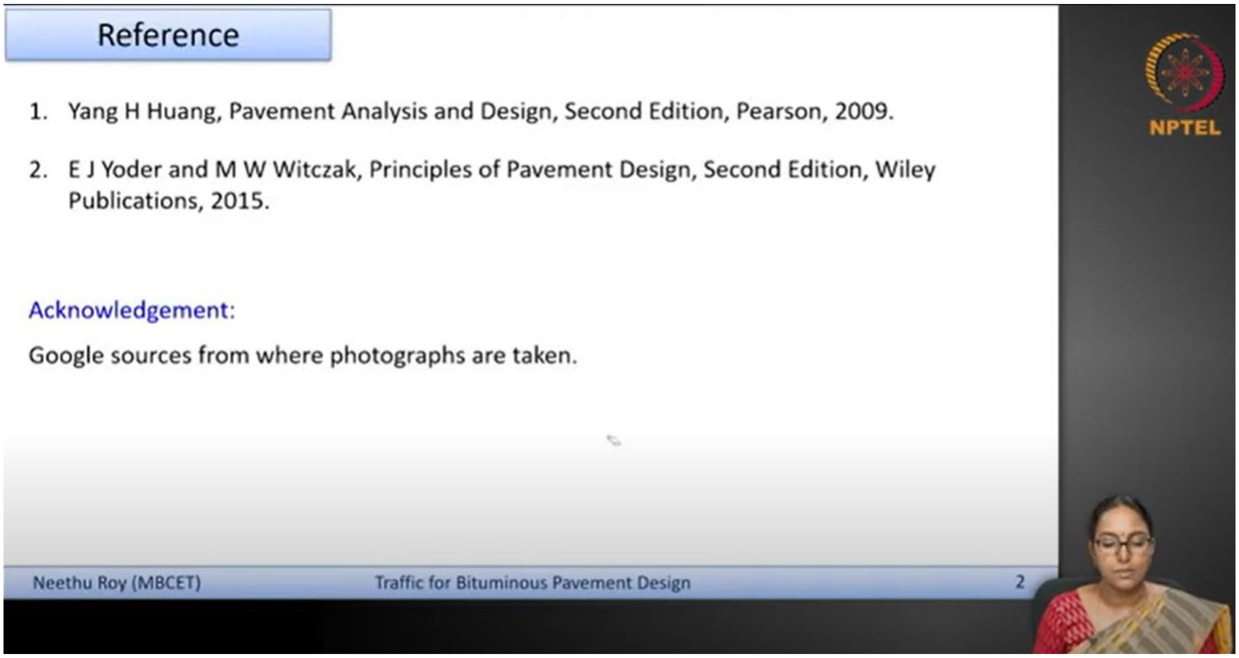

So, the references for this session are Pavement Analysis and Design by Huang and Principles of Pavement Design by Yoder and Witczak and I also will be discussing the code provisions. My acknowledgement to the Google sources from where some photographs are taken.

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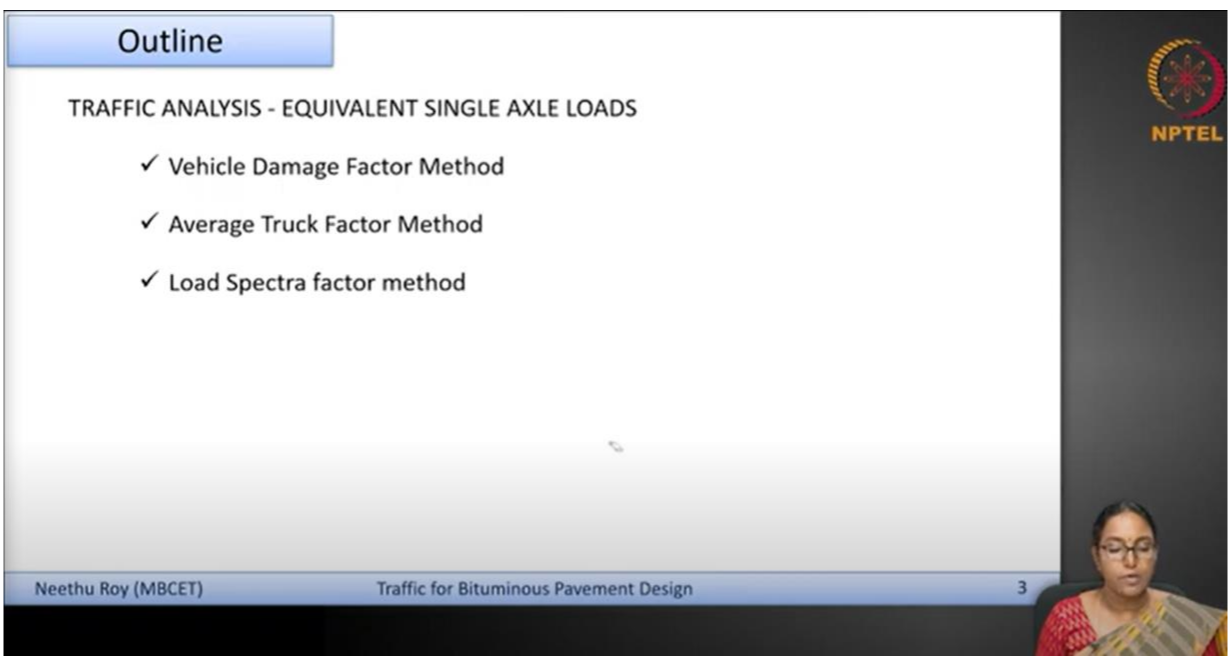

So, the outline of this session will be, you will see how the traffic is analyzed in terms of equivalent single axle loads by three different approaches. The first one is a vehicle damage factor method, the second is an average truck factor method and the third is a load spectra factor method.

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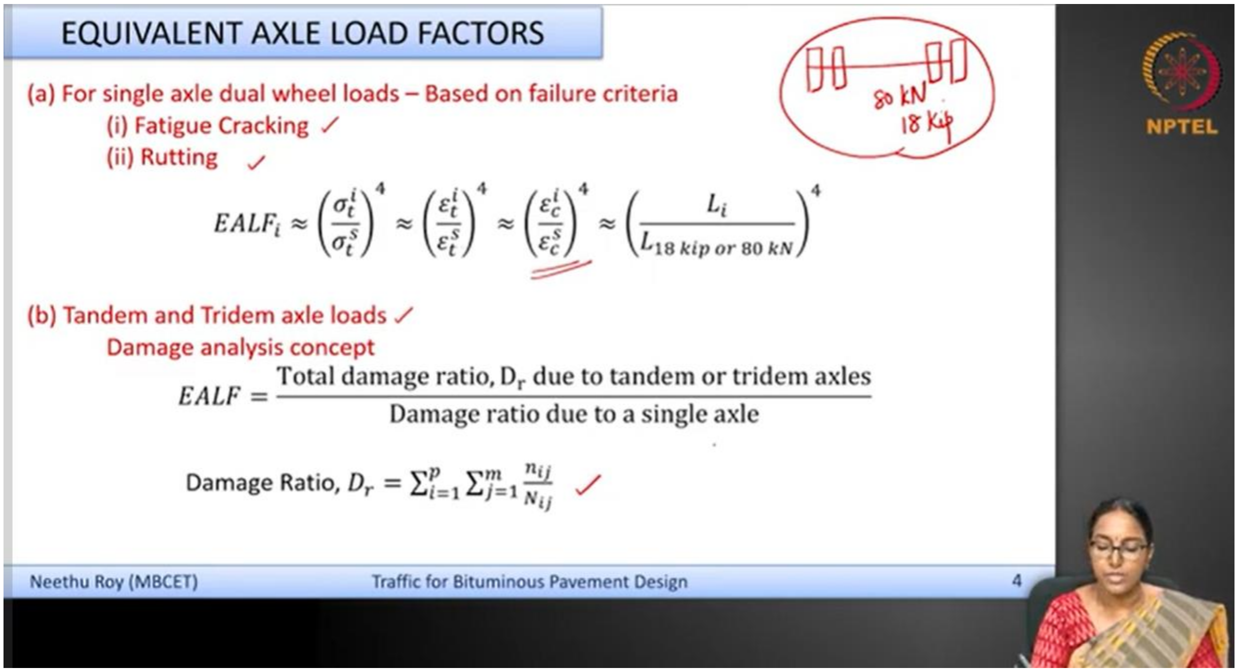

In the last lecture, we discussed that you want to convert all the given axles or the load types or the vehicle types to some standard axle. The standard axle that you have considered is a single axle dual wheel having a total load of 80 kN or 18 kip. So, this was the standard axle that you have considered and you wanted to convert all the given axles to this standard axle. So, for the single axle dual wheels of different wheel loads, what we have seen is that this conversion factor can be determined based on the failure criteria. So, we have considered the two failure criteria which are mostly used for pavement design. One is fatigue cracking and second one is rutting and accordingly we have determined what the EALF factor is for each of the axle load.

$$EALF_i \approx \left(\frac{\sigma_t^i}{\sigma_t^s}\right)^4 \approx \left(\frac{\varepsilon_t^i}{\varepsilon_t^s}\right)^4 \approx \left(\frac{\varepsilon_c^i}{\varepsilon_c^s}\right)^4 \approx \left(\frac{L_i}{L_{18\ kip\ of\ 80\ kN}}\right)^4$$

So, the fourth power law is considered and σ_t represents the tensile stress on the flexible or the bituminous layer, i represents the axle load under consideration and s is the standard axle load. Now, this what we have observed is that if you use the fatigue cracking criteria or the rutting criteria, it more or less gives a similar results as you see that in the case of fatigue cracking. You can also determine the equivalent axle load factor using strains, where ε_t represents the tensile strain at the bottom of the bituminous layer. Whereas if you are considering the rutting criteria, your EALF that is equivalent axle load factor can be determined using compressive stress on top of the subgrade layer (ε_c). So, this is what we have found out or this is a conversion factor or the EALF factor for single axle dual wheels.

