Analysis and Design of Bituminous Pavements

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Lecture - 34

Reliability in pavement design – Part 04

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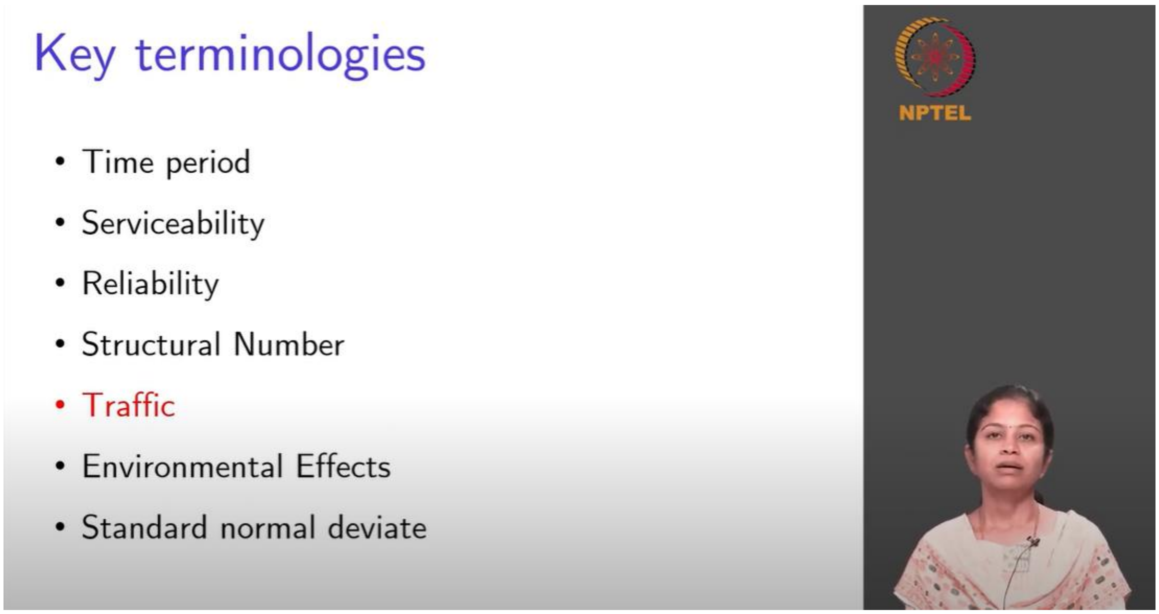

So, next we will look into the traffic aspects. I am sure most of the aspects related to traffic should have been discussed in an earlier lecture wherein the traffic parameters such as ESAL, EALF and then the conversion from vehicle to axles in terms of VDF or truck factor should have been discussed. However, for the sake of completeness, I am just going to discuss some specific aspects related to traffic. So, the standard axle again you know what a standard axle is. The standard axle which is going to be considered for design is 80 kN single axle load. So, this is the standard axle which is specified in AASHTO. The equation given here is used to convert an axle of any load to an equivalent standard axle load or it is used to arrive at the EALF factor. Now it has number of parameters W_{tx}, W_{t18}, L_x, L_2, G_t and β_x. So, G_t is defined as in here, it depends upon the initial serviceability level 4.2, terminal serviceability level and then constants, another constant and β_x depends upon, I will define what L_x is and L_2 is, it depends on the axle type and then the structural number. So, these are the parameters, let us see what they are.

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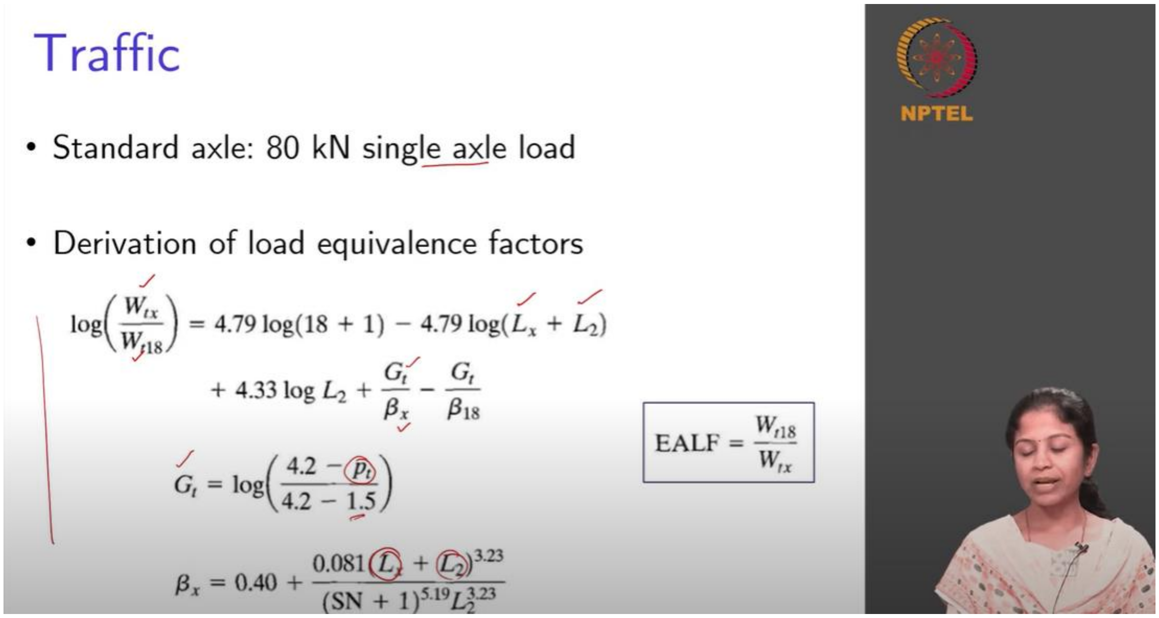

So, W_{tx} is the number of x axle load applications, so this is like any given axle load at the end of time t. So, if I observe for my design period, how many axle load repetitions I have for a given axle load and W_{t18} is the number of 18 kip or 80 kN single axle load applications in the given time t. This is nothing but standard axle load repetitions. So, we have defined these two parameters in this equation W_{tx} and W_{t18}. Next is L_x and L_2, L_x is the load in kPa on one single axle, one set of tandem axle or one set of tridem axle. Again, I am sure you know what single tandem and tridem axles are. So, this is the load on one set of single axle or if I take one set of tandem which is two single axles closer to each other, on the whole set of tandem axle what is the load is L_x and L_2 is the axle code, you use one for single axle, two for tandem axle and three for tridem axle. Depending upon the axle under consideration, I might use 1, 2 or 3 for these axles. So, these are the terminologies that we are using here.

