**Analysis and Design of Bituminous Pavements**

**Dr. Neethu Roy**

**Department of Civil Engineering**

**Indian Institute of Technology, Madras**

**Lecture – 13**

**Traffic Analysis - ESWL - Part 1**

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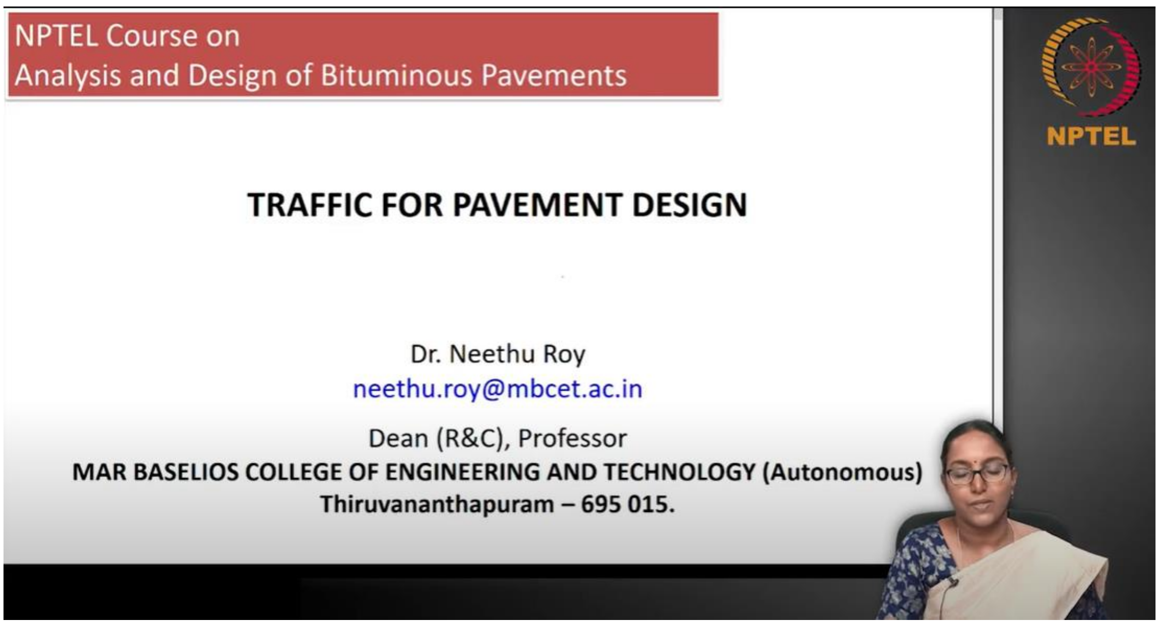


Hello everyone. In the coming sessions, we are going to discuss about how traffic is considered for the bituminous pavement design. So, the reference textbooks for this particular session are Payment Analysis and Design by Yang Huang and the code of practice of IRC 3 and acknowledgement to Google sources from where some pictures are taken. So, the outline of this session and the coming sessions will be, we will discuss about how the traffic is considered for pavement design. There are essentially three approaches, one is a fixed traffic, the other is a fixed vehicle or a fixed axle load and the third one is a variable traffic or a variable vehicle approach. So, these three methods will be discussed.

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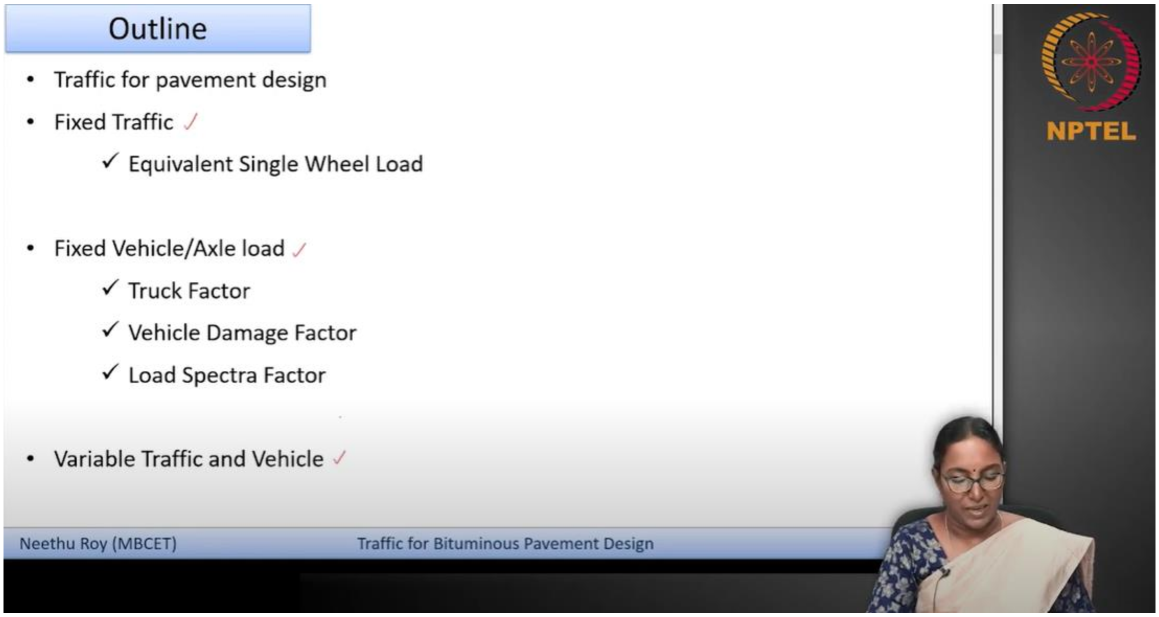