Now, if you have a tandem axle or a tridem axle loads, you cannot directly find the critical strains as ε_t, ε_c, etc. under a tandem or a tridem axle load and use this expression to find the EALF that is not directly possible. Because, one tandem axle cannot be considered as equal to one single axle dual wheel or it cannot be considered as equivalent to two single axle dual wheels also. So, it will be somewhere in between. So, that is why you need to adopt a damage analysis concept in the case of tandem axle and tridem axle to determine the EALF rather than directly using the ε_t and ε_c under those axle loads. So, what you have seen is that you have to determine the damage ratio as given here.

$$\mathrm{EALF} = \frac{\text{Total damage ratio due to tandem or tridem axles}}{\text{Damage ratio due to a single axle}}$$

$$\text{Damage ratio } D_r = \sum_{i=1}^{p} \sum_{j=1}^{m} \frac{n_{i,j}}{N_{i,j}}$$

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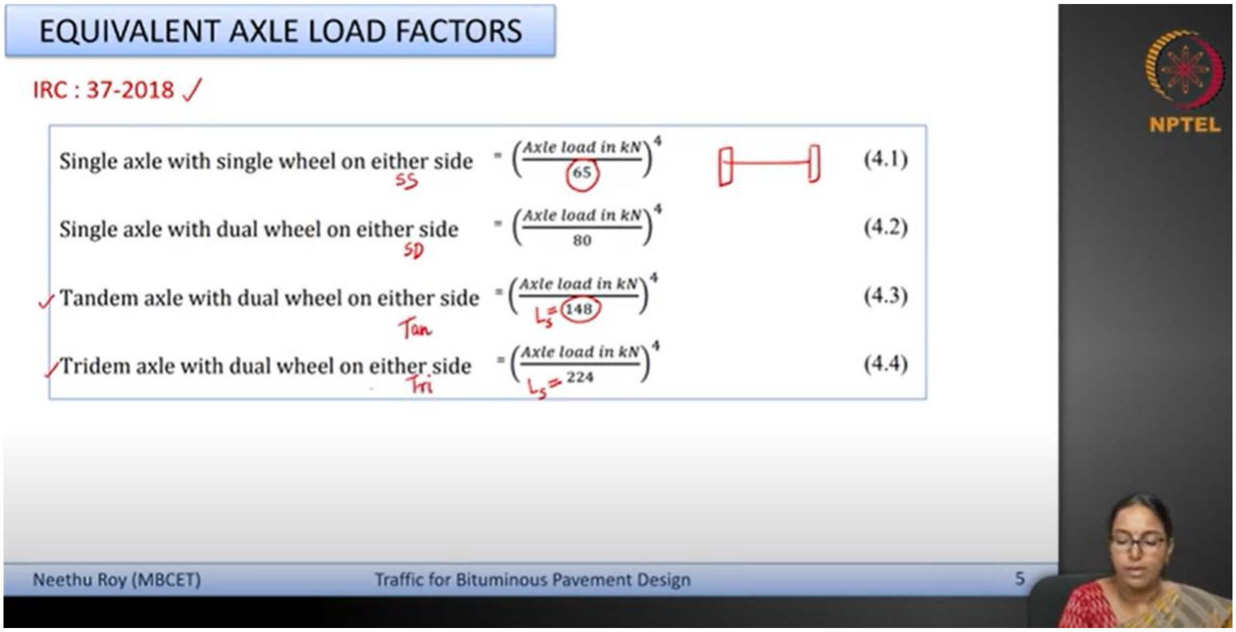

And then what we have seen is that in IRC 37 2018, the equivalency factors are given in terms of the fourth power law.

$$\text{Single axle with single wheel on either side} = \left(\frac{\text{Axle load in kN}}{65}\right)^4$$

$$\text{Single axle with dual wheel on either side} = \left(\frac{\text{Axle load in kN}}{80}\right)^4$$

$$\text{Tandem axle with dual wheel on either side} = \left(\frac{\text{Axle load in kN}}{148}\right)^4$$

$$\text{Tridem axle with dual wheel on either side} = \left(\frac{\text{Axle load in kN}}{224}\right)^4$$

So these are the equivalent axle load factors given in IRC 37 to convert a single axle single wheel, a single axle dual wheel, a tandem axle and a tridem axle to an equivalent single axle dual wheel assembly like this.

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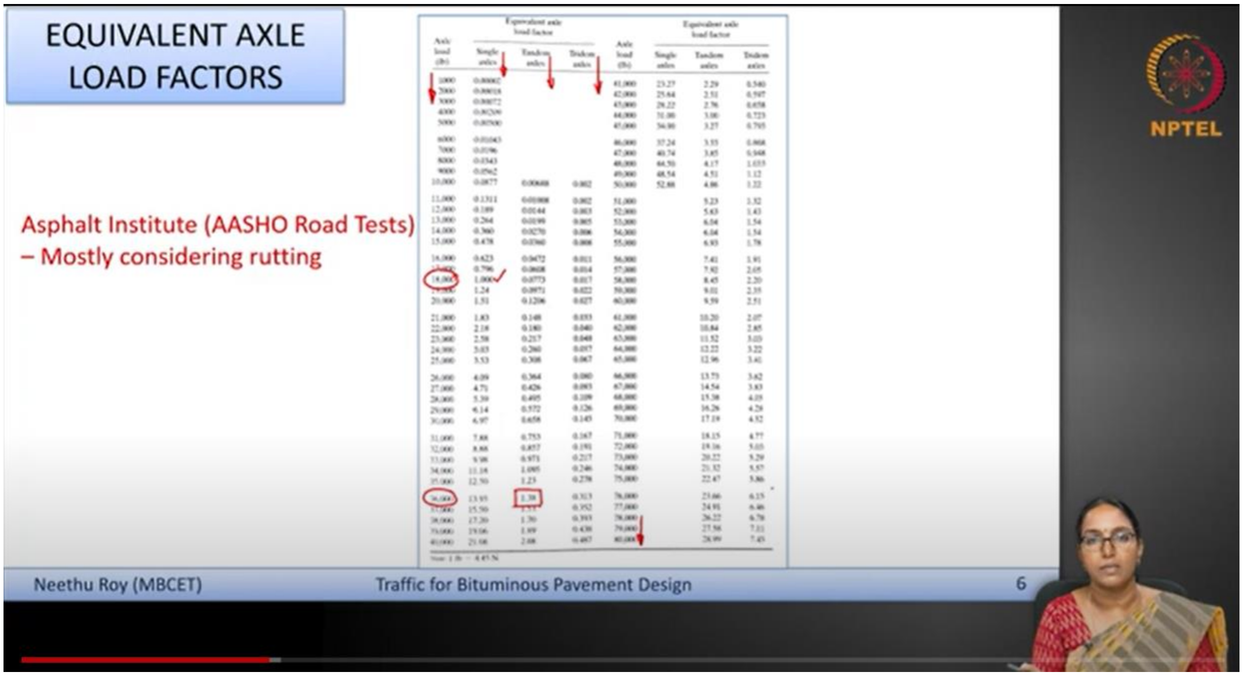

Now coming to the Asphalt Institute method based on the AASHO, the American Associate of State Highway Officials road test, mostly the failures were considered to be from rutting and from this AASHO test results they have given the equivalent axle load factors. Mostly, it will be on this fourth power law itself. So we see that for the different axle loads here, this is a table representing the equivalency factors. For different axle loads you see from 1000 pounds to all with the way up to 80,000 pounds, the equivalent axle load factors are given. We can have a quick look, you see that if it is 18 kip or 18,000 pounds, you see that the equivalency factor for a single axle is 1. Whereas if you consider 36 kip for example, suppose you have a tandem axle which is coming with double the load which is 36 kilo pounds you see that the tandem axle equivalency factor is not 2 but it is 1.38. So from this table you can directly take the equivalent axle load factors if you are designing as per the Asphalt Institute method. So this is what we have discussed so far in the last lectures on what is that equivalent factor that has to be used to convert the given axle load to a standard axle load.

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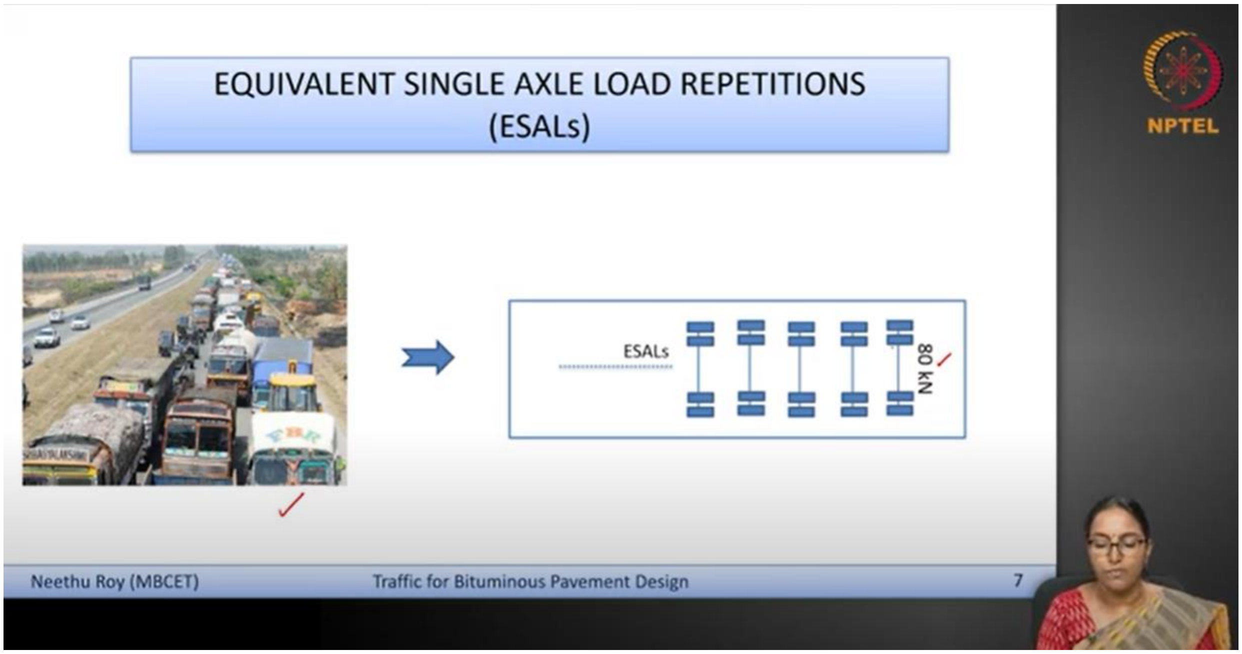

Now let us see how to arrive at the equivalent single axle load repetitions from the total traffic. See what you see here is a traffic which comprises of different types of trucks with different axle configurations and having different weights. Now what you have to convert it to? You have to convert it into a number of repetitions of 80 kN single axle dual wheels. So as you see here, you call it as equivalent single axle load so we call it as ESALs. So how to do this conversion and how to get it by applying the equivalency factors is what we are going to discuss in this lecture.