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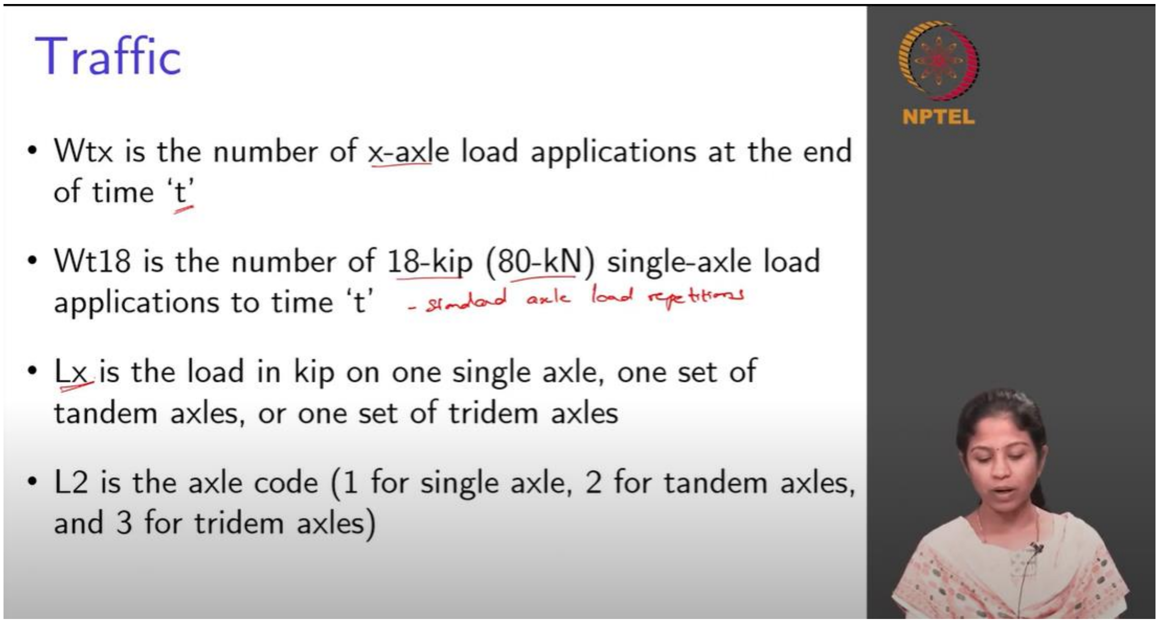

The next is structural number as defined earlier, it is a function of thickness and the modulus of each layer and we all know that it also depends upon the drainage conditions. Then P_t is the terminal serviceability level which indicates like you know the pavement conditions which can be considered as failure. So, we have already defined what P_t is and G_t is a function of the terminal serviceability index and β_{18} is the value of β_x when L_x is equal to 18. So, when you substitute the load to be 18 and when you take L_2 which is nothing but the axle group type to be equal to 1, that is β_{18} . So, you can compute it for any x value, it is for 18 kip standard axle load we use as 18. So, for any other load we can compute this value.

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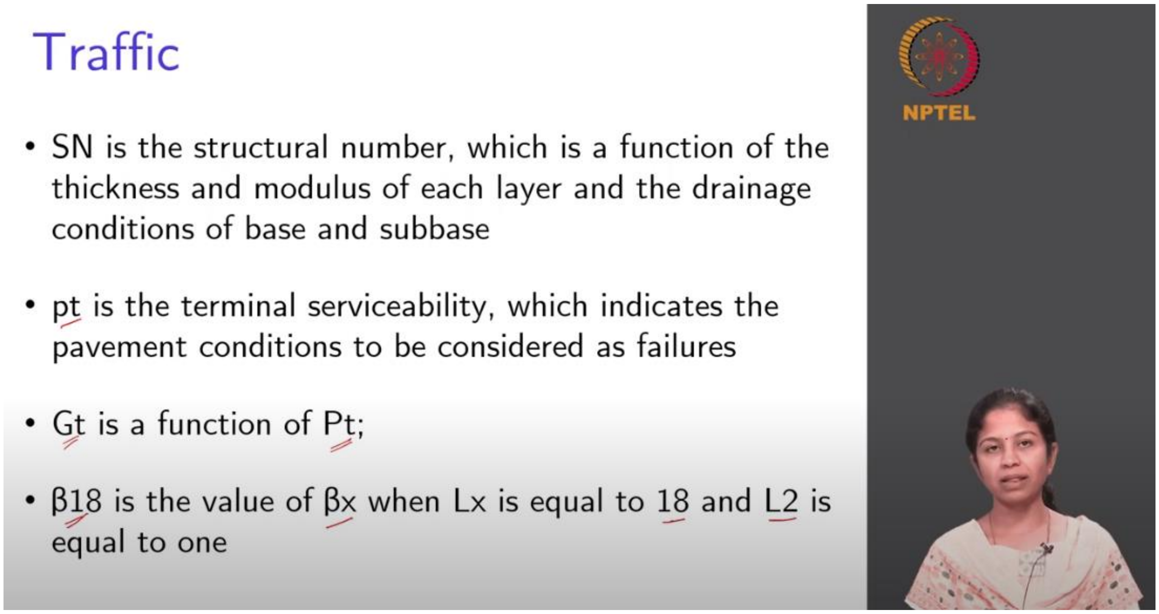

So, after computing all these things, then we get log of W_{tx} by W_{t18}. So, EALF is defined as W_{t18} by W_{tx} which is the weight carried by a standard 18 kip load to the weight carried by any other load for different type of axles. So, that is computed here.

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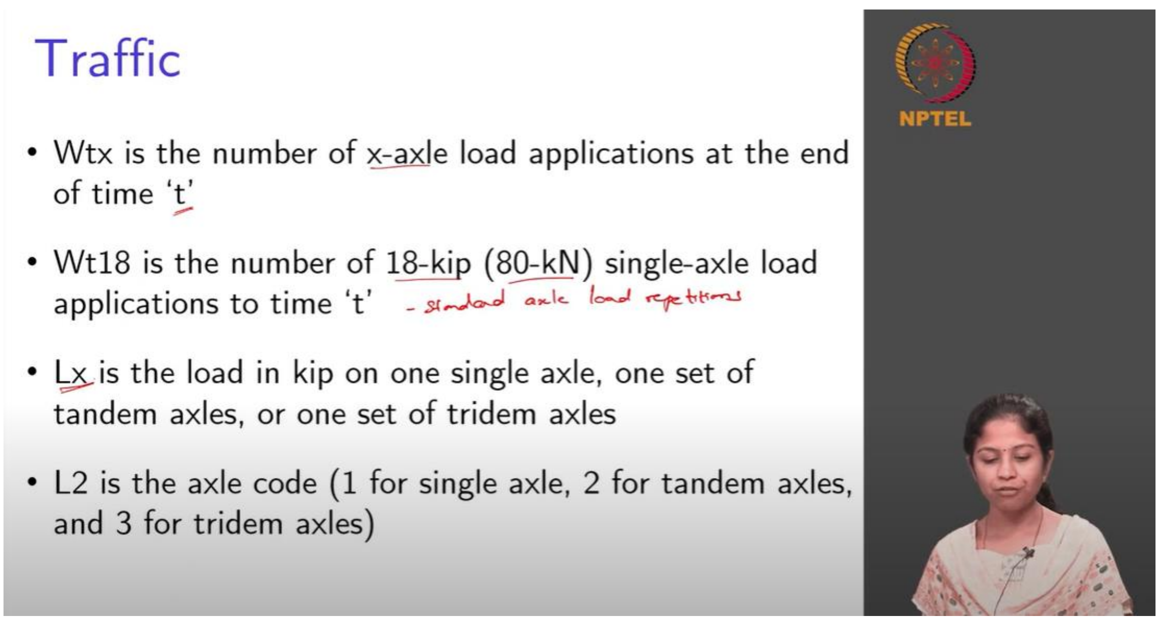

We will now see how to calculate EALF for a specific example. So, let us consider a case wherein the P_t value is 2.5, the structural number value is 5. So, we have to determine the EALF value for 32 kPa. So, in the equation which is given there, the unit is kPa. So, P_t is 2.5, SN is 5 and it is the load, 32 kPa. So, when we substitute all these things, we will be able to get G_t from this equation where I will substitute 2.5 for P_t and I will also be able to substitute the values in this equation. So, we have L_x 32, we have L_2. It is a tandem axle. So, we have to substitute L_2 as 2 in this equation. We have SN as 5. So, once we substitute all these values, we will be able to get β_x and then we can compute the same β_x. Instead of this, you just substitute for a β_{18}, L_x is 18 and L_2 is 1. So, in this equation, you substitute this, we will be able to get β_{18}. Substitute in this equation. So, you can do it on your own and check whether you are getting these values, L_x is 32, L_2 is 2. So, G_t will be this value, β_x is this, β_{18} is this and this is the EALF value. So, you can check whether you are getting this. This is how EALF is computed. So, now what we have done is we have computed any given axle load to a standard 80 kN or 18 kip axle load repetitions.

