Analysis and Design of Bituminous Pavements

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Lecture -15

Traffic analysis - EALF

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Hello everyone, in this lecture we are going to discuss the Fixed Axle Load Approach or the Fixed Vehicle Approach for the analysis of traffic for bituminous pavement design.

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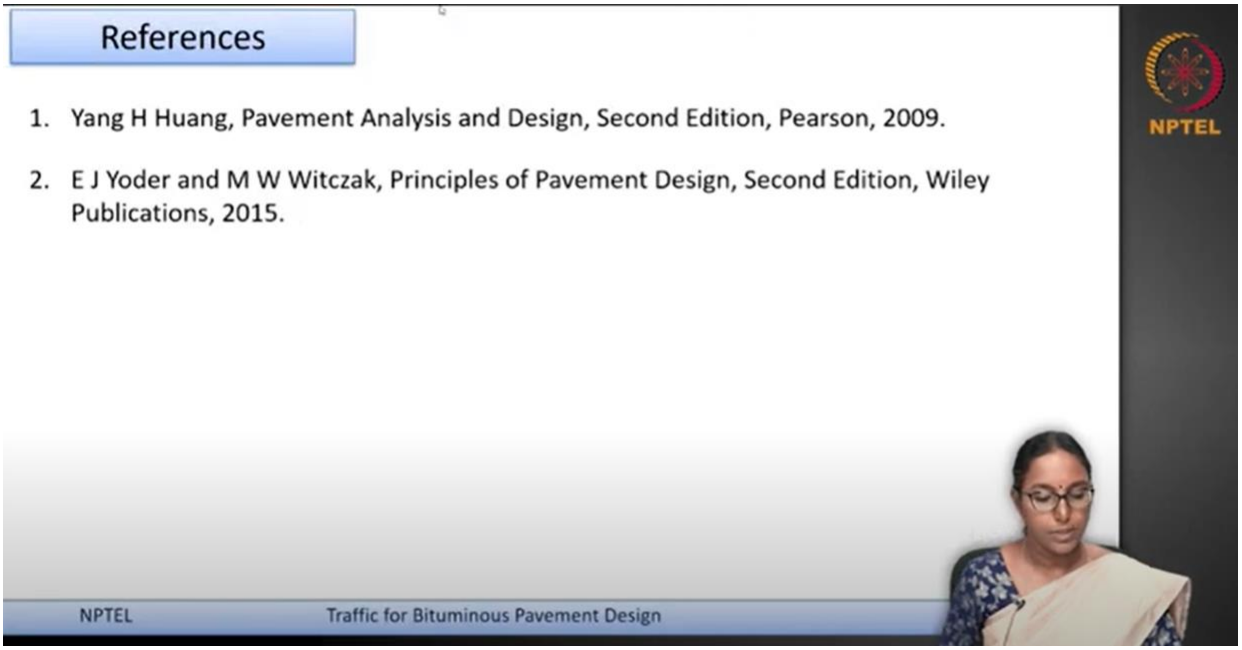

These are the references. You have the Pavement Analysis and Design by Huang and the Principles of Pavement Design by Yoder and Witczak.

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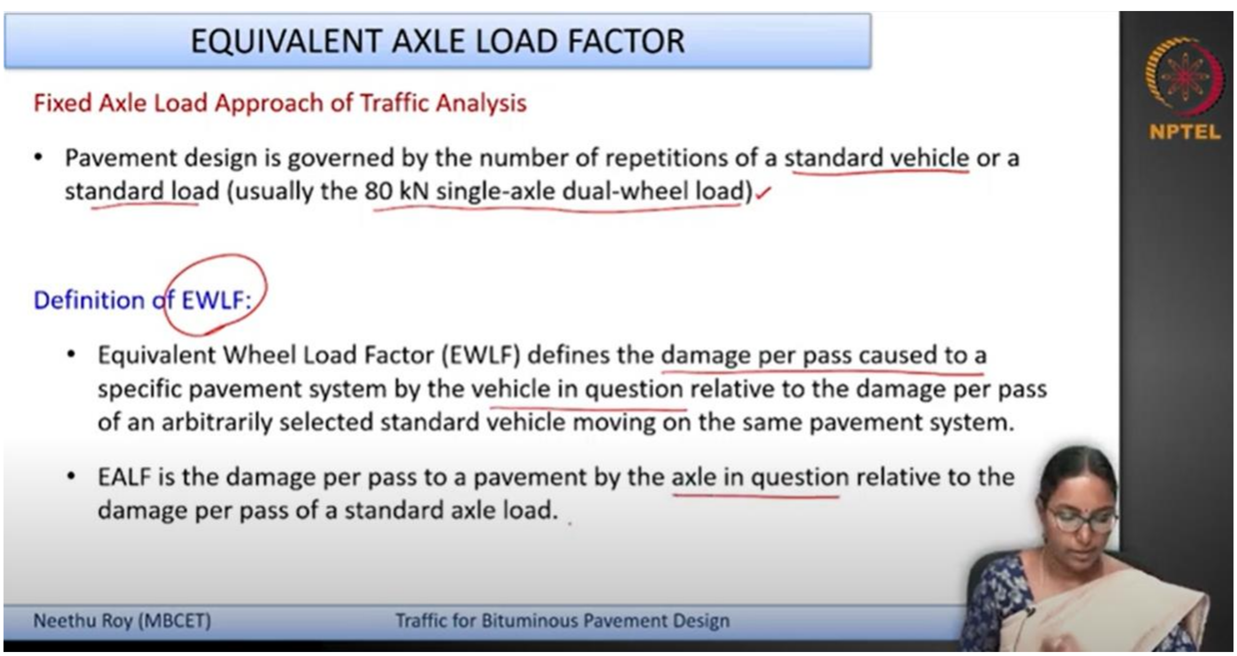

The fixed axle load approach of traffic analysis is that the pavement design will be governed by the number of repetitions of a standard vehicle or a standard load. Usually an 80 kN single axle dual wheel is considered as a standard load. So, all the different classes of axle loads and axle load configurations are converted to an 80 kN single axle dual wheel load assembly and the number of repetitions of this axle over the design period will be considered for the design of the flexible pavement. Now, in order to convert this different classes of vehicles or different classes of axle loads to a standard axle, you use something called an equivalent wheel load factor.

The definition for equivalent wheel load factor is the damage per pass which is caused to a specific pavement system by the vehicle in question relative to the damage per pass of an arbitrarily selected standard vehicle that is moving on the same pavement system. You can define it as damage per pass to a pavement by the axle in question relative to the damage per pass of the standard axle load.

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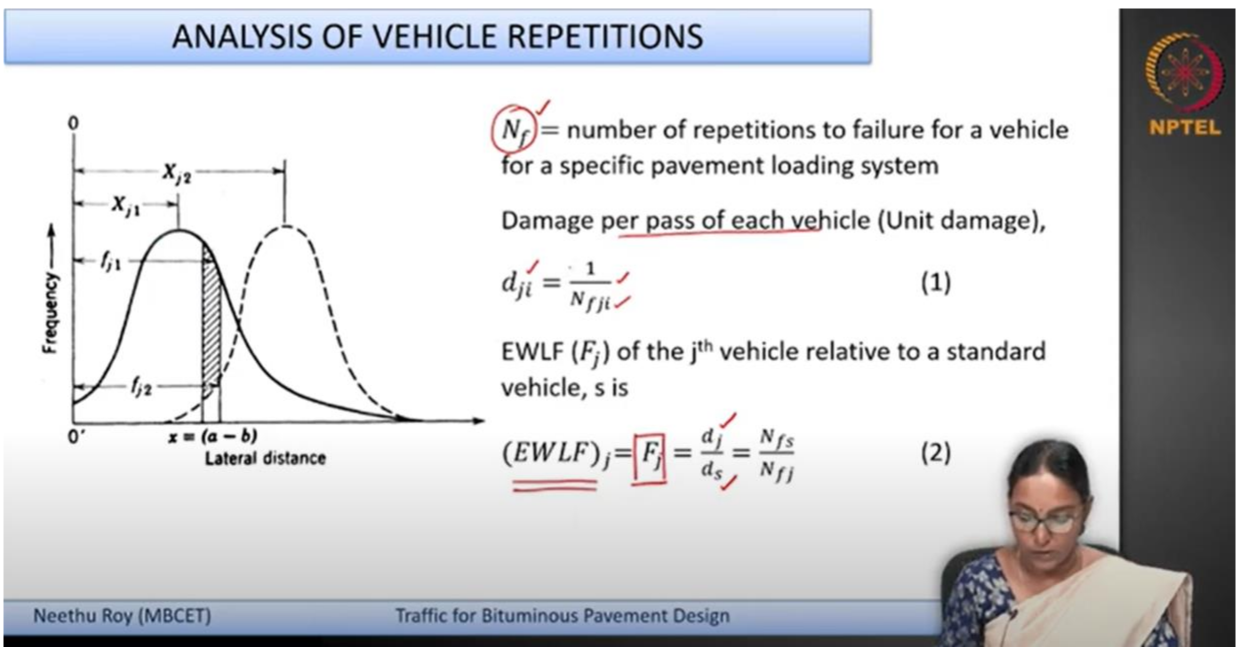

Now, let us discuss the passage of vehicles on a pavement system or how these vehicle repetitions are to be considered, or how the vehicle wander is to be considered. A plot is made here with the lateral distance of the pavement from the edge. Let us say, this is the edge of the pavement and this is the lateral distance from the edge and the frequency of load distribution of different classes of vehicles is plotted here. Say, for example, we consider two vehicles J1 and J2 which travel on this pavement. You can see that this load distribution will form a more or less normal distribution with the mean load distribution at a distance of x_{j1} from the left edge of the pavement and x_{j2} representing the mean location of the load distribution of the second class or the J2 class of vehicle. Now, each vehicle is assumed to wander laterally in the pavement system such that the stress or strain repetitions of the j^{th} vehicle along a pavement interval of a small section of x can be denoted as f_{ji} which means that I am considering, say J1 class of vehicle in a small distance of x in the pavement. Let the frequency of load stress or strain application is given by this small f letter. So, this is the distribution for the first vehicle and this is the distribution for the second vehicle here.