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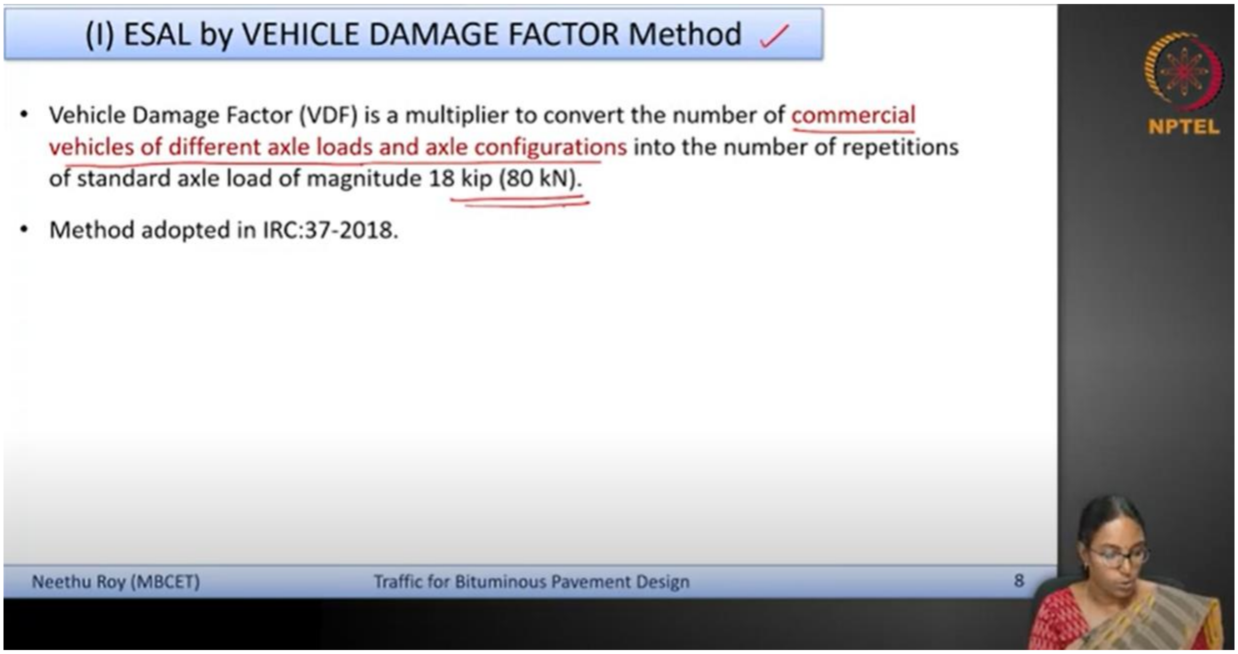

Now there are three approaches, one is a vehicle damage factor method, the second is truck factor method or an average truck factor method and the third one is load spectra factor method. We will see each one of this one by one. So the first one is the vehicle damage factor or you generally call it as VDF. VDF is a multiplier to convert the number of commercial vehicles of different standard axle loads and axle configurations into the number of repetitions of the standard axle load of 80 kN single axle dual wheel or 18 kip. Now this is a method that is adopted in IRC: 37-2018.

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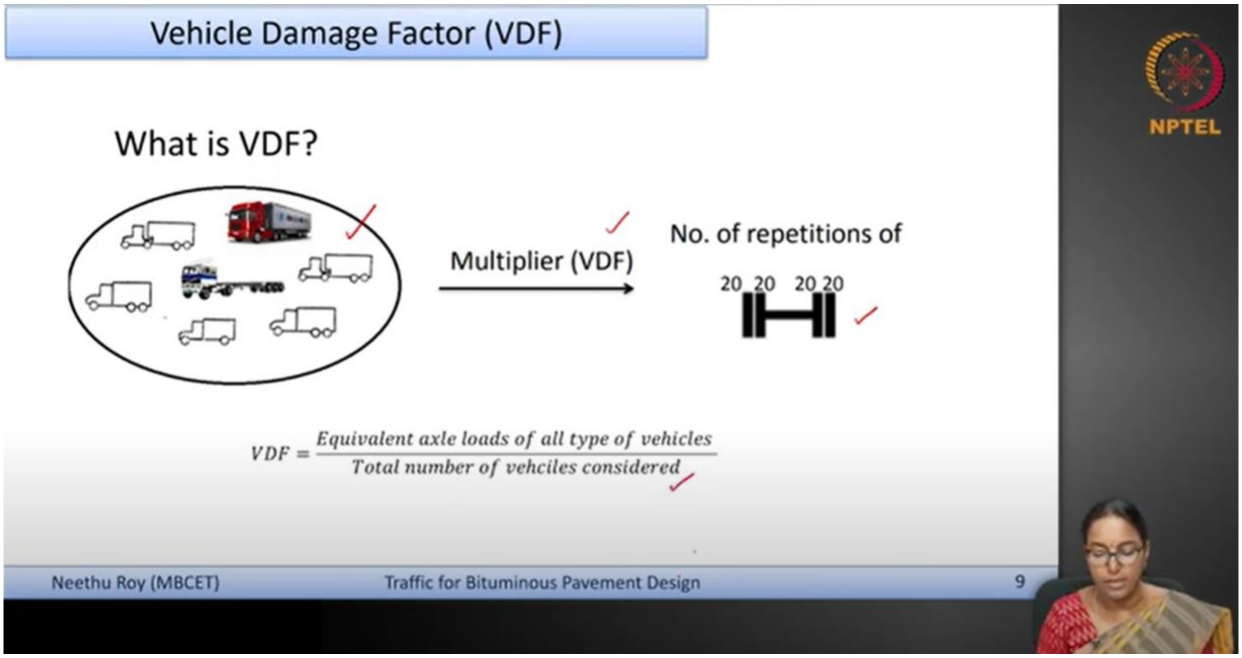

We will see what this VDF is. See this is the traffic load or the traffic in the stream as I have already shown. You have different classes of trucks you have different trucks with different loading as well as different axle configurations. You have to find that one multiplier which can convert it into number of repetitions of the standard axle. So how to get this one multiplier or this vehicle damage factor is that you will find out what is the equivalent axle loads corresponding to all the axle loads of all the vehicles in the stream. Then sum it up divided by the total number of vehicles considered will give you one vehicle damage factor for the entire stream together.

$$\text{VDF} = \frac{\text{Equivalent axle loads of all types of vehicles}}{\text{Total number of vehicles considered}}$$

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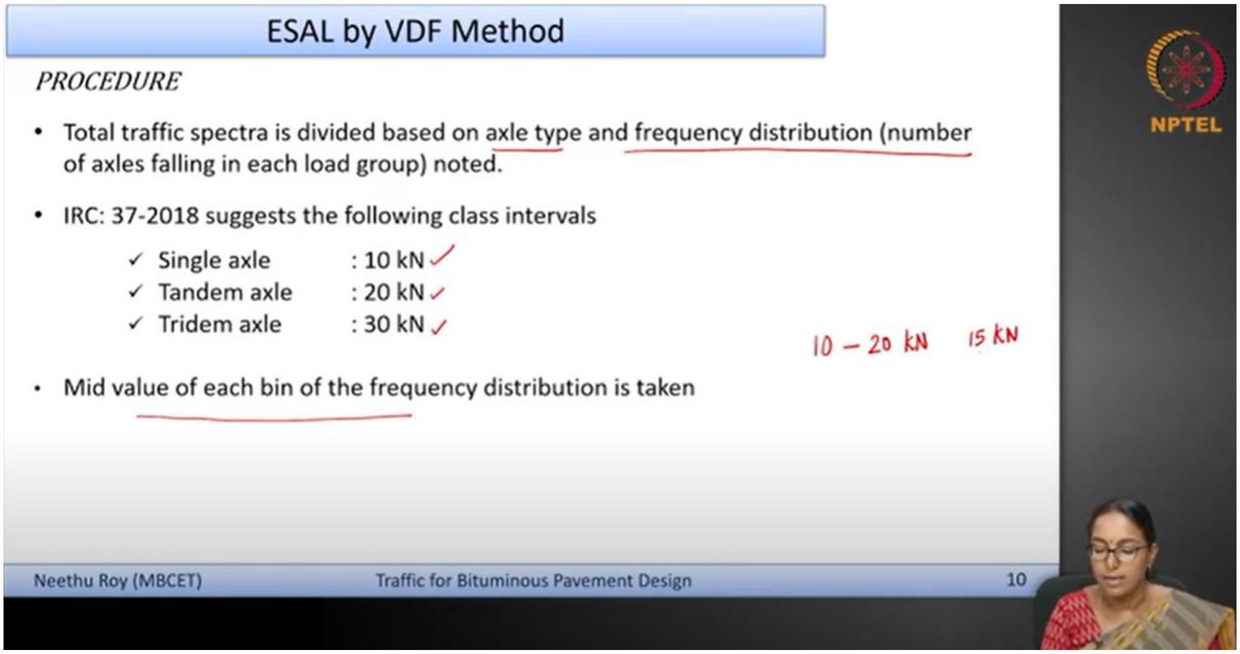

Now let us see how to calculate it. So let me explain the procedure. Firstly I will be explaining with respect to the IRC: 37-2018 approach. So first of all what you need is the total traffic spectra the traffic load data has to be collected and then this traffic load data will be divided based on the axle type and a frequency distribution table can be prepared. So for each axle type we will see how many numbers of axles are falling in each load group.