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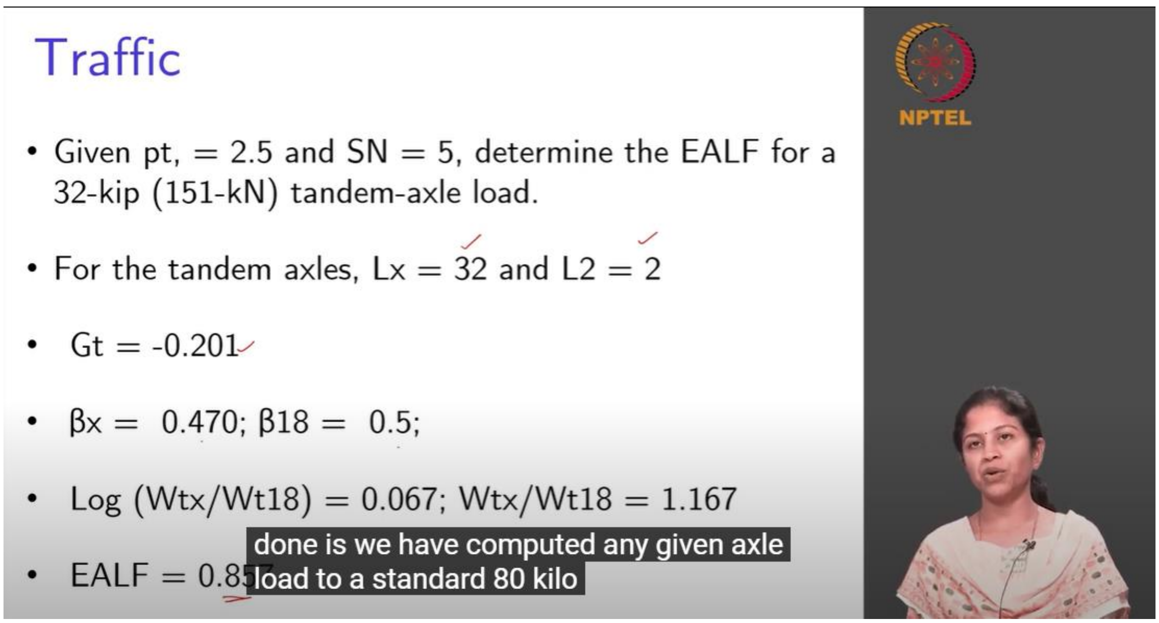

The next is to account for mixed traffic. Usually, we will do a traffic volume survey wherein we will be counting the number of vehicles and not the number of axles. So, usually in a traffic volume survey from AADT, we will only be getting a vehicle count. Now how to compute this, convert this vehicle count into axles or axles to vehicle. So, that is done using the parameter called truck factor. So, this ESAL which is equivalent standard axle load repetition is a function of AADT, many other parameters which you have seen here. So, we are interested in this parameter which is called as the truck factor. Again in the previous lecture on traffic, you would have been introduced to this equation to compute the ESAL. So, I am just skipping that and just going through the truck factor equation alone. And this is also something which you should have learnt earlier, but I will just briefly walk through this. So, this truck factor is a sum of p_i which is percentage of repetitions for i^{th} load group and F_i is equivalent axle load factor which we have completed earlier. So, this is what is the percentage of axles in a given load into the equivalent axle load factor for that. So, we are converting all axle load groups into standard axle load groups. Now it is all in terms of standard axle load repetition. How to convert that into number of vehicles? We use a parameter called A which is nothing but the average number of axles per truck. So, this truck factor is kind of identical to the VDF. Again, you should have been introduced to the differences between VDF and truck factor.

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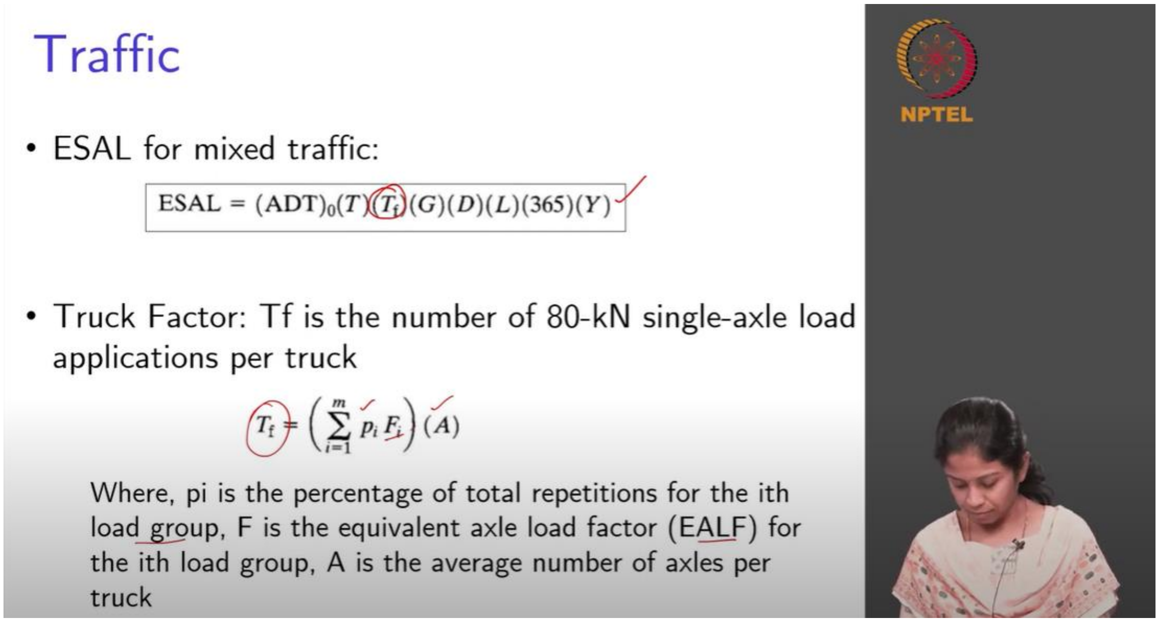

So, how to compute this truck factor? A small illustration. We have axle load under from different axle load groups. For each axle load group, we can define an EALF value and we also count the number of axles in each of these axle load groups. We multiply the number of axles into EALF to get ESAL. So, we sum that up for all the axle load groups divided by the number of trucks weighed. So, this is going to give me the truck factor or which is nothing but the multiplicative factor to convert the number of vehicles. It is number of vehicles because we are dividing it by the number of trucks weighed. So, we are using this parameter to convert the number of vehicles into equivalent number of 80 kN standard axle load repetitions. So, we are using a truck factor for that. This is with respect to traffic and we have the environmental effects next.