Now, let us assume that N_f is the number of repetitions to certain failures for a vehicle class on a specific pavement system. Let us assume that each vehicle class as N_{fj} number of repetitions or the number of repetitions to failure is noted as N_f on a particular pavement system. Now, if there are $N_{f\,ji}$ passes of a vehicle that cause damage or failure, then the damage per pass of each vehicle is denoted as unit damage (d_{ji}) where ji represent the vehicle class and N_f is the number of repetitions to failure and small d represents the damage per pass.

$$d_{ji} = \frac{1}{N_{f\,ji}}$$

Now, the equivalent wheel load factor as we defined is the damage caused by the j^{th} vehicle or the vehicle in question to that of the damage caused by a standard vehicle. So, the equivalent wheel load factor for the j^{th} vehicle F_j is given by the following equation where s indicates the standard vehicle.

$$(EWLF)_j = F_j = \frac{d_j}{d_s} = \frac{N_{fs}}{N_{fj}}$$

Since the number of repetitions to failure and the damage per pass are inversely proportional, you say that the equivalent wheel load factor is equal to the number of repetitions to failure of the standard vehicle by the number of repetitions to failure of the j^{th} vehicle.

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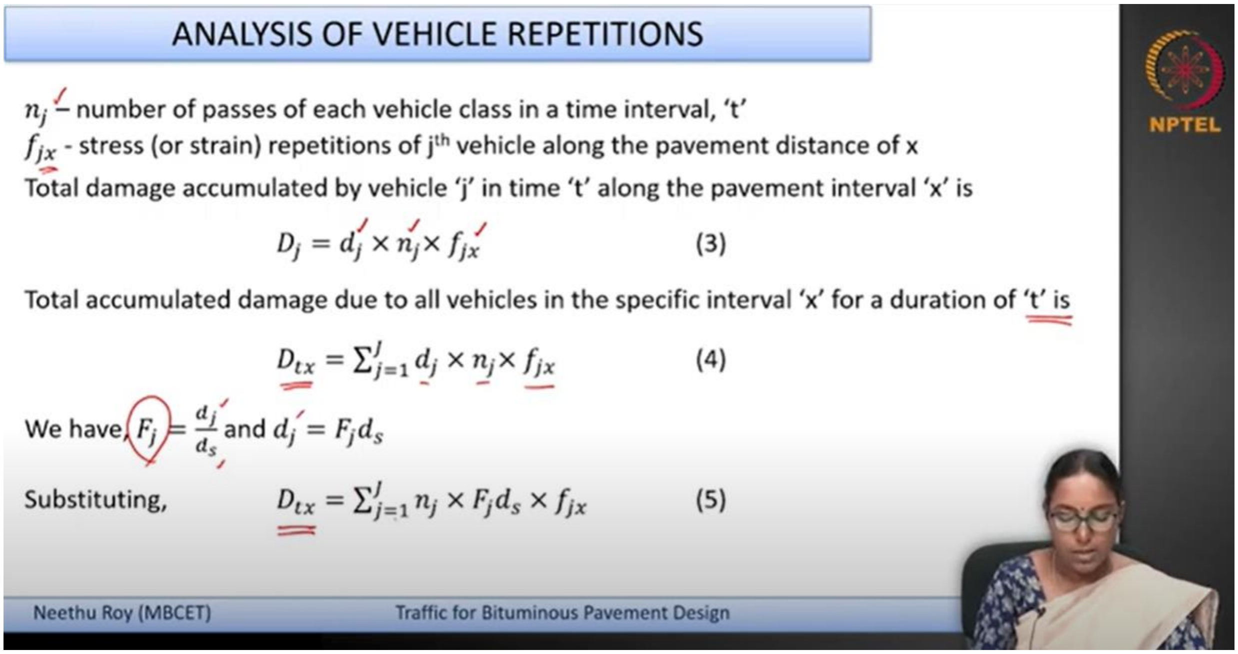

Now, let us say that n_j represents the number of passes for one vehicle class of j in a time interval of t, and f_{jx} is the stress or strain repetitions of the j^{th} class in a small distance of the pavement say x which is seen in this picture which is denoted as this a - b or the small distance of x. Then the total damage that is accumulated by this vehicle class j in a time t on the small pavement interval of x is given as follows.

$$D_j = d_j \times n_j \times f_{jx}$$

If you consider different classes of vehicles, then for a small pavement interval of x for a duration of time t the total damage that is caused is,

$$D_{tx} = \sum_{j=1}^{J} d_j \times n_j \times f_{jx}$$

The total accumulated damage from all vehicle classes for time t in a small pavement section of x distance is given by the equation below.

$$D_{tx} = \sum_{j=1}^{J} F_j d_s \times n_j \times f_{jx}$$

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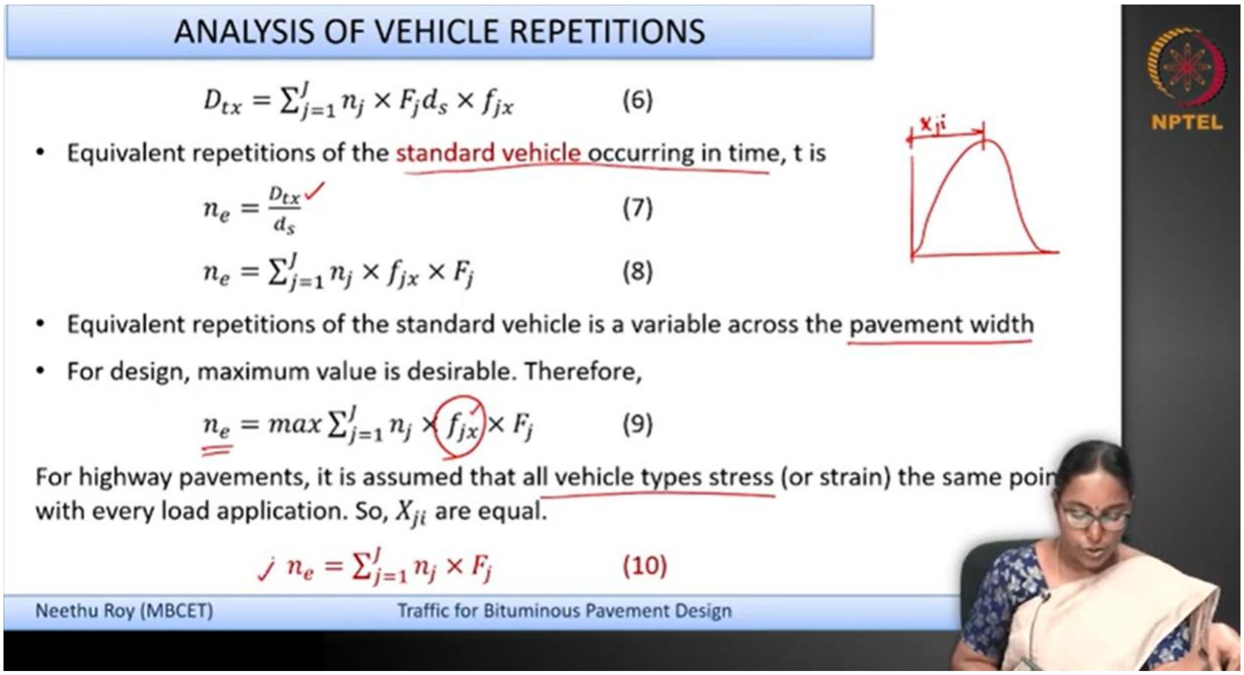

Now suppose you are considering the standard vehicle, the equivalent repetitions of the standard vehicle occurring in time t can be written as,

$$n_e = \frac{D_{tx}}{d_s}$$

As D_{tx} represents the total damage and d_s is the damage per pass of a standard vehicle, the number of repetitions of the standard vehicle for failure can be obtained like this.

$$n_e = \sum_{j=1}^{J} F_j \times n_j \times f_{jx}$$

So what you see is that this equivalent repetition of the standard vehicle is a variable across the pavement width. At various pavement widths if you consider, you will get different numbers of repetitions for failure and as far as the design is concerned we are interested in finding the maximum number of repetitions which can lead to failure. For the design, the number of repetitions is taken as the maximum of this.

$$n_e = \max \sum_{j=1}^{J} F_j \times n_j \times f_{jx}$$

Now if in the case of an airport pavement, it is very you know reasonable to consider this vehicle wandering over the pavement you know over the pavement section whereas in the case of highway pavements, it can be assumed that all these vehicle types will stress or strain the same point for during every load application. So what you can see is that in this distribution of load, this distance is constant or x_{ji} for the i^{th} vehicle is constant for all classes of the vehicle so that you can take this frequency of stresses or strain f_{jx} as unity so that the number of repetitions of the standard vehicle occurring in time t can be written as follows.

$$n_e = \sum_{j=1}^{J} F_j \times n_j$$

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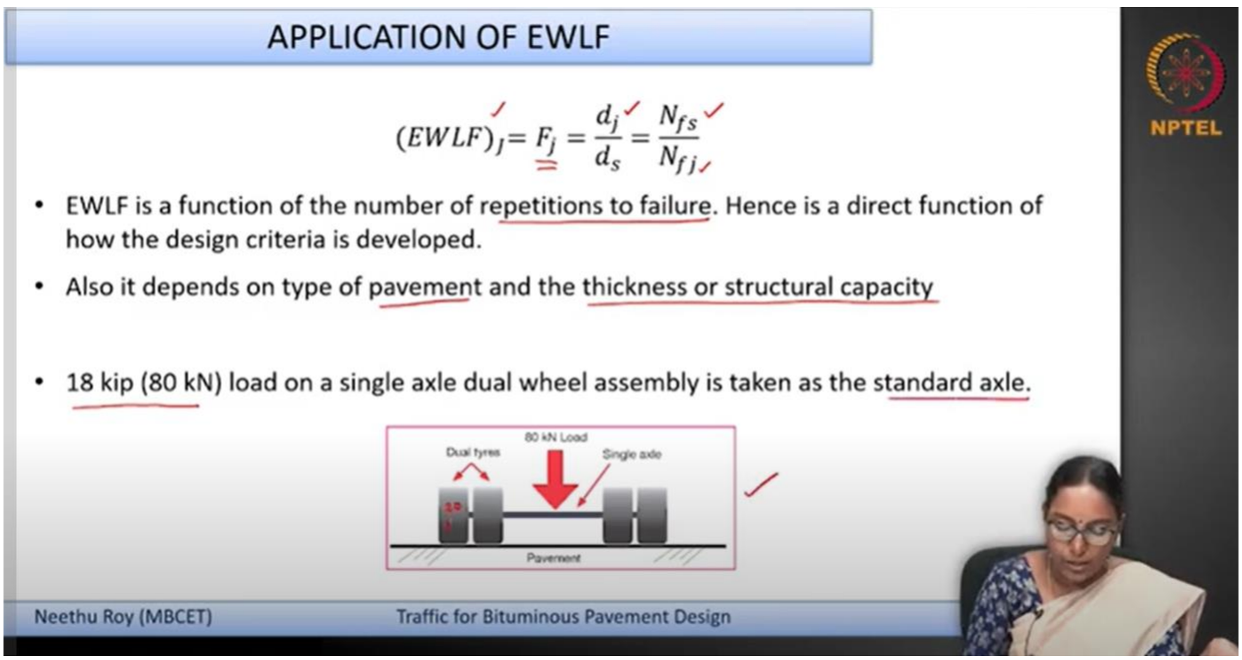