Now what you do is that you divide it into a number of intervals or class intervals. Essentially now how you divide it into the class interval can affect the VDF value. So IRC 37 suggests that you group or make bin sizes of 10 kN for the single axle loads. If it is a tandem axle load you can have make a bin size of say 20 kN and for tridem axle loads you can make a bin size of 30 kN. Essentially because the loads will be larger so you can have a range of 30 kN as the class interval.

Now you consider you divide the entire axle load into each frequency and the mid value of each of the bin of the frequency distribution will be considered. Say for example in the case of the 10 to 20 kN axle load bin, 15 kN will be taken as the average load in that category and the equivalent axle loads will be found out by multiplying the frequency that is falling in each one of this bin size with their corresponding EALF values. So see what you see is that your 15 kN is the mid value of that bin of that particular group, you find out what is its EALF using these expressions as given in the equivalency factor expressions given in IRC 37 which is for example if it is a single axle dual bin the given axle which is 15 kN divided by 80 raised to 4. So that will give you the EALF factor. Now once you get the EALF factor, you can multiply the EALF values corresponding to the number of axles in that group.

Suppose there are like say 25 axles in this group, so you get the EALF for this particular axle load group and multiply it with 25 that is the frequency that will give you the conversion to equivalent single axle loads for that bin or for that axle group.

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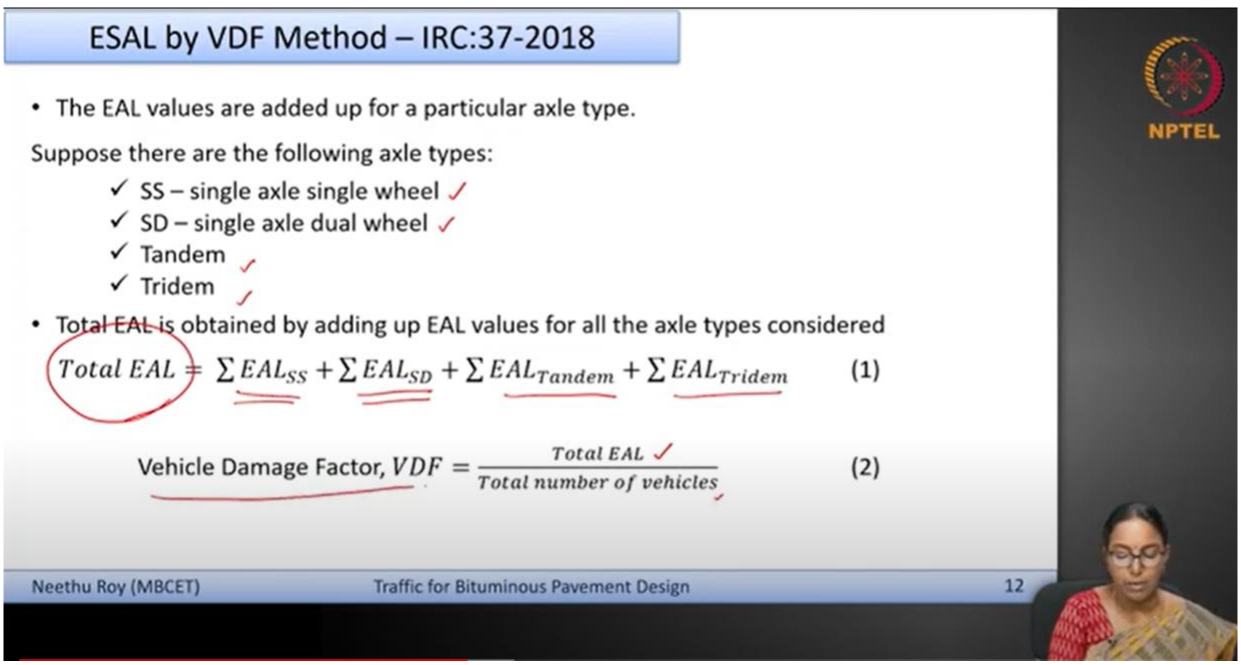

So for a particular axle type, you have different axle load groups you add all the equivalent axle load values together to get the total ESAL corresponding to that axle group.

$$\text{Total EAL} = \sum \text{EAL}_{\text{SS}} + \sum \text{EAL}_{\text{SD}} + \sum \text{EAL}_{\text{Tandem}} + \sum \text{EAL}_{\text{Tridem}}$$

$$\text{VDF} = \frac{\text{Total EAL}}{\text{Total number of vehicles}}$$

Say for example, if you have different axle types such as single axle single wheel (SS), single axle dual wheel, tandem axle, tridem axle etc. So from the traffic, you have divided all the single axles from all the vehicles together put it in different class groups and then you have determined the equivalent axle loads for that. Similarly, you have found out the equivalent axle loads for all the single axle dual wheels in that vehicle group. Similarly the tandem axle and the tridem axle and all these equivalent axle load values can be added together to get the total EAL value. As you see here, the total equivalent axle loads is equal to the whole spectrum you have considered, say 1000 vehicles divided by the total number of vehicles will give you this vehicle damage factor for that axle the load spectra that you have collected.

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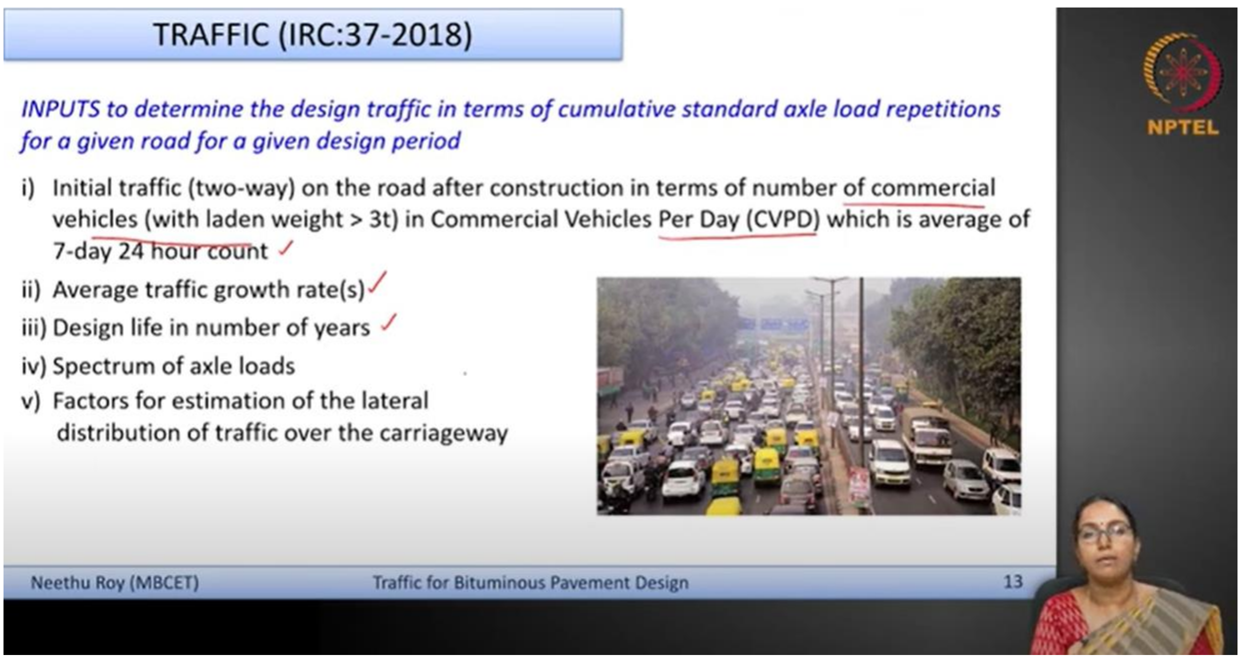

Let us discuss how to consider the traffic as per IRC 37 and what is the input that goes in here. So what I have discussed is only the vehicle damage factor. Now this vehicle damage factor has to be used to get the total ESALs. So let us see of the traffic of the actual traffic so let us see how that is done. So the input that you require is the initial traffic. Now what you are going to find out is what is the cumulative standard axle loads for a given road for a given design period for which you are going to design the pavement structure. So first you need the initial traffic.

Normally the two way traffic on the road after construction in terms of the number of commercial vehicles CVPD or the commercial vehicles per day is to be considered.

The vehicles or the trucks or the heavy commercial vehicles having laden weight more than 3 tons will be considered for pavement design. And in order to get these commercial vehicles per day you have to take the average of a 7 day 24 hour count. So this number of commercial vehicles per day should be the count at the beginning of the functioning of the new structure or the new pavement. Then you need the average traffic growth rates of either the growth rate for the entire vehicle classes or different growth rate for the different vehicle groups. And then the design life in number of years and the spectrum of axle loads.

As I said you need the axle load information so that is the spectrum of axle loads and also other factors for the estimation of a lateral distribution of traffic over the carriage way. So these are the input data that are required. We will discuss each one of them one by one.