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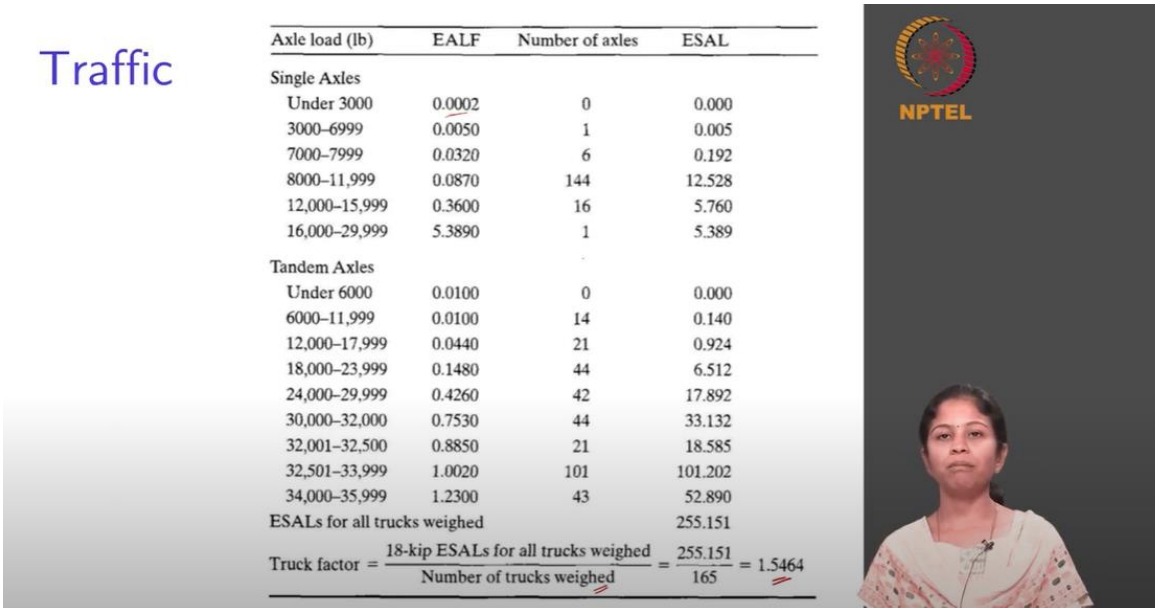

Axle load (lb)	EALF	Number of axles	ESAL
Single Axles			
Under 3000	0.0002	0	0.000
3000–6999	0.0050	1	0.005
7000–7999	0.0320	6	0.192
8000–11,999	0.0870	144	12.528
12,000–15,999	0.3600	16	5.760
16,000–29,999	5.3890	1	5.389
Tandem Axles			
Under 6000	0.0100	0	0.000
6000–11,999	0.0100	14	0.140
12,000–17,999	0.0440	21	0.924
18,000–23,999	0.1480	44	6.512
24,000–29,999	0.4260	42	17.892
30,000–32,000	0.7530	44	33.132
32,001–32,500	0.8850	21	18.585
32,501–33,999	1.0020	101	101.202
34,000–35,999	1.2300	43	52.890
ESALs for all trucks weighed			255.151

$$\text{Truck factor} = \frac{\text{18-kip ESALs for all trucks weighed}}{\text{Number of trucks weighed}} = \frac{255.151}{165} = 1.5464$$

So, these environmental effects take into account of the loss in serviceability. We have already seen that due to the traffic load repetitions we will have loss in serviceability. So, this loss in serviceability can also happen because of environmental effects. So, this is defined separately for swelling which happens in soil layers and also the frost and heave action. So, there is a loss of serviceability because of the swelling action individually because of this frost and heave action individually and the total loss in serviceability due to the combined effect of these two phenomena is also given here.

So, the total ΔPSI is of swelling and frost and heave and this is given with the age of the pavement. So, let us take a case wherein the pavement is 13 years old. So, I am interested in computing the total loss of serviceability index. So, I read from this.

So, there is about 0.73 loss in the P_0 value. We have P_0 and P_t. So, the P_0 value, there is a loss of about 0.73 because of the environmental effects. So, this is taken into account here.

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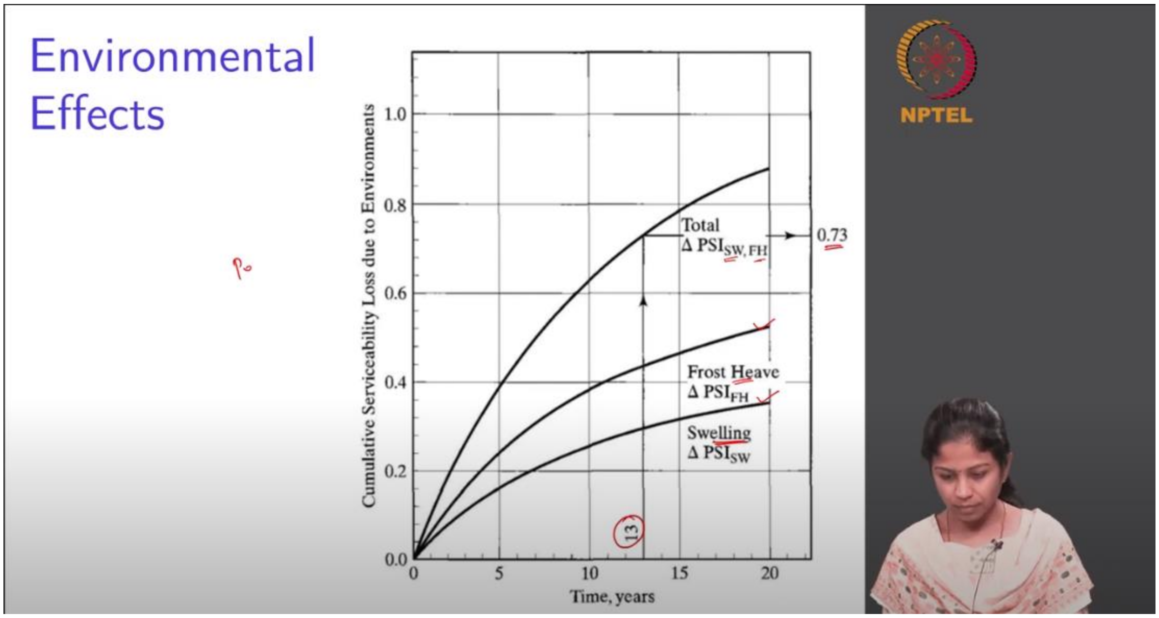

We also have a parameter called effective roadbed resilient modulus. In one of the previous lectures on climate, we have discussed how the resilient modulus varies with respect to the moisture content in soil. So, we had discussed that the resilient modulus is not a constant value, but it depends upon the moisture content that is present in soil which is going to fluctuate with the rainfall content. So, the effective roadbed soil resilient modulus is nothing but an equivalent modulus that would result in the same damage if seasonal modulus values were actually used. So, if this variation in modulus over the years is taken into account and if that is used, what would be the equivalent modulus? So, that is computed from here and used for computation. So, this is calculated using the relative damage concept. So, what is the damage when the modulus is this much with respect to the damage when the modulus value is some other value. So, that relative damage factor is calculated here. Let us not get into the details, but I will just simply show you how to arrive at this effective roadbed resilient modulus. So, we have the resilient modulus values which are defined for each month. So, January, this is the value which is measured, which is the roadbed soil modulus, Feb March and all those things. Now what is this relative damage? This u_f value is computed like this. This is some constant value × M_R or it can be directly read from this scale wherein if we have the soil bed resilient modulus here, we will be able to read the relative damage on the other side of the scale. So, it can be either read from this scale or it could be computed using this equation. Now I arrive at the relative damage for each of these resilient moduli. So, I sum up this relative damage and I divide it by the number of seasons. So, I get this value 25.30, I divide it by 12 because we have taken 12 seasons which is on a monthly basis. I could also take 4 seasons like summer, winter or the rainy season kind of I can divide it into any number of seasons. Since we have taken 12 months here, I divide it by a factor of 12. So, 2.11 is the average u_f value. Use it back in this equation to compute the M_R value and that is nothing but the effective road bed resilient modulus. So, we use that value which is computed for the $\overline{u_f}$. So, we get the corresponding M_R. So, that value will be used for design in terms of the resilient modulus value. So, this is how we take into account of the variation in modulus value because of the effect of moisture content.