Now let us see how this equivalent wheel load factor can be used in the analysis of traffic for pavement design. As we have already discussed, the equivalent wheel load factor F_j is the damage per pass of a vehicle in question to the damage per pass of the standard vehicle. Or, it is the number of repetitions to failure due to a standard vehicle by the number of repetitions to failure due to the vehicle or this axle in question.

$$(EWLF)_j = F_j = \frac{d_j}{d_s} = \frac{N_{fs}}{N_{fj}}$$

So EWLF is a function of the number of repetitions to failure. It is a direct function of the failure criteria you are going to discuss, the type of pavement and also the thickness or the structural capacity of the pavement. Now as far as the highway pavements are considered, 18 kip or 80 kN single axle dual wheel assembly is taken as the standard axle as you can see here each wheel has a load of 20 kN. So a total of 4 wheels having a total load of 80 kN or 18 kip is considered as the standard axle.

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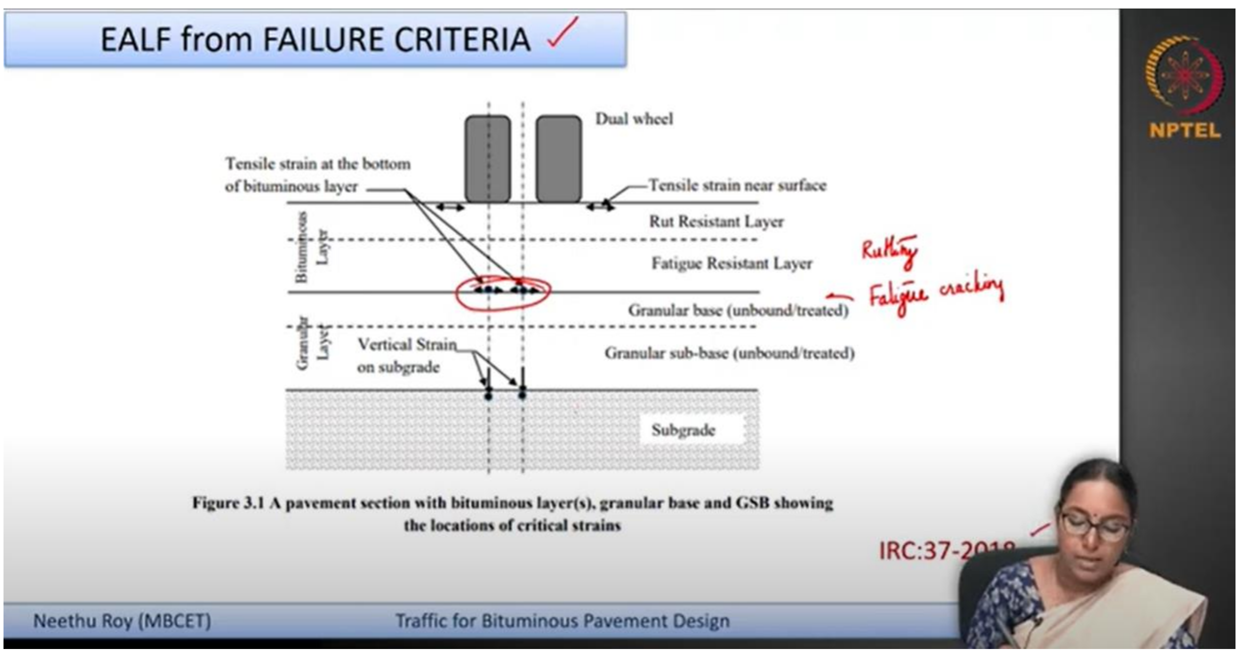

As I said, the equivalent axle load factor will depend upon the failure criteria that we use for pavement design. This is the typical pavement cross-section taken from the IRC: 37 - 2018. The two critical strains or the two critical failure mechanisms that are considered for the pavement design as per IRC 37 are the rutting in the pavement structure and the fatigue cracking. The fatigue cracking is related to the tensile strain at the bottom of the bituminous layer and the rutting of the pavement structure or the subgrade rutting is related to the vertical compressive strain on top of the subgrade.

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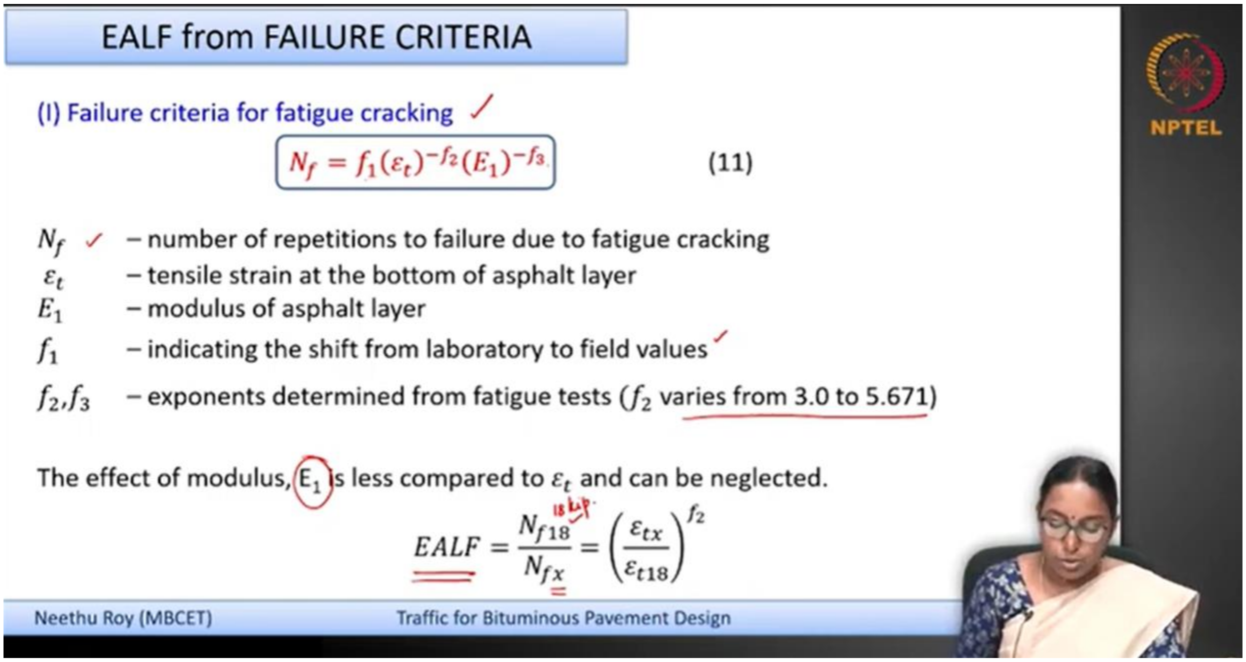

So let us see how the equivalent axle load factors are determined from the failure criteria. As I said, the two failure criteria that are normally considered are fatigue cracking and rutting. Now the distress transfer function for fatigue cracking is given by

$$N_f = f_1(\varepsilon_t)^{-f_2}(E_1)^{-f_3}$$

This is a distress transfer function for fatigue cracking where N_f represents the number of repetitions to failure due to fatigue cracking, ε_t is the tensile strain at the bottom of the asphalt layer and E_1 is the modulus of the asphalt layer.

Of the three coefficients f_1, f_2 and f_3, f_2 and f_3 are the exponents that are to be determined from the material behavior from the fatigue test and it is seen that the f_2 varies from 3 to 5.671 from various studies. f_1 is the parameter that indicates the shift of the performance of the material in the laboratory to the number of repetitions to failure as observed in the field. From this expression from studies, it is observed that the effect of the modulus E_1 is less compared to the effect of tensile strain on the number of repetitions to failure. Hence this E_1 factor can be neglected so that your number of repetitions to failure is proportional to the tensile strain at the bottom of the asphalt layer ε_t. Now EALF is defined as the number of repetitions to failure of a standard axle which is 18 kip.

$$\text{EALF} = \frac{N_{f\,18}}{N_{f\,x}} = \left(\frac{\varepsilon_{tx}}{\varepsilon_{t\,18}}\right)^{f_2}$$