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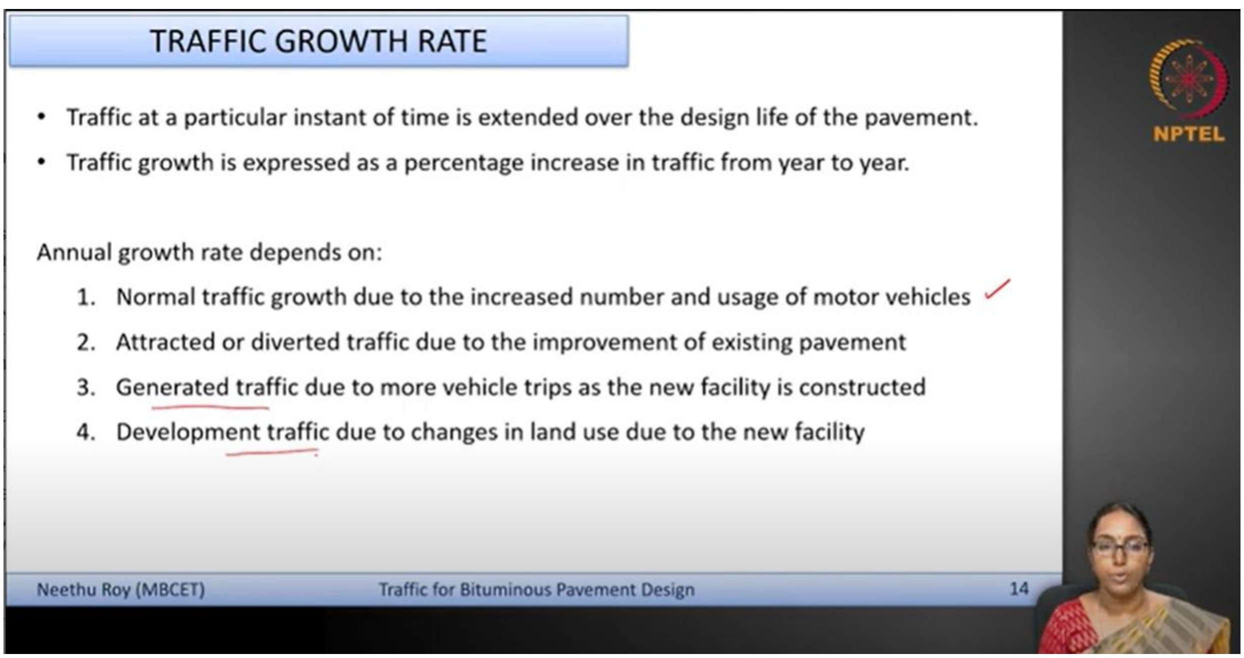

The first one is the traffic growth rate. Now this value has to be extended over the design period so as to get the cumulative traffic.

So you need what is the rate at which this traffic grows. Now this traffic growth rate is expressed as a percentage of increase or percentage increase from year to year. Now how does this traffic grow? The first thing is that there can be a normal traffic growth over the years due to increased number of usage of motor vehicles. Now there could be other possible reasons of increase in the traffic growth. One is the attracted or diverted traffic due to the improvement of an existing pavement or due to the construction of a new pavement.

It may attract more traffic towards that. So that can increase the traffic or that can contribute to the traffic growth. And another is generated traffic because since a new facility or a pavement is created, there could be more traffic that is generated because more vehicle trips may happen. And another one is that development traffic because there could be changes in the land use or development of the region because of this new facility which can attract more traffic. So all these reduced reasons can contribute to the traffic growth and while estimating the growth rate you have to consider all these factors. And of course the traffic growth over the previous years can be considered to predict the traffic growth in the coming years.

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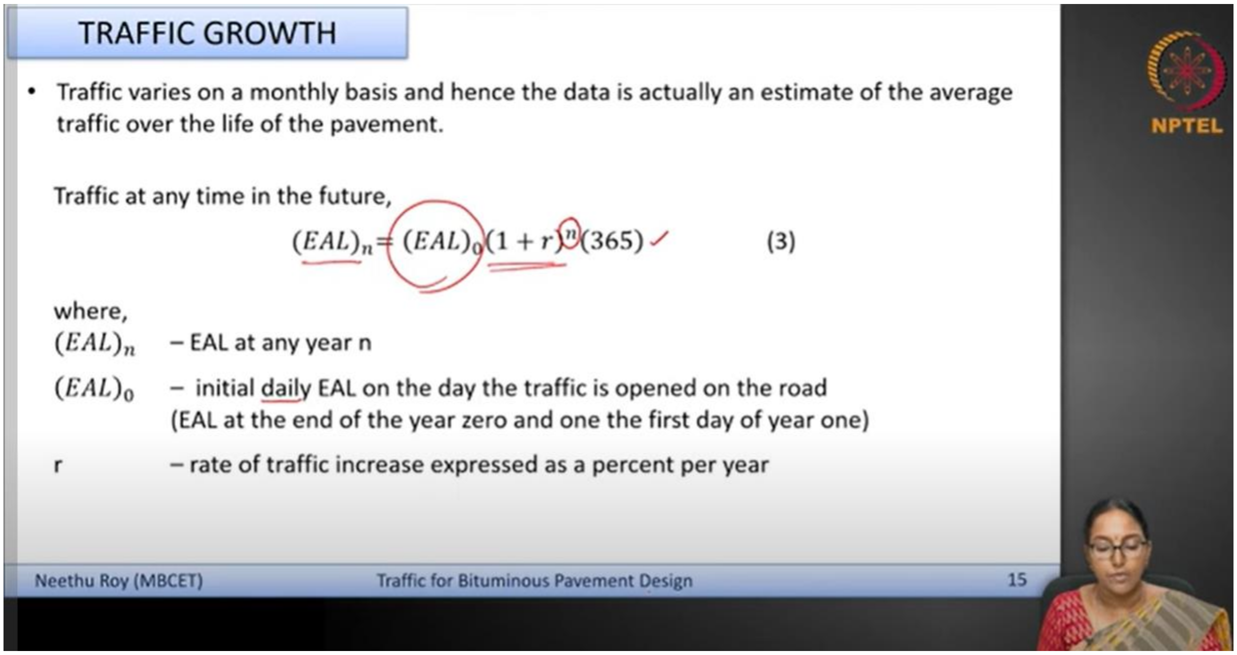

One more aspect is that this traffic actually varies on a daily basis as well as on a monthly basis. So the data that you actually use is an estimate of the average traffic over the life of the pavement. Now let us say that we know what the traffic initial traffic is on day 1 or day 0 say for example EAL_0. Now if you want to find out what is the traffic on a future date EAL_n then you can find it by projecting it by this expression.

$$(\mathrm{EAL})_n = (\mathrm{EAL})_0\,(1+r)^n 365$$

Now $(\mathrm{EAL})_0$ here is the initial daily traffic. On the day the traffic is opened on the road or you can consider that it is the at the end of the 0^{th} year or that is at the starting of the first year. If you project it to a future year which is after n years and r is the growth rate, you will get the yearly traffic in a future year.

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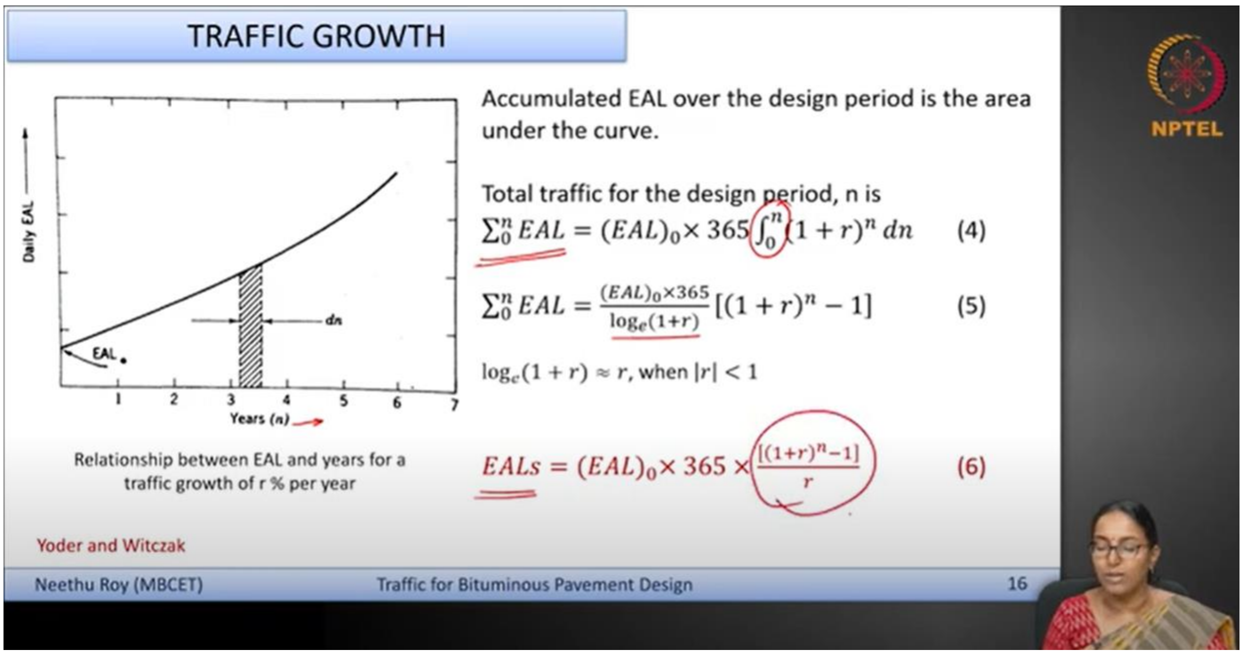

Let us assume this is the traffic growth rate. So the daily EAL or equivalent axle loads, likewise it can be the number of vehicles or number of trucks and so on. So let us say that the daily equivalent axle loads increases in this fashion. So this is a trend that is given or the growth trend over the years in n years. Now for the design you need to find out suppose you are going to design the pavement for n years you want to find what is the traffic that is accumulated over this design period, you have to calculate the area under this traffic progression curve.