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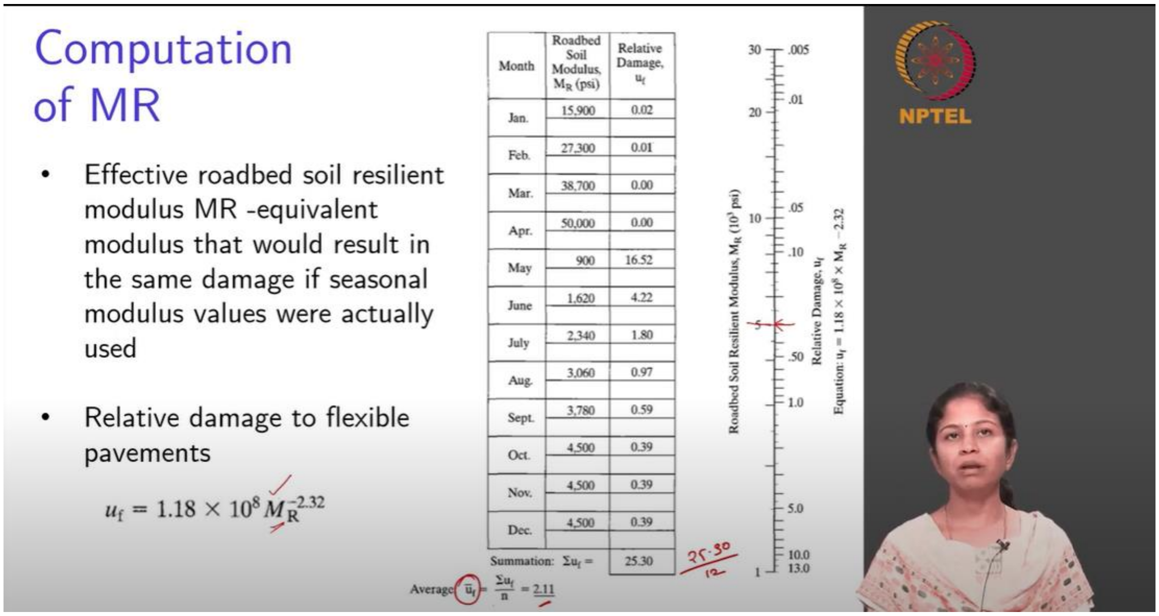

Then finally, we will compute the standard normal deviate which is based on a given reliability level. So, let us say W_{t18}, $\log W_{t18}$ is the maximum number of standard axle load repetitions that can be taken by that particular pavement. This is the maximum value. This value is my allowable number of load repetitions. See if I want, if we assume a 50% reliability level, then this could also be my actual number of load repetitions. If my actual and allowable are equal, then it is said that I am having a 50% reliability level. But let us say that I want a higher reliability level. So, I do not want it to come to my allowable, but I wanted to keep it at a slightly lower level. Then how much we want to space it from this allowable number of load repetitions. That is given using this term $Z_R \times S_0$. So, let us say if I wanted for a reliability level of R, I compute the Z corresponding to R multiplied by the standard deviation. So, that many spaces I move it on this. This is my $\log W_{18}$. This will be my expected number of repetitions or actual number of repetitions. So, you can see they are not equal, but I have slightly moved it away from this allowable number of load repetition to increase my reliability. So, Z_R can be defined as $\log W_{18}$- $\log W_{t18}$. This is again actual and this is allowable. I compute these two. So, that is given by my reliability level.

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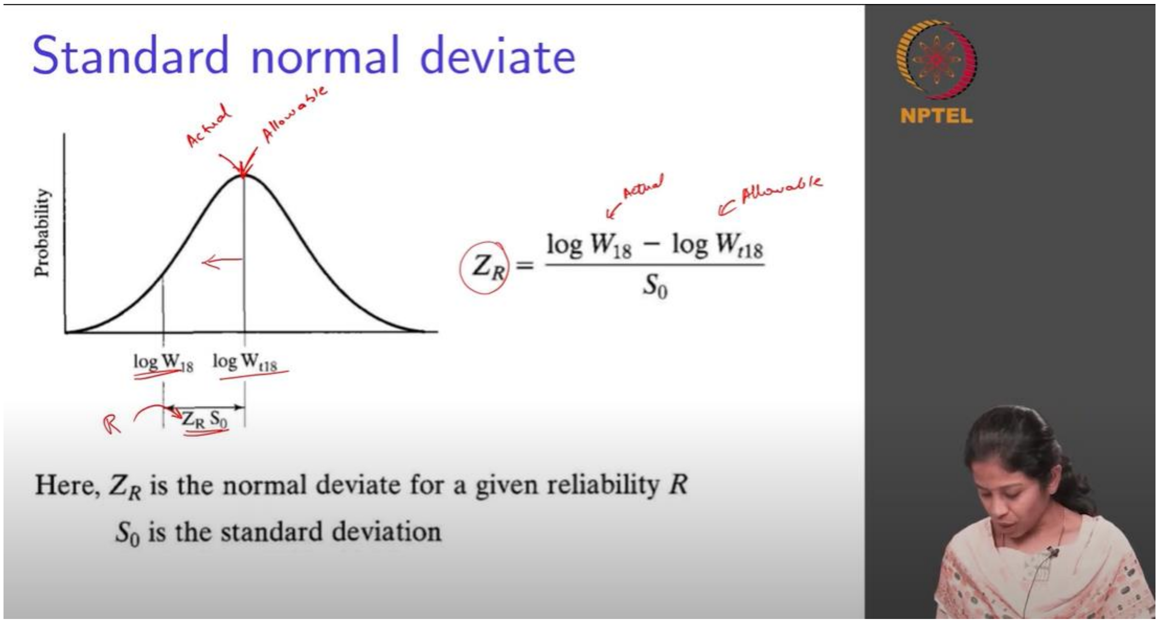

So, now in this perspective, let us see the predicted or actual and allowable number of axle load repetitions. So, this is my predicted value W_{18}. So, this is a function of the standard normal deviate because I do not want it to be same as actual but I want it to be slightly lower than that. So, this many values I add to the allowable number of repetitions. So, Z_0 plus this constant. So, we have this equation here. So, you can see there is a small difference here ΔPSI. This is given in terms of P_t and then we compute all the other values, whereas the allowable number of 80 kN load repetitions is given as $\log W_{t18}$. This is the allowable number of load repetitions to reduce the PSI value from P_0 to P_t. If you remember the previous slide, one of the previous slides, I had shown that it reduced from P_0 to P_t over N_t load repetitions. That N_t is nothing but defined in terms of $\log W_{t18}$. So, we have predicted or actual or expected number of load repetitions and we have allowable or maximum number of load repetitions it can carry.