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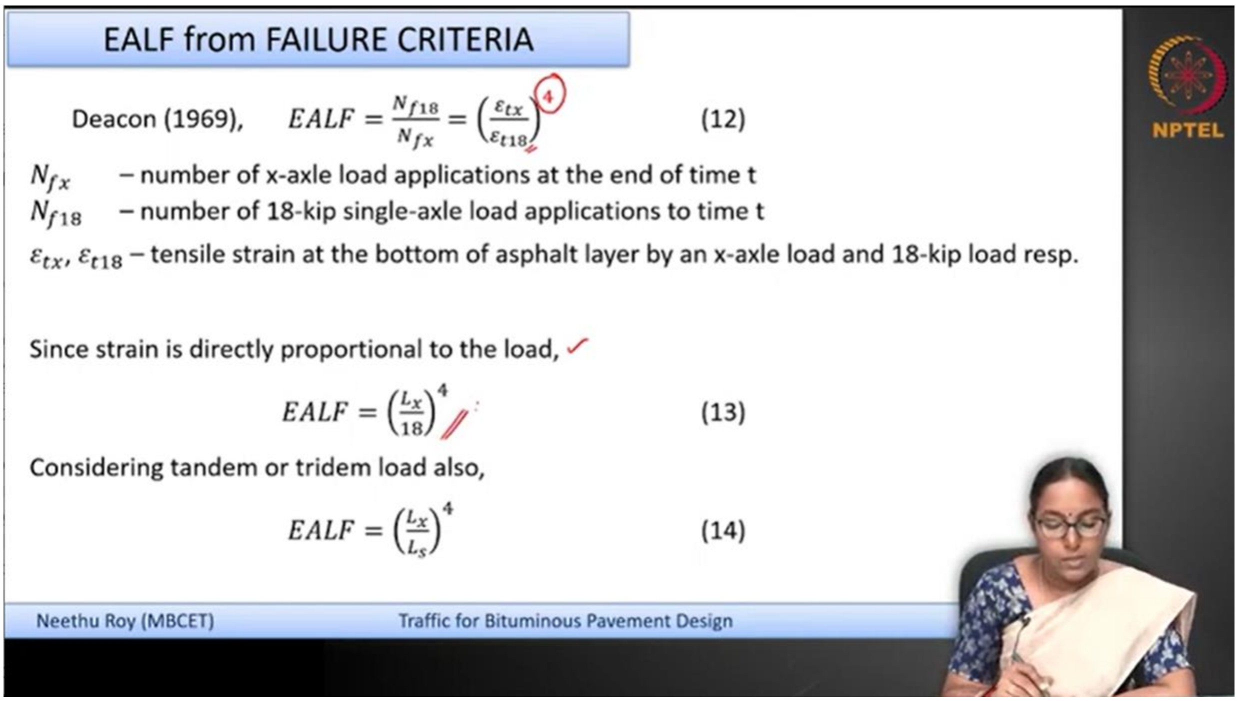

Now Deacon (1969) has given a value of f_2 = 4 so that EALF can be defined as the tensile strain of the vehicle in question or the axle in question by the tensile strain due to an 18 kip axle raise to 4.

$$\text{EALF} = \frac{N_{f\,18}}{N_{f\,x}} = \left(\frac{\varepsilon_{tx}}{\varepsilon_{t\,18}}\right)^4$$

$N_{f\,x}$ is the number of repetitions to failure due to an x axle load application and $N_{f\,18}$ is the number of repetitions to fatigue failure due to an 18 kilo pounds single axle load application during a time t. Now since the strains are directly proportional to the loads, you can write EALF as also equal to the load of the x axle divided by load of the 18 kip axle which is 18 kilo pounds raise to 4. This is for a single axle dual wheel. Suppose, you have to consider the tandem or the tridem axles as well, you can just write it as L_s which is load due to the standard axle.

$$\text{EALF} = \left(\frac{L_x}{18}\right)^4$$

$$\text{EALF} = \left(\frac{L_x}{L_s}\right)^4$$

This factor can be used to convert different axle loads to a standard axle load.

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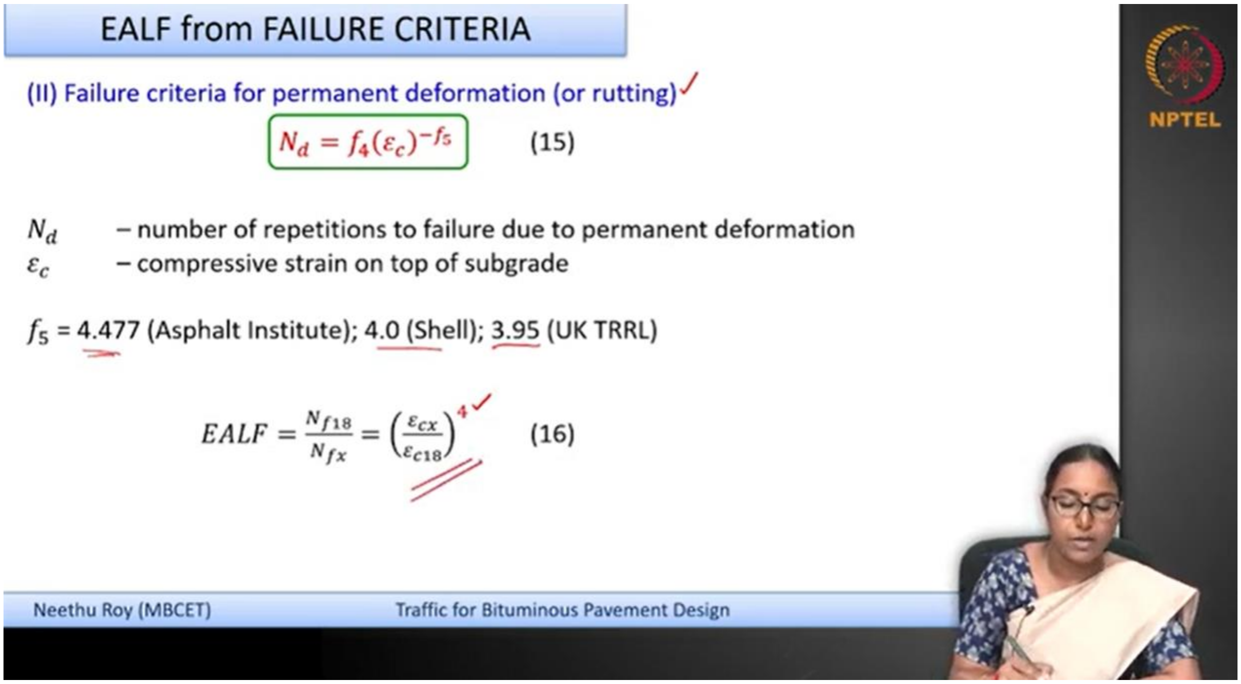

Let us see the failure criteria due to the permanent deformation or rutting. The distress transfer function is given as follows.

$$N_d = f_4(\varepsilon_c)^{-f_5}$$

N_d is the number of repetitions to failure due to permanent deformation and ε_c is the compressive strain on top of the subgrade as we have seen from that figure. Now different studies have found different values for these f_4 and f_5 parameters and Asphalt Institute has given a value of f_5 as 4.477, Shell has given a value of 4 and UK Transport Road and Research Laboratory has given a value of 3.95. So on an average, you can take a value of 4 so that the equivalent axle load factor again becomes the number of repetitions to failure due to the 18 kip axle by the number of repetitions to failure.

$$\text{EALF} = \frac{N_{f\,18}}{N_{f\,x}} = \left(\frac{\varepsilon_{cx}}{\varepsilon_{c\,18}}\right)^4$$

This is the EALF if you are considering the permanent deformation or rutting as a failure criterion.

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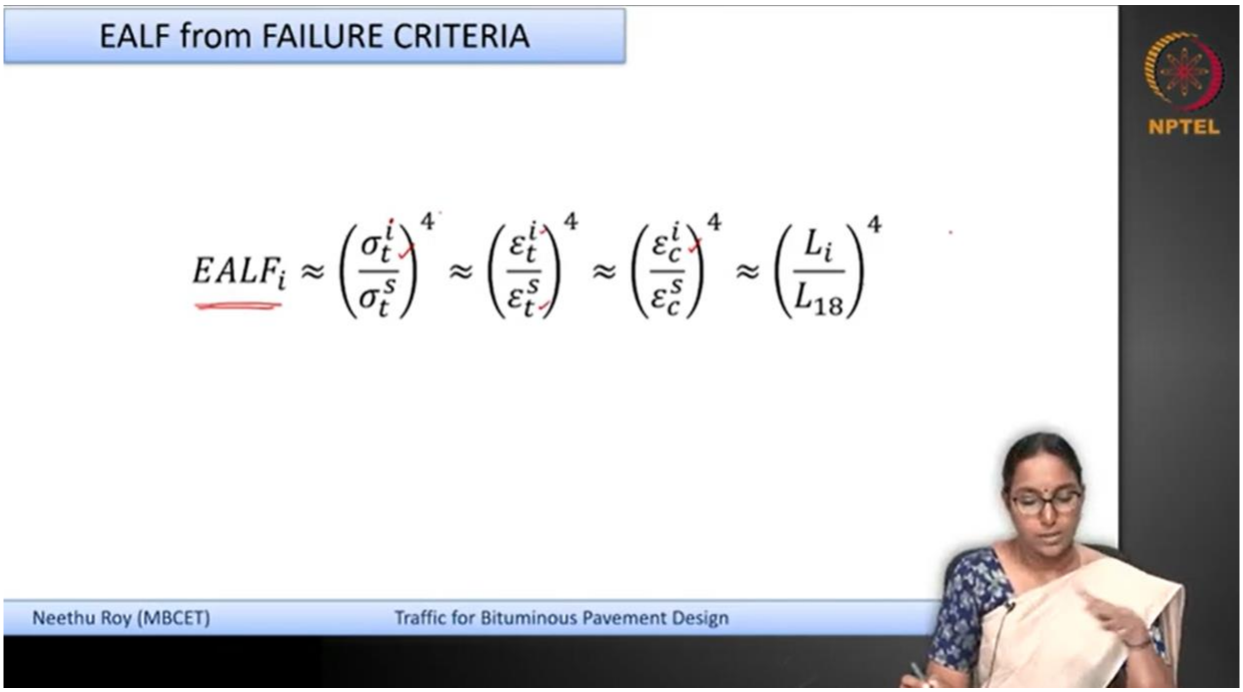

So from this EALF analysis using the failure criteria, the fourth power relation is used to convert the axle load in question to a standard axle of 18 kip or 80 kN.

$$\text{EALF}_i \approx \left(\frac{\sigma_t^i}{\sigma_t^s}\right)^4 \approx \left(\frac{\varepsilon_t^i}{\varepsilon_t^s}\right)^4 \approx \left(\frac{\varepsilon_c^i}{\varepsilon_c^s}\right)^4 \approx \left(\frac{L_i}{L_{18}}\right)^4$$