So how to get this area under the curve? We can first find out what is the total traffic for these n years from this graph. What you have to do is that you have to integrate the value from the 0^{th} year to the n^{th} year for to find the total traffic. So you can see this written here in expression.

$$\sum_0^n \mathrm{EAL} = (\mathrm{EAL})_0\, 365 \int_0^n (1+\mathrm{r})^{\mathrm{n}} \mathrm{dn}$$

Integrating the above expression, you get,

$$\sum_0^n \mathrm{EAL} = \frac{(\mathrm{EAL})_0\, 365}{\log_e(1+\mathrm{r})}\left[(1+\mathrm{r})^{\mathrm{n}} - 1\right]$$

Now the growth rates are mostly less than say 10%. So when |r| is less than 1, your $\log_e$ (1+r) is close to r. So we can replace this with r so that the total equivalent axle loads over the n years is as follows.

$$\mathrm{EALs} = (\mathrm{EAL})_0 \times 365 \times \frac{\left[(1+\mathrm{r})^{\mathrm{n}} - 1\right]}{\mathrm{r}}$$

So this factor here $\frac{[(1+r)^n - 1]}{r}$ can be termed as G, which is the growth factor. So this is how you estimate the traffic growth and you find out what is the total traffic at a future date or what is the total traffic over the design period which has to be considered for design.

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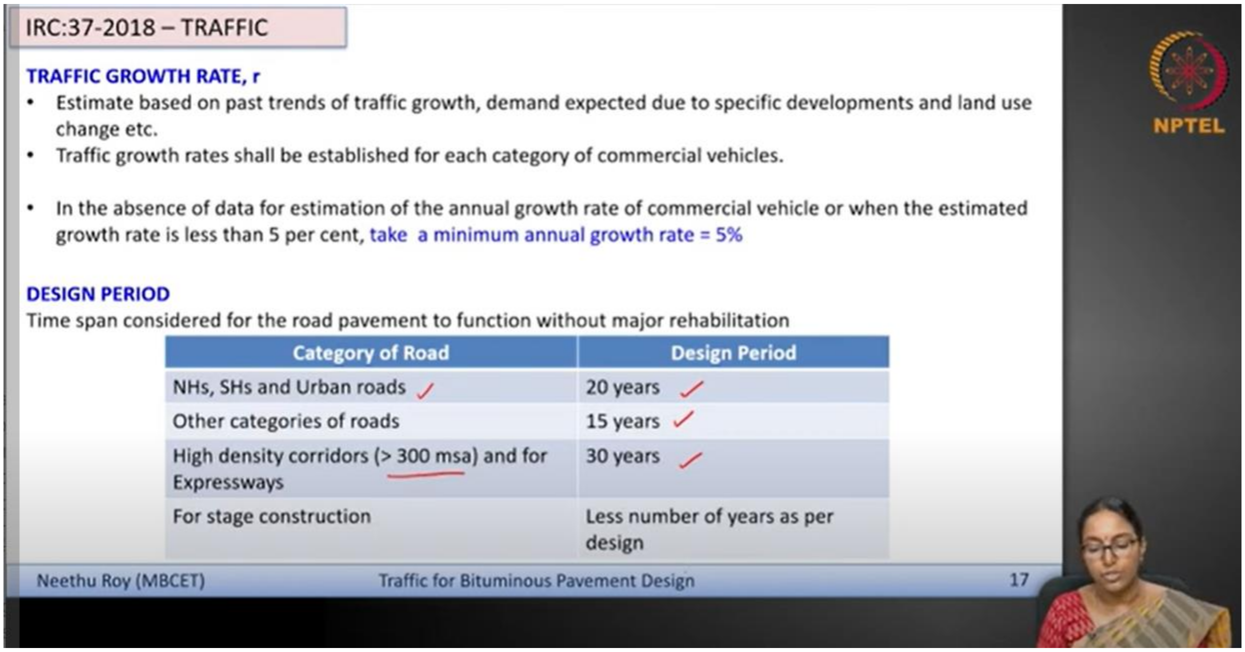

Now the traffic growth rate as I already mentioned it can be estimated based on the past trends of traffic growth and also what is the demand that is expected to the specific development and land use change etc. Because traffic growth rate need not be same for all classes of vehicles like for one truck type it may be different from another one. So you can estimate the traffic growth rates for different categories of commercial vehicles. And if this data is not available, IRC suggests that the annual growth rate of commercial vehicles if it is less than a 5 percentage also you have to take a minimum annual growth rate of 5 percentage.

And regarding the design period n, IRC 37 says that you can choose the number of years for which the road is designed based on the class of the road as well as the way in which this construction is planned. So essentially if the category of the road is national highways, state highways or urban roads you can choose a design period of say 20 years. Whereas for other categories of roads like minor roads or district roads and so on you can choose up to 15 years for the design of bituminous pavements. And in the case of high density corridors with the total equivalent standard axle loads which is more than 300 million standard axles (MSA) and for expressways and all, you go for a larger design period of 30 years. Now you may not always do this construction at the beginning itself for the total design period. You can go for a stage construction also that is possible in the case of flexible pavements or bituminous pavements. So this, if it is a stage construction you can choose a lesser design period, lesser number of years for the design as per the how the stage construction is planned.

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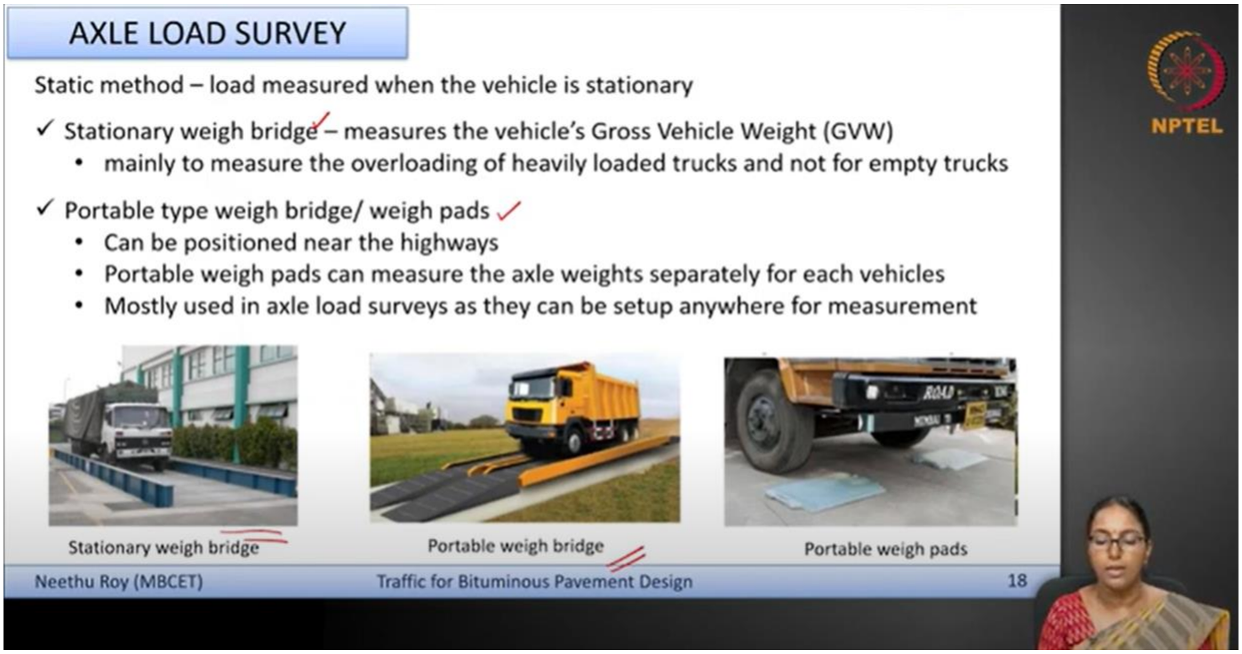

Now in order to get this axle data you have to conduct axle load survey. Now the axle load survey has to be conducted on a similar section or a similar stretch of road like the one which we are going to construct or on a similar category of road you can do the axle load survey to investigate what will be the type of axle load spectra that will come in the new construction or the new pavement that you are planning. So in order to conduct this axle load survey you can have a static method or a weigh in motion method. So in the static method what you do is that the load of the vehicles will be measured when the vehicle is stationary.

For which you have the stationary weigh bridges or you can use portable type weigh bridges or weigh pads. As you can see here, see this is a stationary weigh bridge. So what is done is that the vehicle will be allowed to stand on top of that weigh bridge and then you can calculate or you can measure what is the total weight of the vehicle. Now this type of weighing is essentially done for measuring the overloading of heavy loaded trucks and not for empty trucks this method is used. Now in the road if you want to get the actual axle load spectra you normally go for this portable type weigh bridges or weigh pads. This can be positioned near to the highway where you want to conduct this axle load survey and you can ask the vehicles to move over on top of these weigh pads or weigh bridges and the weights of these vehicles or the axles can be noted. In the case of portable weigh pads like this, you can measure the axle loads separately. Suppose it is a tandem axle, you can first ask the driver to move this vehicle on the first wheel of the tandem axle on top of this weigh pad you can measure that and then you can move the next wheel and measure the load. So for each axle you can measure the vehicle loads separately.

Now in this picture you see that, two weigh pads are used so that you can measure the load on the whole axle together but sometimes this also may not be happening. What you can use is that you can use a single weigh pad with the assumption is that on the either side of the axle, both the wheels will be carrying equal amount of load or it is equally distributed on both sides. So you will just measure the weight of one wheel on one side of the axle so that multiplying it with two will give you the total weight on the axle. So this is the portable weigh pads or you can also have portable weigh bridges which is slightly bigger in size. So essentially for the axle load survey that you do in highways you go for this portable weigh pads.