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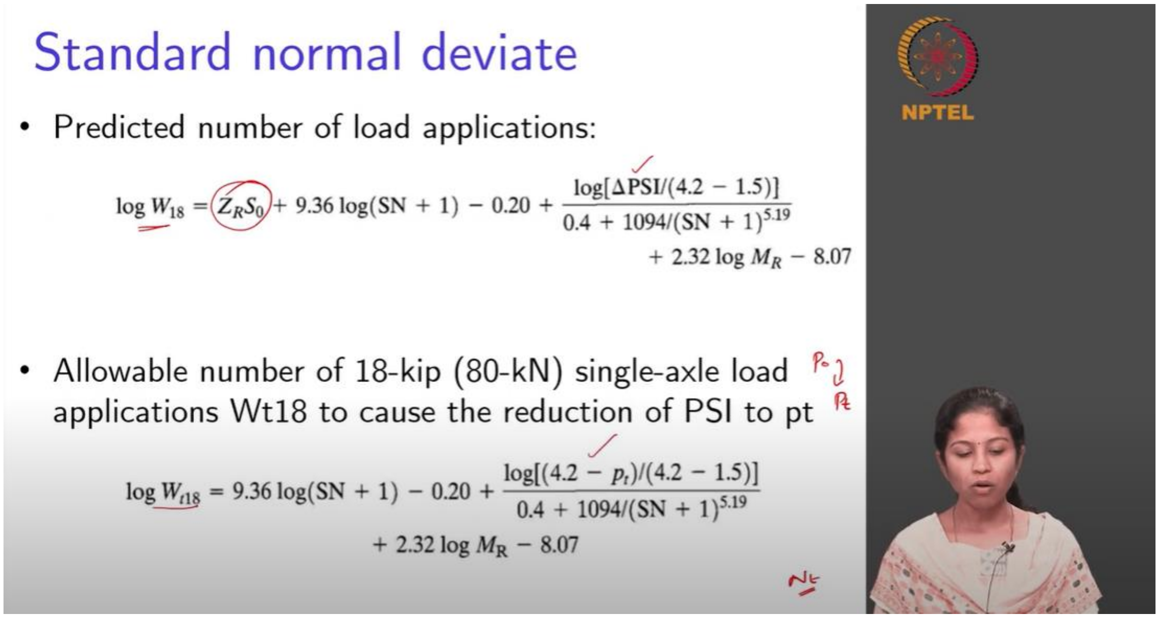

Now using these two, again, how do you calculate this Z_R value, you can arrive it from a standard normal table. So, this is nothing but the area between the curve from 0 to any given value. So, this is nothing but your Z value. So, for a given reliability level, I have just shown a part of this graph. So higher reliability values are not given in this. There are values in the bottom it continues, the table continues for higher Z values. So, if you look at the bottom, we have 90, 95 percent, 99 percent reliability level. So for that 90 percent reliability level, I will be able to read the Z value from this graph. So, I will pick the Z value and I will be using it to compute the $\log W_{18}$ value. Then once I get this value, we will be able to execute the design procedure.

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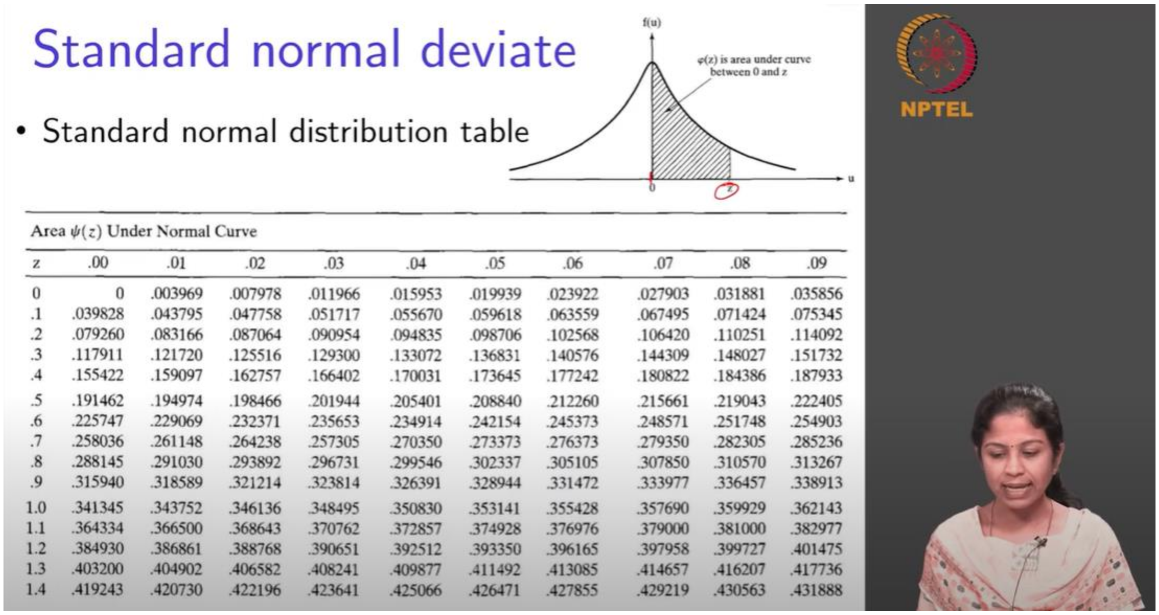

Area $\psi(z)$ Under Normal Curve

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0	0	.003969	.007978	.011966	.015953	.019939	.023922	.027903	.031881	.035856
.1	.039828	.043795	.047758	.051717	.055670	.059618	.063559	.067495	.071424	.075345
.2	.079260	.083166	.087064	.090954	.094835	.098706	.102568	.106420	.110251	.114092
.3	.117911	.121720	.125516	.129300	.133072	.136831	.140576	.144309	.148027	.151732
.4	.155422	.159097	.162757	.166402	.170031	.173645	.177242	.180822	.184386	.187933
.5	.191462	.194974	.198466	.201944	.205401	.208840	.212260	.215661	.219043	.222405
.6	.225747	.229069	.232371	.235653	.234914	.242154	.245373	.248571	.251748	.254903
.7	.258036	.261148	.264238	.257305	.270350	.273373	.276373	.279350	.282305	.285236
.8	.288145	.291030	.293892	.296731	.299546	.302337	.305105	.307850	.310570	.313267
.9	.315940	.318589	.321214	.323814	.326391	.328944	.331472	.333977	.336457	.338913
1.0	.341345	.343752	.346136	.348495	.350830	.353141	.355428	.357690	.359929	.362143
1.1	.364334	.366500	.368643	.370762	.372857	.374928	.376976	.379000	.381000	.382977
1.2	.384930	.386861	.388768	.390651	.392512	.393350	.396165	.397958	.399727	.401475
1.3	.403200	.404902	.406582	.408241	.409877	.411492	.413085	.414657	.416207	.417736
1.4	.419243	.420730	.422196	.423641	.425066	.426471	.427855	.429219	.430563	.431888

Instead of doing the calculations, we can either use this equation to calculate the number of load repetitions or we can use the design chart which is provided to calculate the load repetition. So, how do we use this design chart? It is very simple. We start with the reliability level. So, that is why I said we should first choose what is that kind of highway we are designing, what is the reliability level we are interested in and based on that the whole design follows. So, let us say this is my chosen reliability level. Then we know what is the S_0 value. So, I read the appropriate S_0 value from here. So, from that, this scale gives me the estimated total 18 kip equivalent road repetitions which is nothing but W_{18}. We are interested in computing the W_{t18} value. So, this is my W_{18} value. So, I read from this graph, then I read the road effective road bed modulus, so let us say this is my value 5. So, I read this and then I read this, I need this plot. So, here it gives different values for design serviceability loss. So, we need to know what is the value of ΔPSI because of traffic and because of climate. So, let us take the same example which we did before. For climate, we had seen that for 13 year design period it was 0.73. Let us say for traffic my P_0 value is 4.2, at a given time my value is 3.2, so the loss of ΔPSI is 1, so 1 plus 0.73. So, 1 plus 0.73, so I am getting a ΔPSI value of 1.73. So, I will be able, I should be able to read between this 1.73. Let me just use this value between 1.5 and 2. So, wherever I am meeting this I take this value and I obtain my structural number. So, why are we arriving at the structural number? What are we going to do with the structural number? I will show you in a while. So, this equation uses the expected number of load repetitions to compute the structural number.