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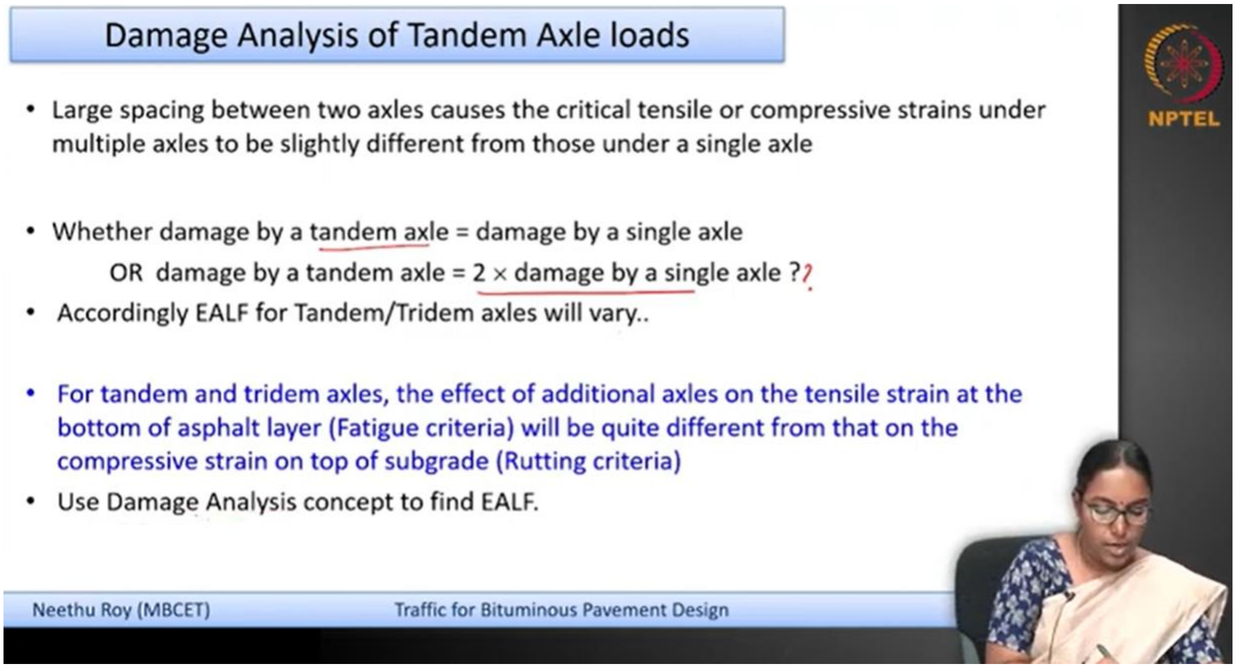

We will now discuss about the analysis of the tandem axle loads or a tridem axle load. We have large spacing between the two axles of a tandem axle. So the critical tensile or the compressive strains under the multiple axles will be different from that of a single axle. In order to find the EALF, you need to see whether the damage caused by a tandem axle is same as that of a damage caused by a single axle or the two axles of a tandem axle is twice the damage caused by a single axle. Accordingly EALF factors of tandem axle or a tridem axle will vary. Now for tandem axle and tridem axle, the effect of these additional axles on the tensile strain at the bottom of the asphalt layer will be quite different from the compressive strain at the top of the subgrade.

This means that if you are considering a tandem or tridem axle, the effect due to fatigue cracking criteria and subgrade rutting criteria may not give you the identical results as you have discussed here. Here in the case of a single axle dual wheel, we have seen that the fatigue cracking criteria based on the tensile strain or the rutting criteria is more or less the same but it may not be same in the case of a tandem or a tridem axle. In such case, we can find out whether in order to get the EALF, you can use a damage analysis concept.

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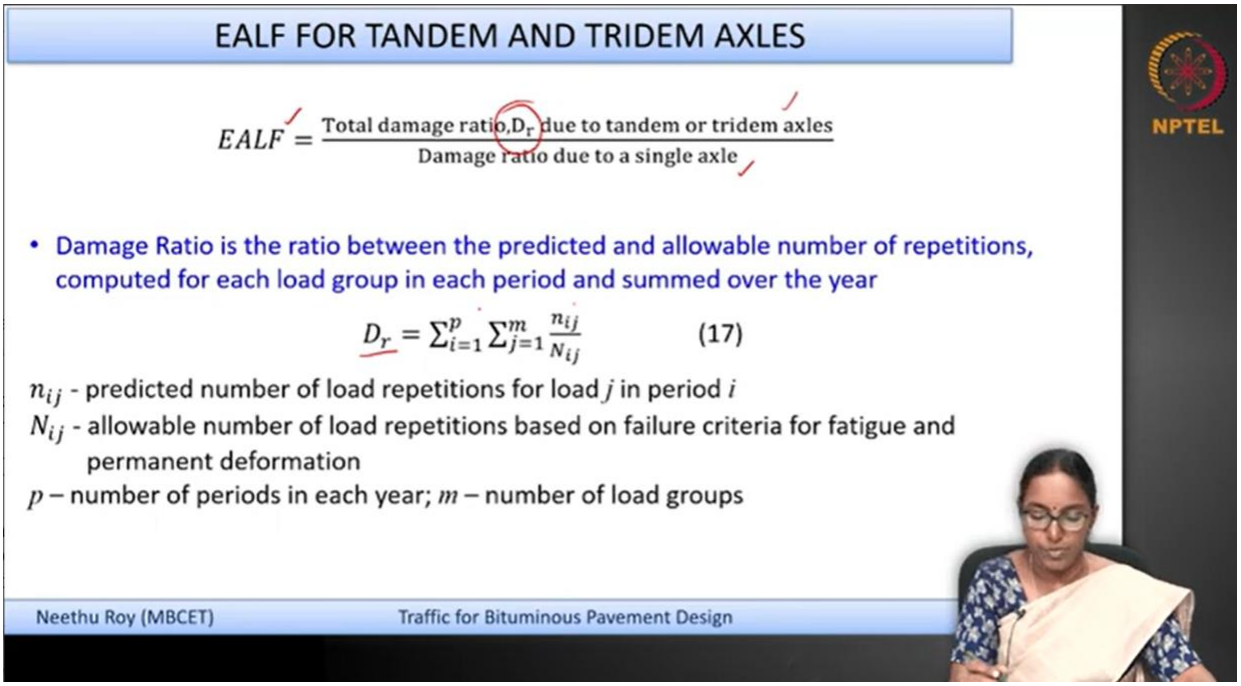

In order to find the EALF based on the damage analysis, you can see that EALF is the ratio of the damage ratio due to a tandem or a tridem axle to the damage ratio due to a single axle. So this ratio can give you the EALF corresponding to the tandem axle or a tridem axle with respect to a single axle. Now how to get this damage ratio? The damage ratio is essentially the ratio between the predicted and the allowable number of load repetitions computed for each load group in each period and summed over a year.

$$D_r = \sum_{i=1}^{p} \sum_{j=1}^{m} \frac{n_{ij}}{N_{ij}}$$

n_{ij} is the load that is predicted in the actual scenario, N_{ij} is the number of load repetitions that are permitted or allowable based on the failure criteria. So you have two criteria, one is the fatigue cracking criteria and the rutting criteria. You can sum up the ratio for all classes of the vehicle and for the different periods. For different periods, you can have different criteria for different number of repetitions to failure. So sum it up for different periods, you get the damage ratio. So from this damage ratio, if you find it for the tandem or tridem and divide it by single axle, you can find the equivalent axle load factor.

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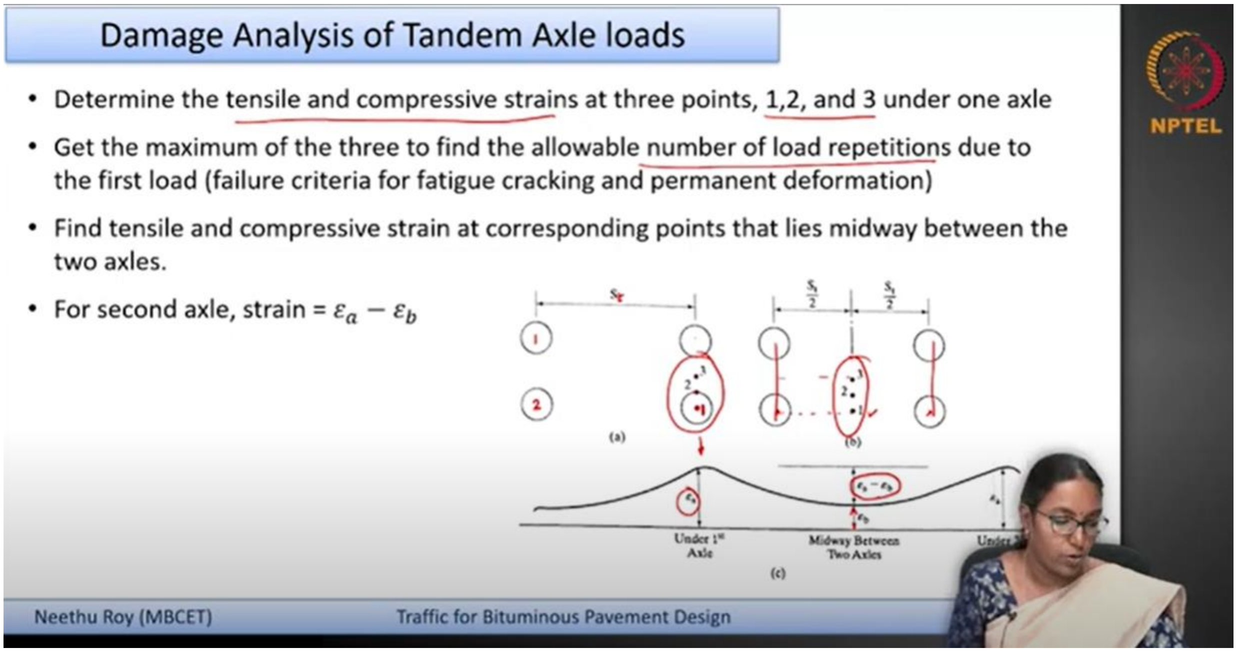

How to do this damage analysis for tandem axle? You have to find out the number of repetitions to know the allowable number of repetitions. In order to get the allowable number of repetitions due to the two criteria you need ε_t and ε_c values. But you have tandem axle with dual wheels. Here, we have a tandem axle with 1 and 2 are the wheels on one side of a tandem axle and 3 and 4 are the other wheels with the tandem spacing of S_t. Now you have to get the number of repetitions to failure using the two failure criteria. You have to determine the tensile and the compressive strains.