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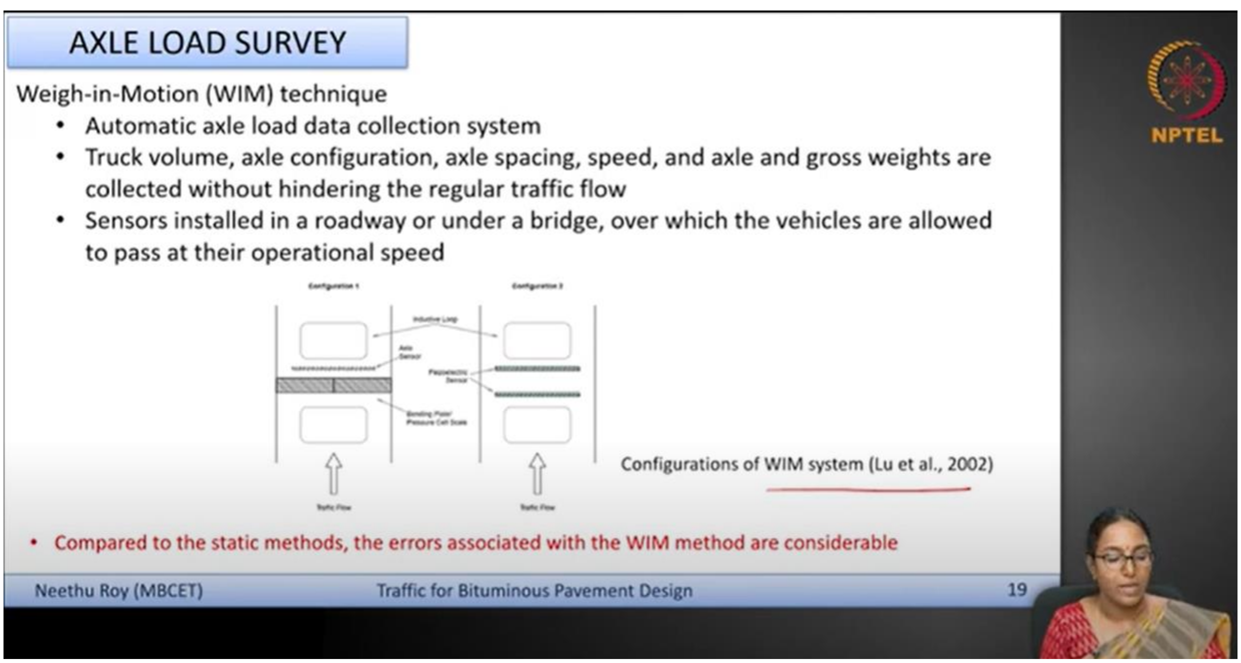

Now the other method is the weigh in motion technique. So this is essentially an automatic axle load data collection system. The major disadvantage with the static method is that you have to ask each one of the vehicle to pass on top of the weigh bridge and it has to be stopped there for considerable time till still you know the weight. So this may cause some disruption to the moving traffic. This can be avoided in the case of a weigh in motion technique. Here the truck volume, the axle configuration, axle spacing, the speed of the vehicle, the axle and the gross weights everything can be collected automatically without hindering the regular traffic flow.

So what is done is that certain sensors will be installed in the roadway or under the bridge over which the vehicles are allowed to pass at their operational speeds itself and then the sensors will capture this data. But compared to the static method, the errors associated with weigh in motion methods are considered to be a little larger. And there can be certain various arrangements of you know sensors on the road to collect this information. You see this is some of the configurations of way in motion systems as per Lu et al. in 2002. So you can see that this is a traffic flow direction and a bending plate or a pressure cell scale is used here and there is an axle sensor also to measure the axles and there is an inductive loop. There are piezoelectric sensors which are arranged to have the weigh in motion measurement of axle loads.

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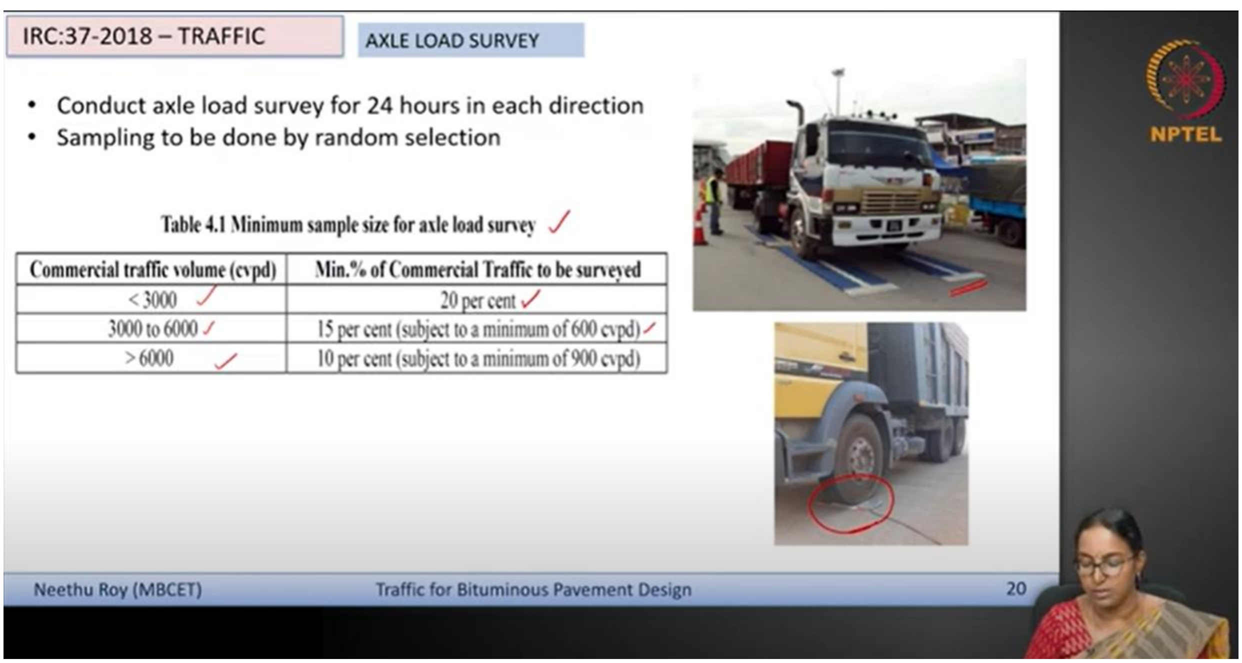

Now as per IRC: 37-2018 it suggests that you have to conduct the axle load survey for 24 hours in each direction of traffic. Now it may not be possible to stop all the vehicles in a particular stream and measure the traffic loads.

So a sampling has to be done and it is suggested that this minimum sample size that has to be chosen in order to conduct this axle load survey is given as at least 20% of the commercial traffic if the number of commercial vehicles per day is less than 300. If the traffic is between 3000 to 6000, at least 15% of the commercial vehicle traffic is to be surveyed, subject to a minimum of 600 CVPD. And if the truck traffic is more than 6000 CVPD, at least 10% of the vehicles are to be surveyed. So these are some of the pictures wherein bigger kind of pads are used for the axle load data collection, whereas this is a small portable type of weigh pads being used for finding the axle loads. So this is how the sampling is done and then the axle load data will be collected.

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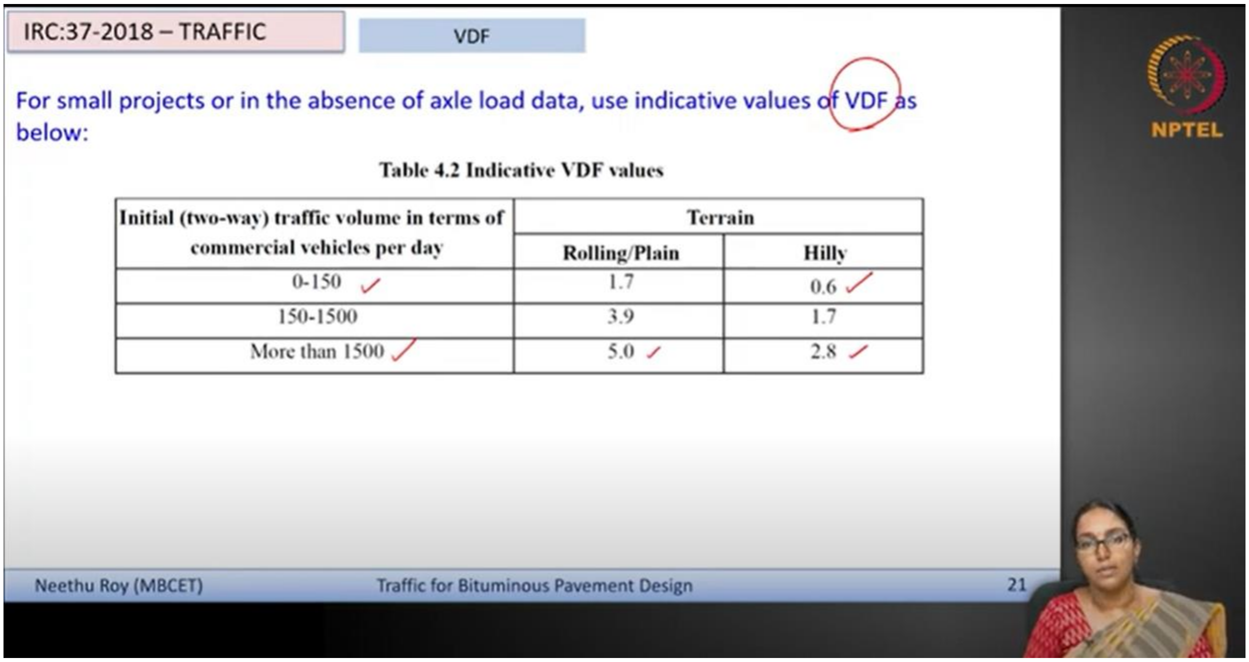

Initial (two-way) traffic volume in terms of commercial vehicles per day	Terrain	
	Rolling/Plain	Hilly
0-150	1.7	0.6
150-1500	3.9	1.7
More than 1500	5.0	2.8

Now using this axle load data we will determine what is the vehicle damage factor and that vehicle damage factor will be used to determine the equivalent standard axle loads for the traffic that is for the design traffic. But IRC 37 also suggests that if it is in the case of small projects or if it is not possible to collect such extensive axle load data then certain indicative VDF values that are given in the code can be used which is given in table 4.2 of IRC 37. If the initial two-way traffic volume in terms of commercial vehicles per day is 0 to 150, you can use a VDF or a vehicle damage factor of 1.7 for plain or rolling terrain. So IRC suggests different VDF values for plain and rolling terrain and the hilly terrain. So in the hilly terrain you can go for a VDF value of 0.6. Similarly, if the CVPD is more than 1500 you can use a vehicle damage factor of 5 or 2.8 respectively. So this is what IRC suggests if you do not have provision for conducting an axle load survey. This is done only for small scale projects.