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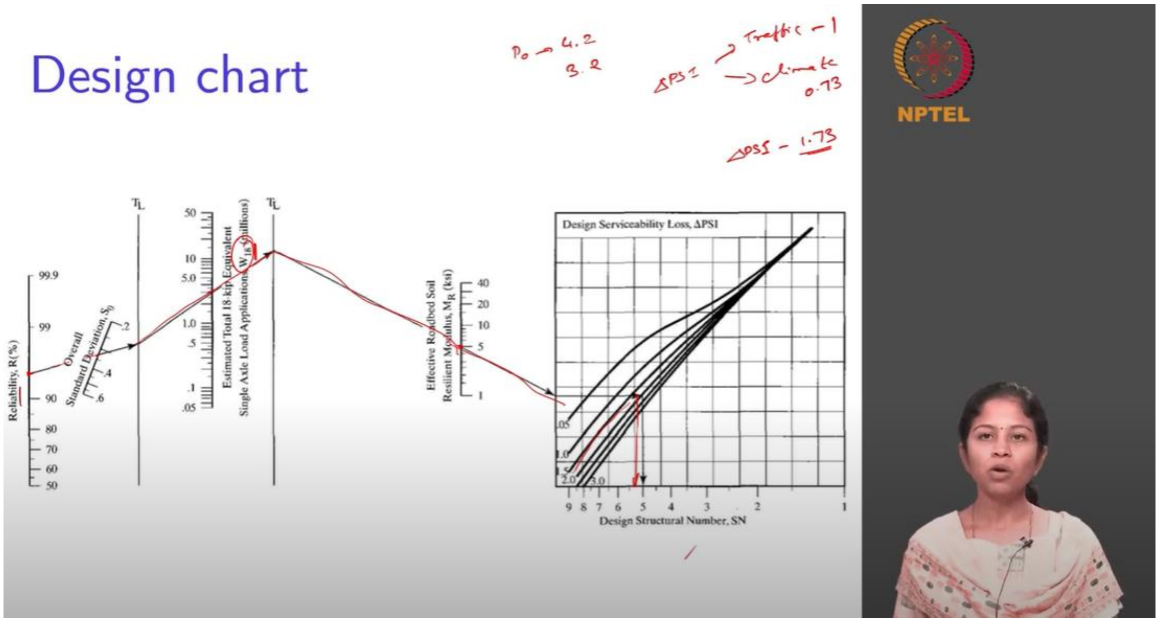

Let us now look into the design procedure. This design can be done in two ways. We can compute ESAL value for chosen thickness. So, we know what is the allowable and what is the actual number of load repetitions. So, accordingly what is the thickness that should be used or we arrive at the thickness for chosen ESAL value. So, how do we do this? We identify a desired reliability level and we choose an appropriate Z_R and S_0. This is kind of the same steps that we had seen in the design chart except that I am just listing it in a step by step manner. Then we identify the ΔPSI value for appropriate environmental conditions and traffic based on the design life, that also we had done earlier. Then we arrive at the effective roadbed resilient modulus. We have seen it how to compute it from the u_f value. So, we arrive at this value. Then we assume a structural number value. We had seen that this structural number is nothing but an indication of the load carrying capacity. It is a function of some constant which is load carrying capacity per unit thickness. Then it is a function of the thickness of individual layer and drainage condition.

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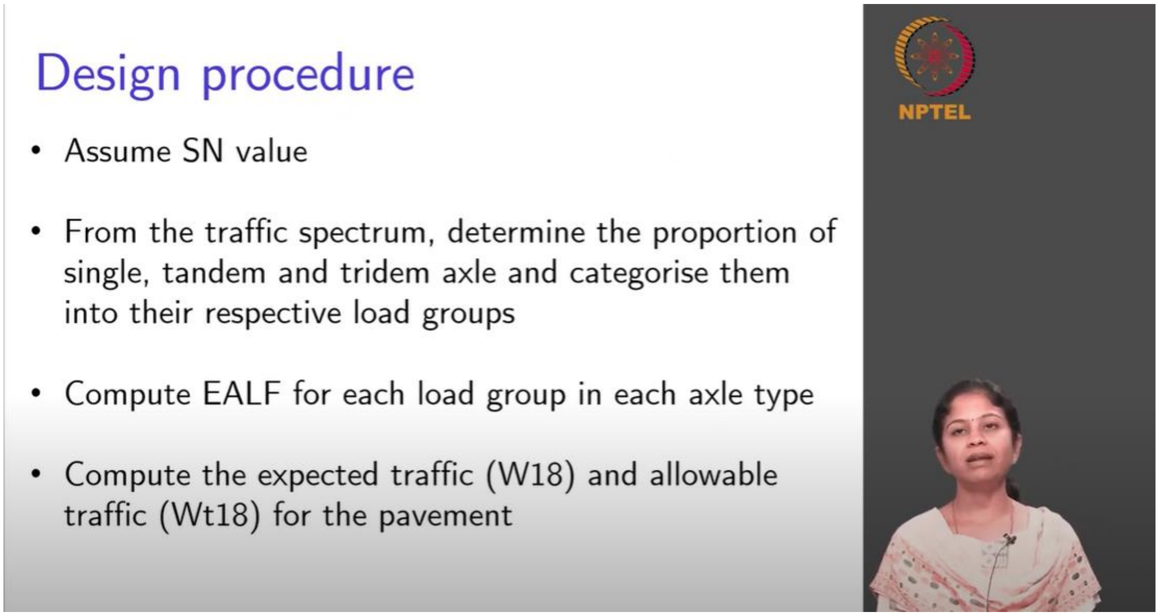

So, let us assume a structural number, later, we can split the structural number into each of these three parameters. So, we assume a structural number, then from the traffic spectrum, we determine the proportion of single, tandem and tridem axles and you categorize them into your respective axle load groups. Then for each axle load group we can compute EALF or we can compute the truck factor directly. Again, we have seen how to compute this truck factor. Now from the truck factor, we can compute the expected traffic which is nothing but the actual traffic W_{18} and allowable traffic or the maximum traffic which is W_{t18} for the pavement.

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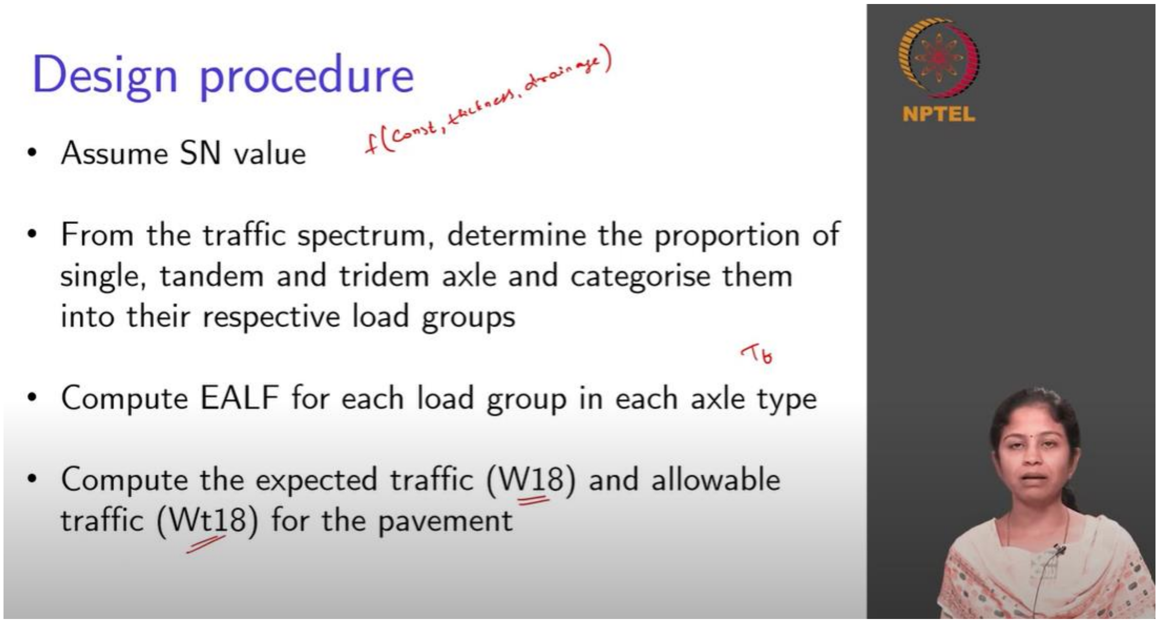