First, we will consider points 1, 2 and 3 under the first axle. The point number 1 is at the center of the first load and point number 2 is edge of the first load and point number 3 is midway between the two wheel loads. So you will find the tensile strain and the compressive strain at three locations. And you can find the maximum of the three so that you will get ε_a. So under the first axle you can find the maximum of these three strain values and that can be used to find the allowable number of load repetitions due to the first load. Next, you have to consider midway between the two axles. This is axle number 1 and this is axle number 2 and S_t is the spacing between the two axles. So midway between them, you have to find out strains at three points.

The strain at midway between the two axles is ε_b. and you have an effect of the other two wheels as well. So what you have to do is that the axial strain that has to be considered for the computation of the allowable number of load repetitions is $\varepsilon_a - \varepsilon_b$. So essentially you are finding two sets of number of repetitions for failure. One is at any one point in this 1, 2, 3 location under the axle and the second one is at any one point in these 1, 2, 3 locations at midway or whichever point is the highest value. So for the first location the value that you have to consider is maximum of the strain at points 1, 2 or 3 and in the case of the second location you have to take $\varepsilon_a - \varepsilon_b$ where ε_a is the load under the first load and ε_b is the load that comes at the midway.

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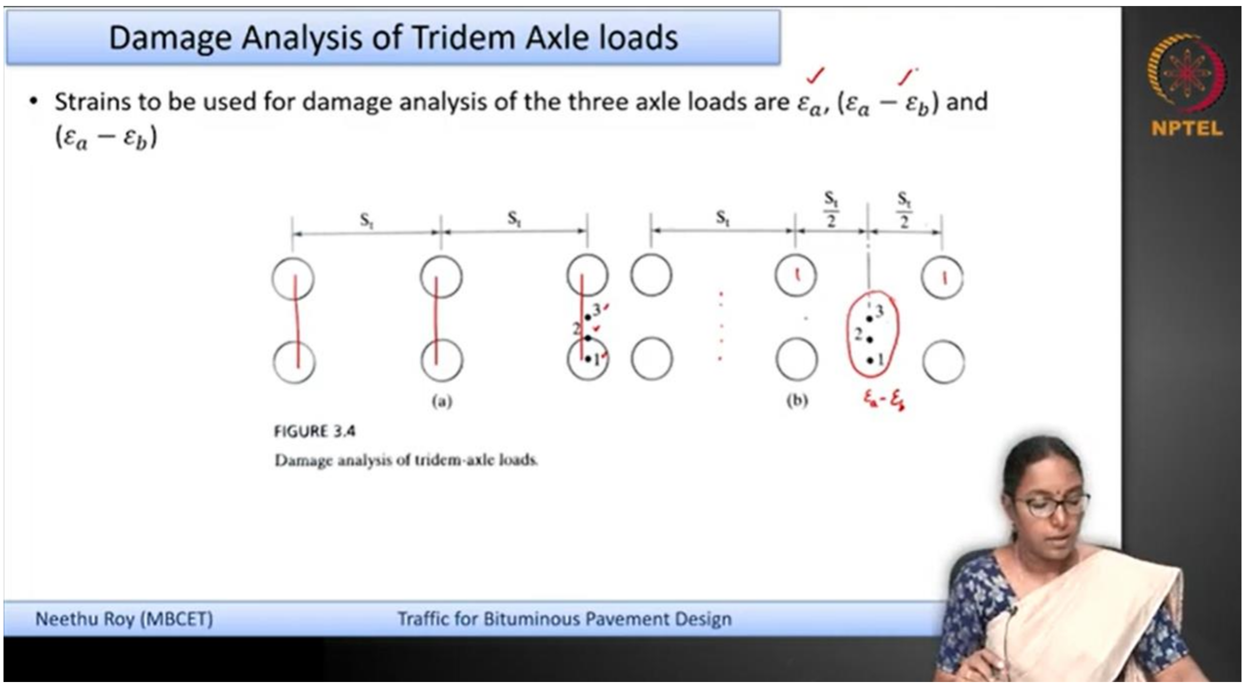

That is how you will take the strains for using in the fatigue and the rutting equations to find the number of repetitions to failure in the case of a tandem load. Now in the case of a tridem axle load, you have three axles. A similar approach has to be done for the damage analysis. First of all under 1 wheel you have to see the 3 points and you have to get the maximum strains under this and for the second case you have to take midway between two axles and for these points, you have to find $\varepsilon_a - \varepsilon_b$. So these 3 values ε_a and essentially $\varepsilon_a - \varepsilon_b$ are to be used in the distress transfer functions for the fatigue as well as for permanent deformation and then find the number of repetitions to failure. So this is how the damage analysis is done for a tandem axle and for a tridem axle.

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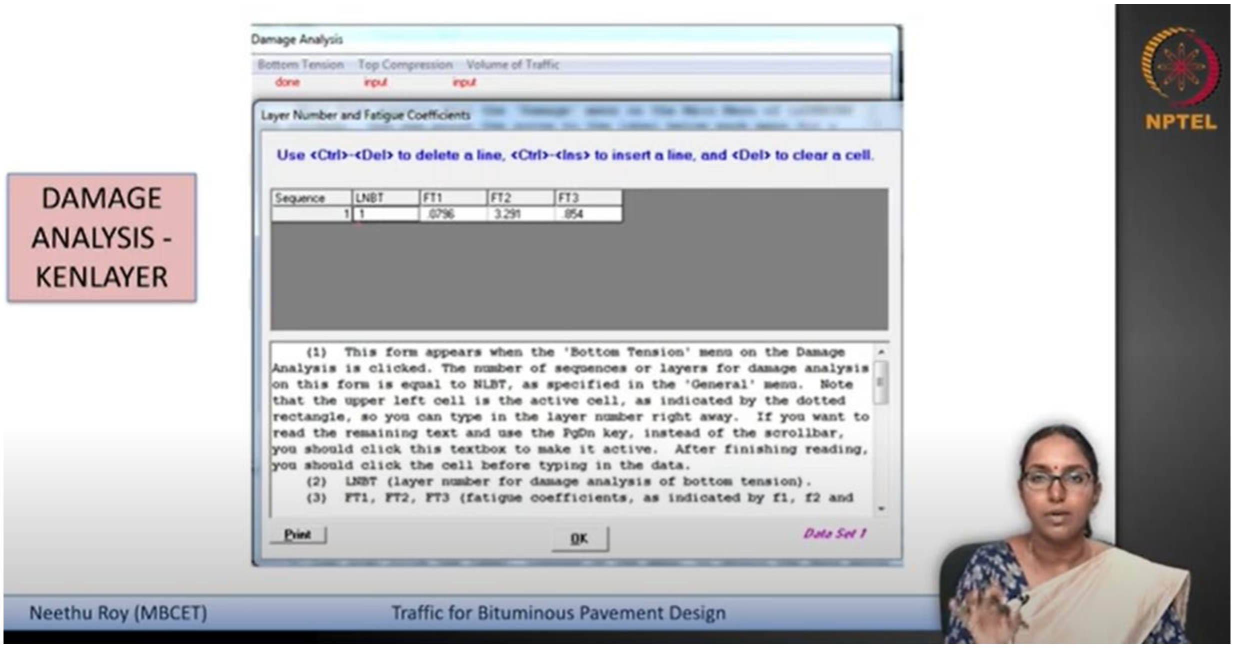

You can use Kenlayer software which is already discussed in this course to do this damage analysis. I have just shown some screenshots of using Kenlayer. So you can see that there is a damage analysis tab is there wherein you can give the FT1, FT2, FT3 are the fatigue coefficients and LNBT is the layer number for which the bottom tension is considered for the fatigue analysis. So for in this analysis, the Asphalt Institute coefficients are used for FT1, FT2, FT3 essentially indicate f_1, f_2, f_3 in our fatigue equation

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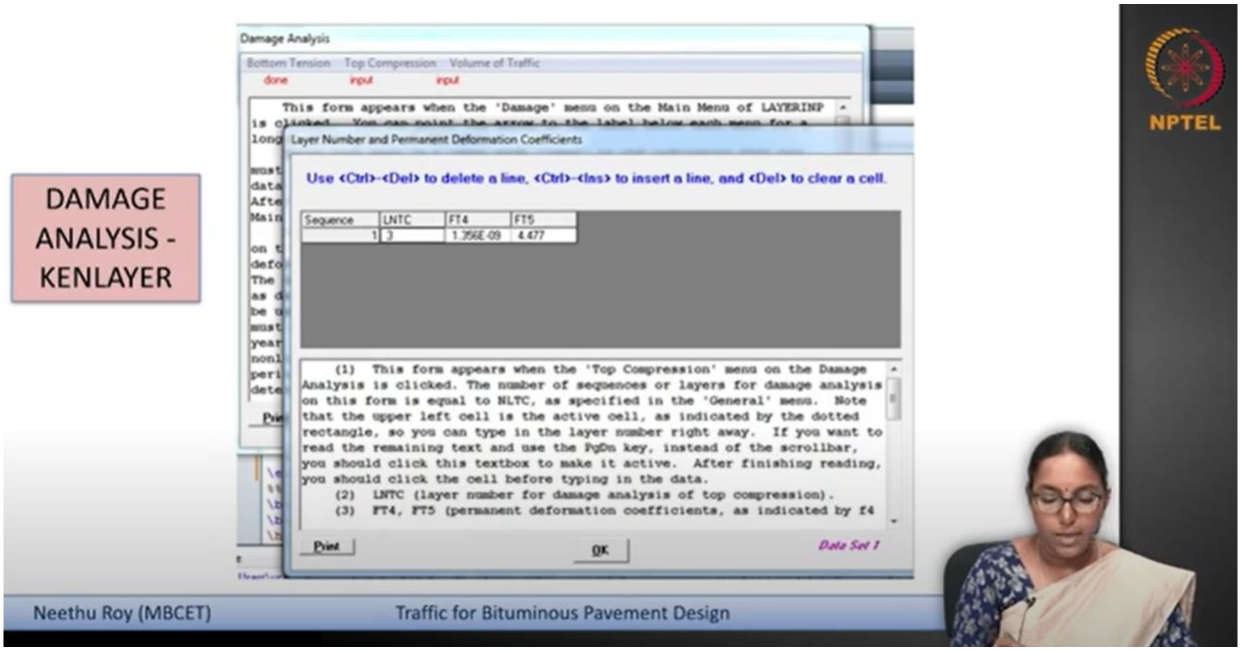

Then you can use the rutting equation where the f_4 and f_5 are given.