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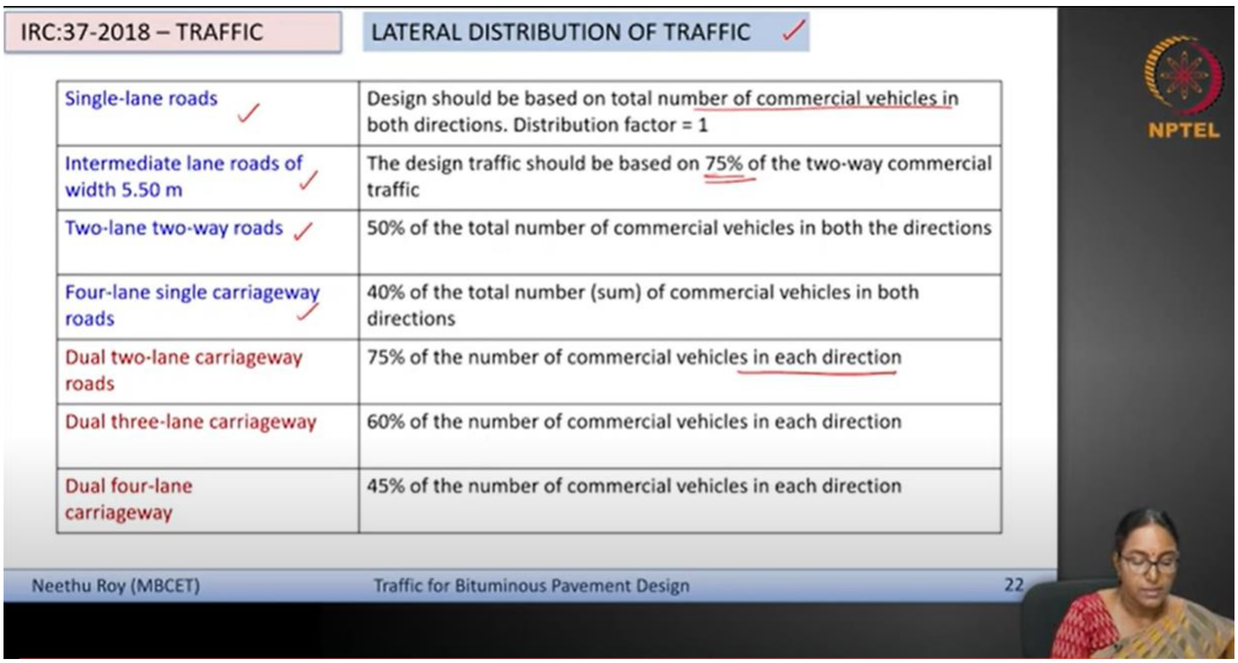

Now the next factor that is to be considered for determining the equivalent standard axle loads is the lateral distribution of traffic. Now you can have different number of lanes and you will have traffic in both directions like say if it is a north south road you will have the northbound traffic as well as the southbound traffic. Now based on the number of lanes, number of vehicles or the percentage of traffic that will stress or strain a particular point in the traffic will vary.

So based on that you need not design for the 100% of the traffic on the road but you can have a certain lateral distribution factor. So we will see what is the lateral distribution factor that can be used based on the number of lanes and whether it is a divided lane or an undivided one. If you have a single lane road then in that case you have to design based on the total number of commercial vehicles in both the direction or the direction distribution factor has to be taken as 1. So let us assume that this is a single lane road. You have vehicles moving in both directions to the north as well as south direction.

Then the chances that every vehicle will load a particular point in the pavement are 100 percent. So you have to use the entire traffic for the design for consideration of the design. So that is why the direction distribution factor is taken as 1 and the traffic has to be the total traffic in both the directions. Suppose you have a slightly larger width of road say you call it as an intermediate lane road of 5.5 meter you can choose 75 percentage of the total commercial traffic on both directions since the width is slightly more.

Now if you have a two-lane two-way road, there is lane but it is not a divided one. If you have two lanes, you use 50 percentage of the total commercial vehicles in both directions. Now if it is a four-lane single carriageway so the single carriageway is not divided. You have four lanes you can go for 40% of the total commercial vehicles in both directions. Now suppose it is a dual two-lane carriageway see there is a separator or there is a median in between. Then in that case you take 75 percentage of the number of commercial vehicles in each direction. So what you have to do is you measure the traffic in both directions, you see which is the heaviest traffic and you can take 75 percentage of the commercial vehicle in that particular direction.

If it is a dual three-lane carriageway, it is separator three-lane carriageway then you can go for 60 percentage of the number of commercial vehicles in each direction. Now if it is a dual four-lane carriageway the lane distribution factor can be 45 percentage of the number of commercial vehicles with each direction. So this is how the lane distribution factor is chosen in IRC 37.

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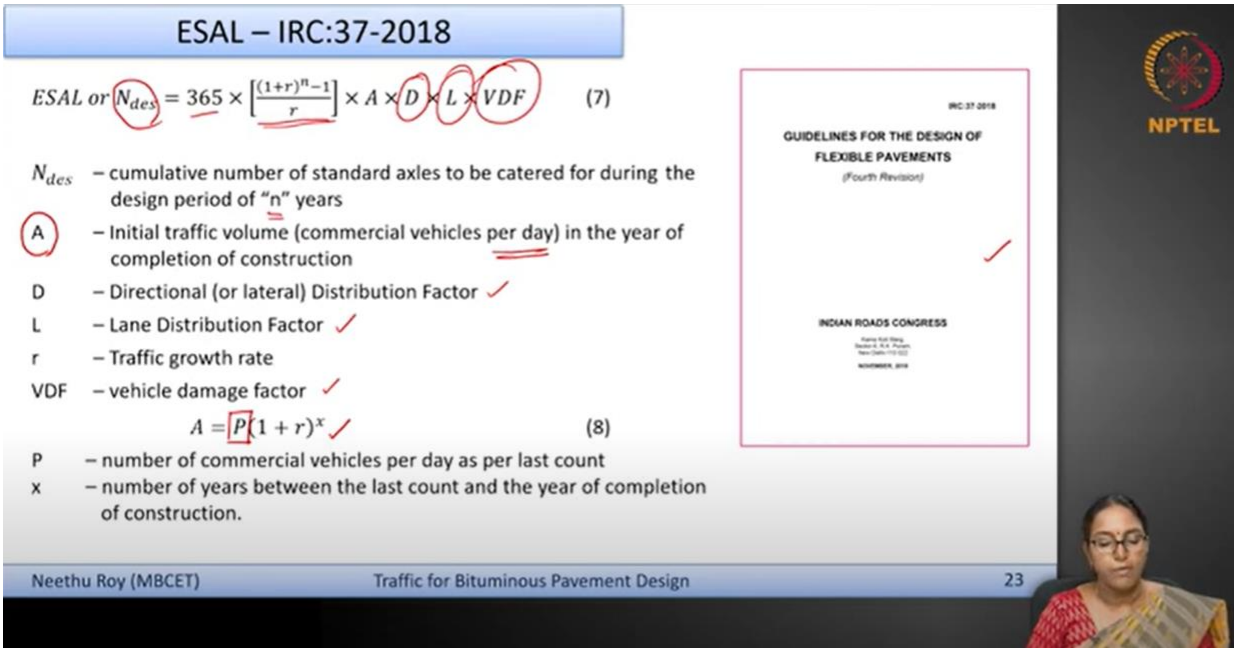

Now let us see based on using all these input parameters how the total design traffic is considered. You call it as N_{design} or the equivalent single axle loads ESALs.

$$\text{ESAL or } N_{des} = 365 \times \left[\frac{(1+r)^n - 1}{r}\right] \times A \times D \times L \times VDF$$

So this is a screenshot of the front page of IRC: 37-2018. Now what is N_{des}? So N_{design} is the cumulative number of standard axles that is to be catered during the design for a period of N years. Suppose n is the number of years for which you are going to design the pavement. Now A is the initial traffic volume or the commercial traffic volume per day in the year of completion of construction or the in the date in which you are opening the pavement for traffic.

Now suppose this data is not available, you might have taken the traffic volume count some years prior to that. Then in that case, first of all you have to find what is the initial traffic volume A before projecting it for n years. So how do you do that?

$$A = P(1+r)^x$$

Here, r is the growth rate and x is the number of years between the year this count is taken and the year of completion of the pavement construction or the year when the pavement is open to traffic. So you will get A that is the initial traffic on that new pavement and then for projecting it to a future date after N years, you get this growth factor. Now multiplying it with 365 will convert it into the yearly traffic. Now we have these three parameters D, L and VDF. So D is the directional distribution factor or the lateral distribution factor that we have already discussed and L is the lane distribution factor. Suppose we have considered the traffic in both direction whether it has to be taken as 50 or 100%. So using the VDF, you are essentially multiplying the VDF with the traffic or the initial traffic so that everything is converted into the equivalent standard axle loads and that is then projected to the future of N years. So this is how the total N_{design} or the design traffic is computed in the case of IRC:37-2018.