So, once we get this, we can compare these two values if the values are different, if the expected traffic is more than the allowable traffic, then we repeat the same design procedure for another SN value or if it is satisfactory, then we can just use this SN value and compute the thickness of individual layers. Because ultimately what we are interested in is the thickness of individual layer, that is what we are determining through pavement design. Here, what we are doing is we know what is the expected traffic and then we are arriving at the thickness for that particular traffic. In IRC what we typically do is we already have predefined the thickness templates. So, we use those thickness values, compute the allowable traffic level and for that we check with the actual traffic. So, the same thing can be done here also. So, let us say if structural number is not satisfactory, then we redo the design. Now, once we arrive at the structural number value which will give us the expected traffic lesser than the allowable traffic, then how do we decompose it into the thickness value of individual layers. So, first to start with, we use E_2 which is nothing but the modulus of the base layer. E_1 is for surface, E_2 is for base and E_3 is for sub base. So, we use E_2 value as the M_R value and get the structural number from this design chart. So, in this procedure we use E_2 as the resilient, E_2 as the M_R value and then we arrive at the structural number from this chart. So for that particular structural number, we also know what is a_1, because it basically depends on the modulus of bituminous layer. So, we compute the thickness of the first layer, layer 1 which is nothing but the asphalt layer. So, again let me repeat, we use E_2 as the resilient modulus, we go to the design chart, compute the structural number from that chart and using the structural number, the a_1 value calculated, we arrive at the thickness of the asphalt layer, this is for layer 1.

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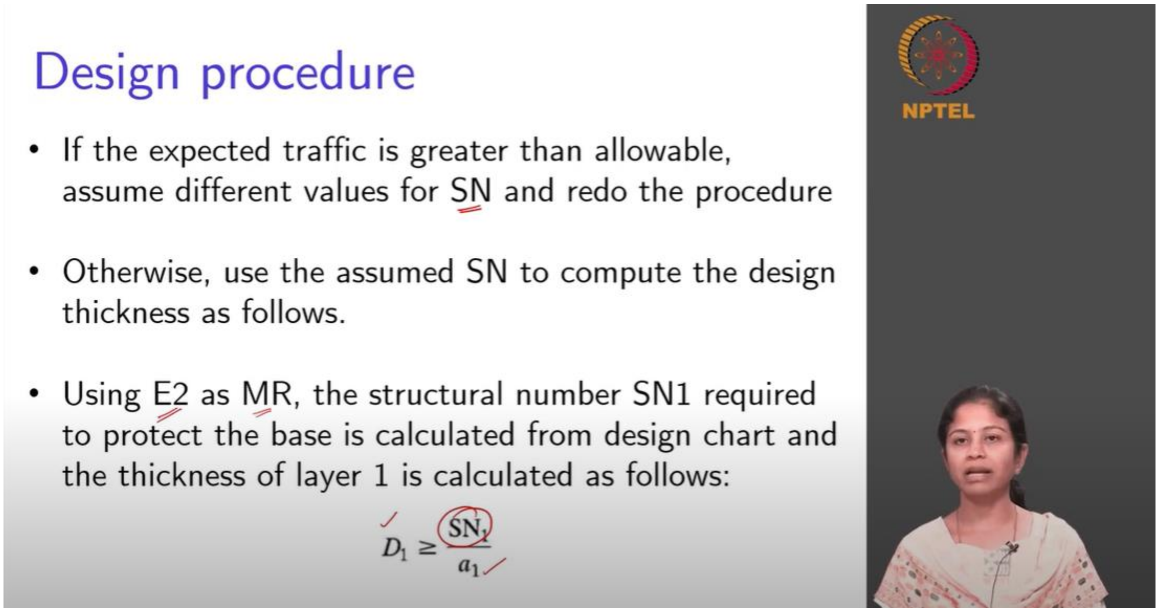

Now having known that, we use E_3 as the M_R value, again go back to the same chart, get the revised SN_2 value and then we compute the thickness of the base layer, right. This is given as D_2 and this is how we compute. It should be greater than or equal to that value because we need a minimum of that particular value. So, you should assume a slightly greater value than the calculated value. Similarly, based on the soil roadbed resilient modulus M_R which is for the subgrade layer, the structural number SN_3 is calculated from the design chart and thickness of layer 3 is computed.

So, this is how we arrive at the thickness of individual layers, once we know what is the structural number. So, this structural number comes from the expected and allowable number of load repetitions. So, once we get that, we have arrived at the thickness of the individual layers. So, this is kind of an overview about the design procedure, which is followed in the AASHTO 1993 design procedure.

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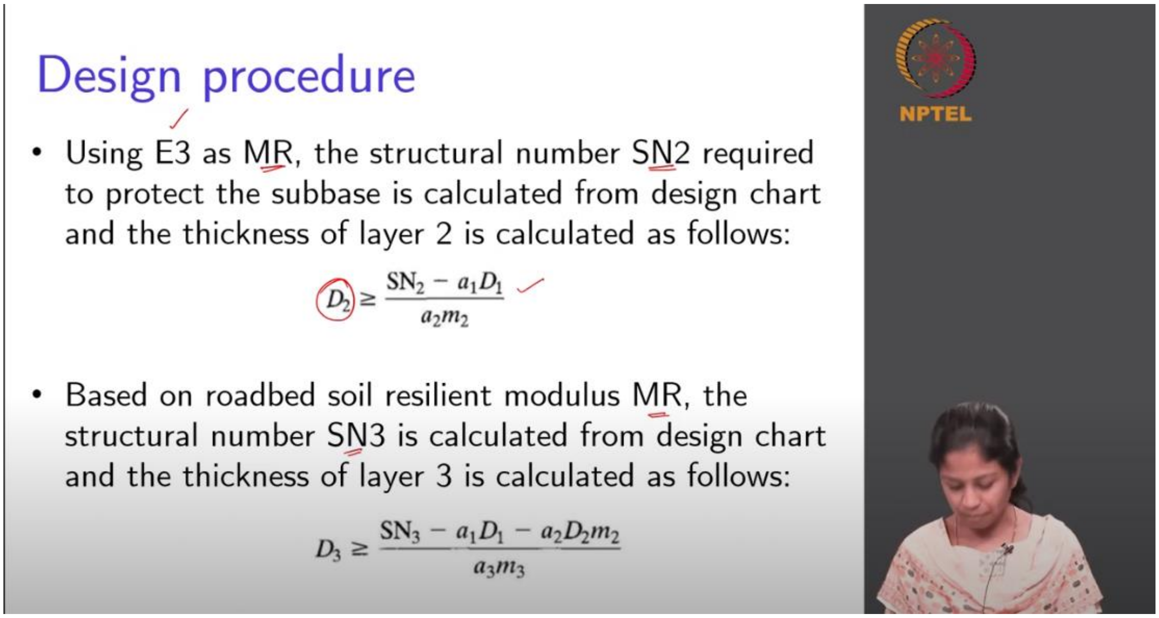

So, let me stop this lecture here. In the next lecture, we will continue discussing about the reliability aspect, but that will be in AASHTO 2004 design procedure, which is the MEPDG version. So, let me stop this lecture here and thank you for your time.