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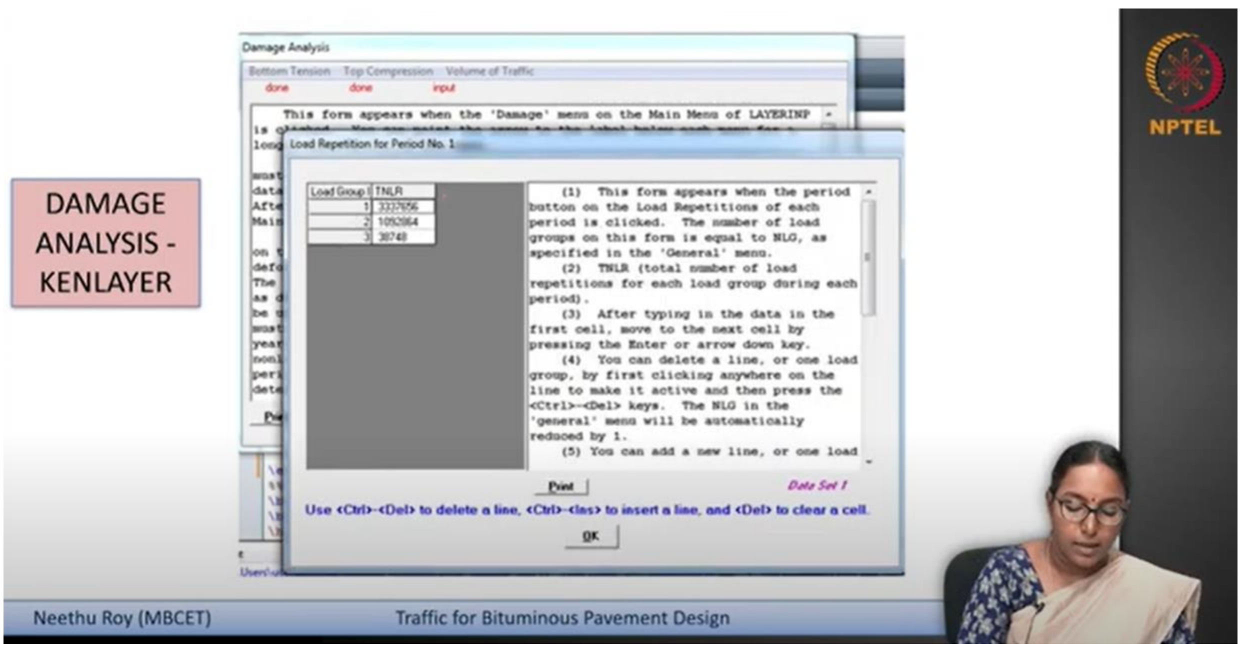

You have 3 different load groups. The total number of load repetitions for each load group during the design period is given. So this is from the traffic survey that you have arrived at this number and that number is the predicted number for the n number of design years.

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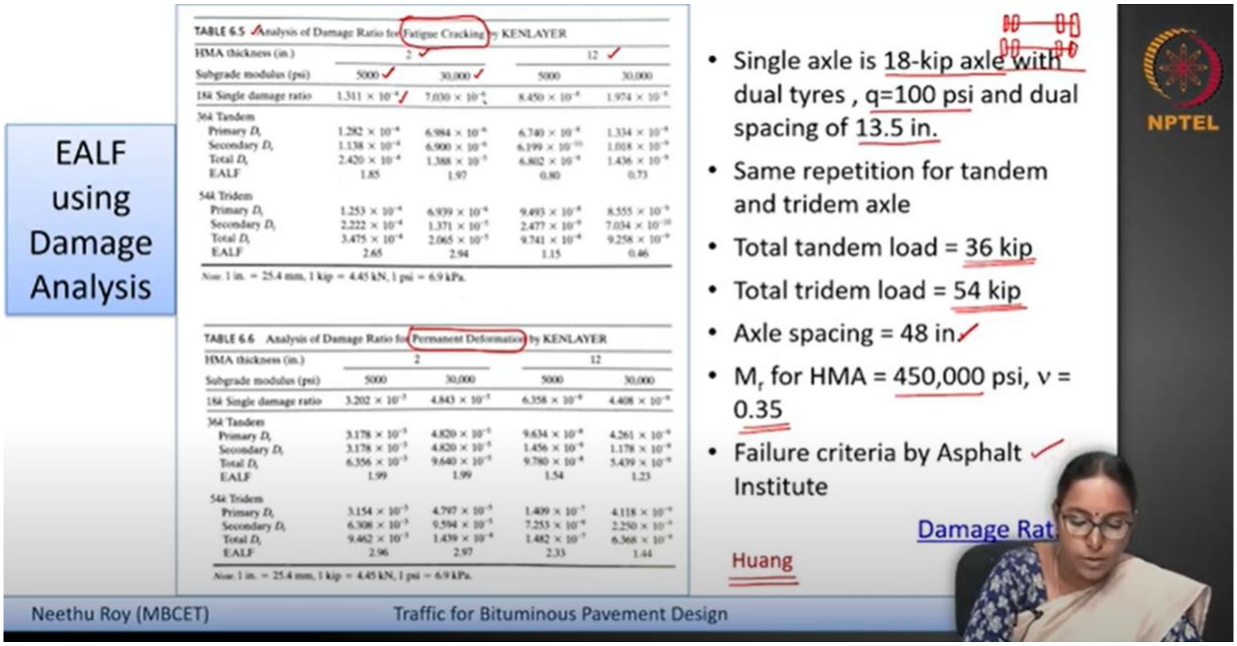

This is one example of the damage analysis that is done. This is taken from the Huang textbook. So this is essentially to make a comparison of how this equivalent wheel load factors will differ for a tridem axle and a tandem axle is what we want to see from this analysis. As you can see here, 2 pavement thicknesses are considered in this study. One is a 2 inch thick pavement and the other is a thicker one which is a 12 inch pavement. And the single axle that is considered in this study is having a 18 kip axle load with dual tires and with the contact pressure of 100 psi and a dual wheel spacing of 13.5 inch. This is the single axle dual wheel that is considered in this study and for the tandem, the same thing is repeated.

So the same load is repeated to get a tandem once and once again it is repeated to get the tridem. The total load in a tandem comes to 36 kip and the tridem load is 54 kip. And in the case of tandem and tridem, the axle spacing is given as 48 inch. And this is a 2 layer system, the pavement layer is considered to have a modulus value of 450,000 psi and a Poisson's ratio of 0.35. Now 2 structures are considered. One is a weak subgrade or a weak foundation having a subgrade modulus of 5000 psi and the second one is strong subgrade having a subgrade modulus of 30,000 psi. Essentially you are considering 2 pavement systems with 2 inch and a 12 inch on a weak subgrade and on a strong subgrade. The failure criterion is selected, the distress function of Asphalt Institute is used and a damage analysis is done and the damage ratios are computed.

For a single axle, you can see from Table 6.5 that the damage analysis is done for the fatigue cracking criteria and the Table 6.6 indicates the permanent deformation criteria. So these are the 2 failure criteria for which the damage analysis is done. The damage ratio for 18 kip single axle is given as 1.311×10^{-4} on a 2 inch pavement with a 5000 psi subgrade modulus. In the case of 30,000 psi subgrade modulus, damage ratio is 7.03×10^{-6}. As we have already mentioned I will just quickly show you what the damage ratio is. Damage ratio is the number of predicted number of load repetition divided by the allowable number of load repetition for the failure criteria that you have considered for its fatigue or permanent deformation.

N_{ij} is what you get from the distress transfer function by capturing the strains at the critical locations. So for a 36 kip standard axle, we see that there is a primary damage ratio and a secondary damage ratio and a total damage ratio as we have already discussed we have to consider 2 locations and get the damage ratios and find the total. So this is the total damage ratio if you are considering a 36 kip tandem axle and a 54 kip tridem axle. The equivalent axle load factor can be obtained as the total damage ratio of the tandem to the total damage ratio of the single axle. This is essentially 2.42×10^{-4} divided by 1.311×10^{-4}, which will give you 1.85 as equivalent axle load factor of the tandem axle. Likewise this tridem axle has an equivalent axle load factor of 2.65 which again is obtained from the ratio of the damage ratio of the tridem to the damage ratio of the single axle.

Now for each of this pavement structures that we have considered you can see that these are the equivalent axle load factor for the tandem and for the tridem based on this damage ratio computation and this is using fatigue cracking as the criteria. So using that value, the damage ratios are computed and from the damage ratios, you can get the damage ratio for the single axle then the damage ratio for the tandem axle and the ratio of that will essentially give you the equivalent axle load factor for the tandem axle. And also you can see that this is the equivalent axle load factor for the tridem axle for the first pavement structure. And the second is a 2 inch pavement on a 30000 subgrade modulus subgrade. So you see these are the equivalent axle load factors.

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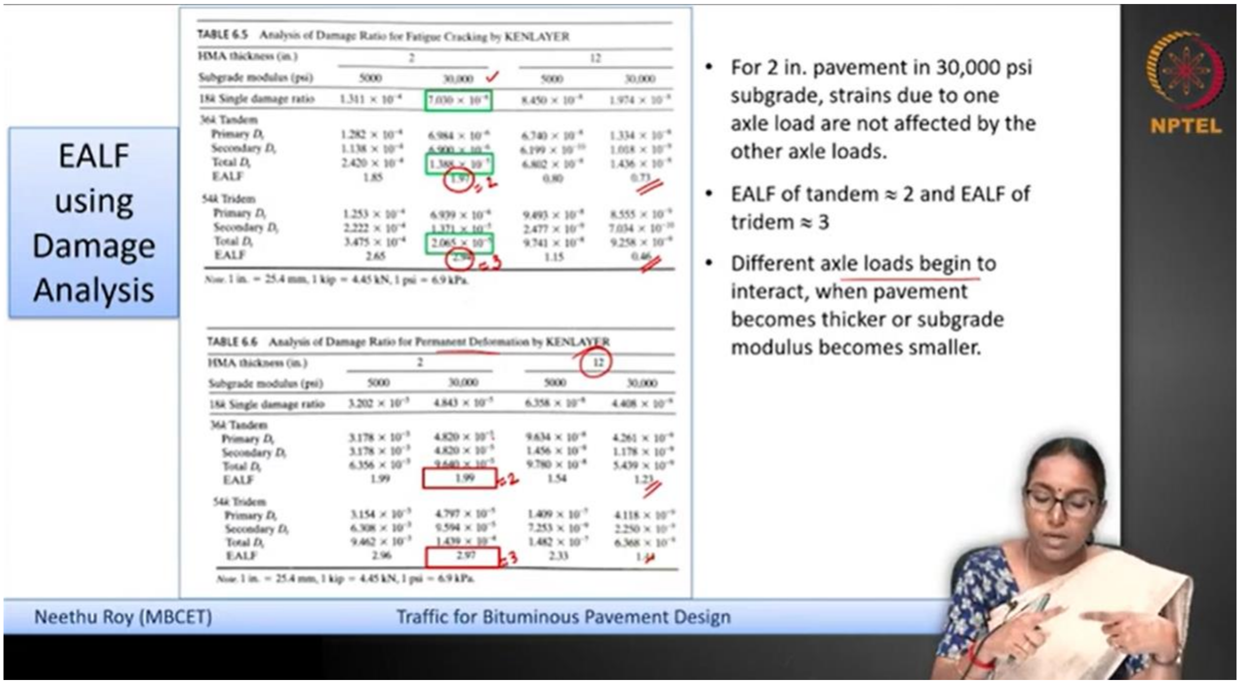

We will note some of the observations from this analysis. See the first one is so in this study there is a thin pavement and a thick pavement. So the thin pavement is a 2 inch pavement and the thick pavement is a 12 inch pavement. So what is observed is that for the thin pavement in a weak subgrade. So the weak subgrade is the one with 5000 psi and the strong subgrade is the one with the 30000 psi. So for the thin pavement on the weak subgrade, we see that the damage ratio due to the permanent deformation is greater than the damage due to fatigue cracking. As you can see here whether it is for a single axle or for a tandem or a tridem axle we see damage due to fatigue criteria (green boxes) is lower than that in the case of permanent deformation criteria. Whereas in the case of a thick pavement on a good subgrade, we can see that the damage ratios due to fatigue cracking is greater than that due to the permanent deformation.

You can notice that the design has to be controlled by the fatigue cracking criteria if it is a stronger pavement, whereas if it is thin pavement or weaker pavements, the design has to be controlled by the permanent deformation. And further you can see that in a 2 inch pavement with

30,000 psi subgrade, the strains due to one axle load are not affected by the other axle load. This means that if I consider a tandem axle load, you can consider it as close to two single axles. And if you are considering a tridem axle, you can consider it as three single axles which means that the strains that are caused by one axle is not affected by the strains caused due to the other axle loads. So see you see here that the EALF factor is 1.97 which is close to 2 and EALF factor for the tridem is 2.94 which is close to 3. So this is approximately 2 and this is approximately 3 when you are using a fatigue cracking criteria. And also when you are using the permanent deformation criteria, you see that the EALF of a tandem axle is close to 2 and the EALF of a tridem axle is close to 3. So what we observe is that each of these axles is actually acting differently. There is not much of an overlap between the strains from the axles. The different axle loads begin to interact when the pavement becomes thicker.

As you see here, the equivalent axle load factor has changed when you are considering a 12 inch pavement. So what is highlighted from this analysis is that the equivalent axle load factor that we use to convert a tandem axle or a tridem axle to an equivalent single axle load will depend upon the pavement structure, the thickness of the pavement layers and the criteria that you are using for finding the EALF whether it is a rutting criterion or the fatigue cracking criteria.

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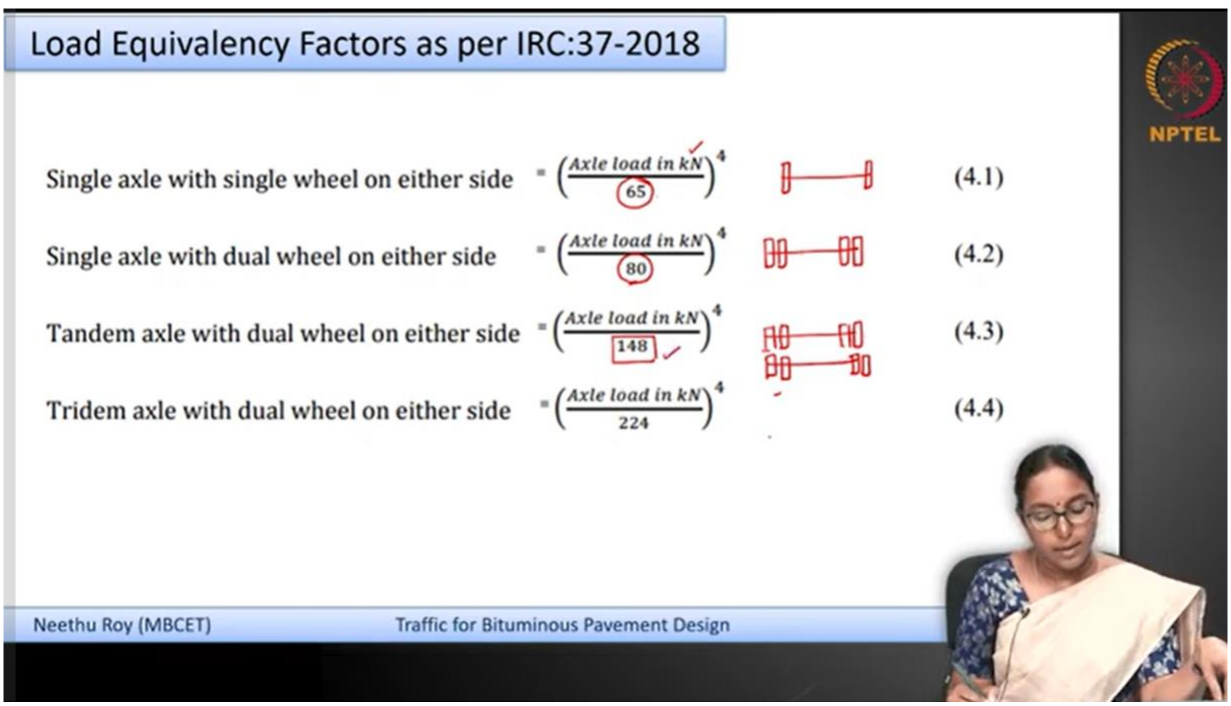

Now as far as the design as per IRC 37 is concerned these load equivalency factors are given by certain standard values like this which is no midway between your two single axles or a single axle load. The equivalent axle load factor can be determined as the axle load of the load in question divided by 65 raised to 4. So this will give you the equivalency factor whereas if you have a single axle with a dual wheel on either side, the standard load is taken as 80 kN.

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

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

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

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

So you can use these expressions and the fourth power law to find the equivalency factors as per the IRC 37 this is discussed in detail when the design using IRC 37 is discussed in this course.

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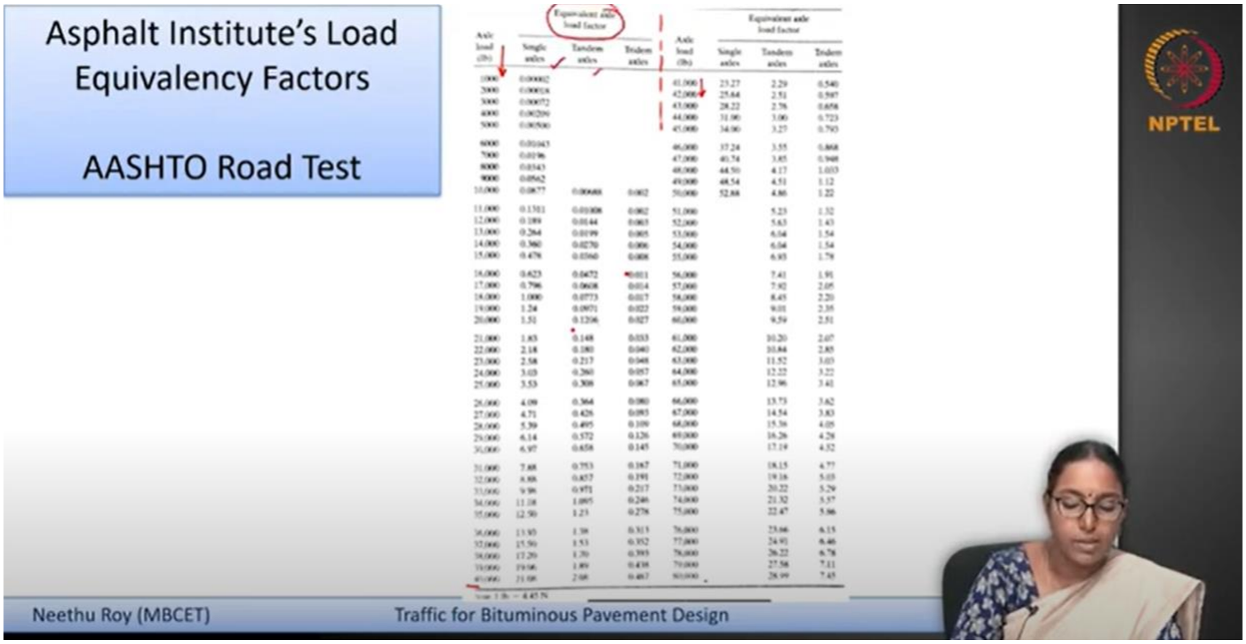

These parameters f_1, f_2, f_3, f_4 and f_5 are determined based on the road test as well as the field test as well as the laboratory investigations. Now from the AASHTO road test, the Asphalt Institute load equivalency factors are given again. This is based on that fourth power expressions for different axle loads from 1000 to this is the table so this table continues so this is still 4, 40,000 and this continues from 41,000 to 80,000. We have the equivalent axle load factors or the EALF factors for single axle, tandem axles and tridem axles are given in the AASHTO road. So this again will be discussed when we discuss the design of the payment based on this approach. What we have discussed is how a single axle load can be converted to a standard axle, how a tandem axle or a tridem axle can be converted to its equivalent standard axles in the fixed axle load approach.