So, you are familiar with the overall pavement design procedure of a mechanistic empirical method, wherein you have the input parameters which are the material properties and the subgrade property, which is the foundation and climatic factors which will affect these properties and the loading that comes on this pavement structure is traffic loading. So, when all this input goes to a trial design strategy, you have the pavement analysis by layered elastic analysis for example, and you can find out the stresses and strains at various critical locations. Then, you have the distress prediction models or the transfer functions which can be used to predict the distresses in the pavement structure and the damage accumulation can be noted and check whether the performance criteria mentioned is met for the design period. If not, you can modify the strategy by taking a different cross section and with different classes of materials and then this whole process can be repeated. So, this part forms the analysis part wherein you will finally finalize a design strategy which will satisfy the performance criteria. Now, various such viable alternatives can then be checked for other aspects such as the life cycle cost analysis, the constructability issues, etc. And then finally, you arrive at the strategy for pavement design.

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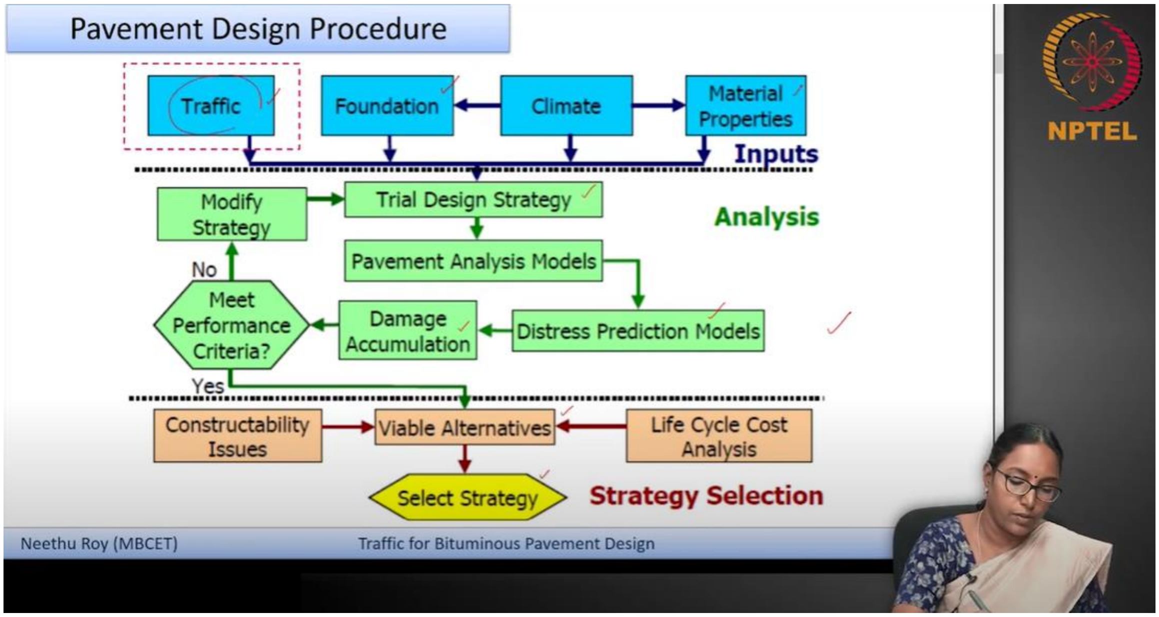


So, as mentioned, the load input that goes in for this pavement design is the traffic load. So, we will be discussing about how this traffic is considered in the flexible pavement or the bituminous pavement design. So, as you know, the traffic comprises of various classes of vehicles, light vehicles, medium vehicles or heavy vehicles. As far as the pavement design is concerned, we consider the heavy vehicles or the heavy trucks with laden weight more than 3 tons. So, essentially the heavy commercial vehicles are considered for design. But these vehicles as you can see comes with different axle configurations, different sizes and they carry different weights. As you can see here, this is a single axle with dual wheel, you can have tandem axles, you can have tridem axles or you can have vehicles with multi axles and they carry different loads and the number of repetitions of these loads over the design period is also another factor.

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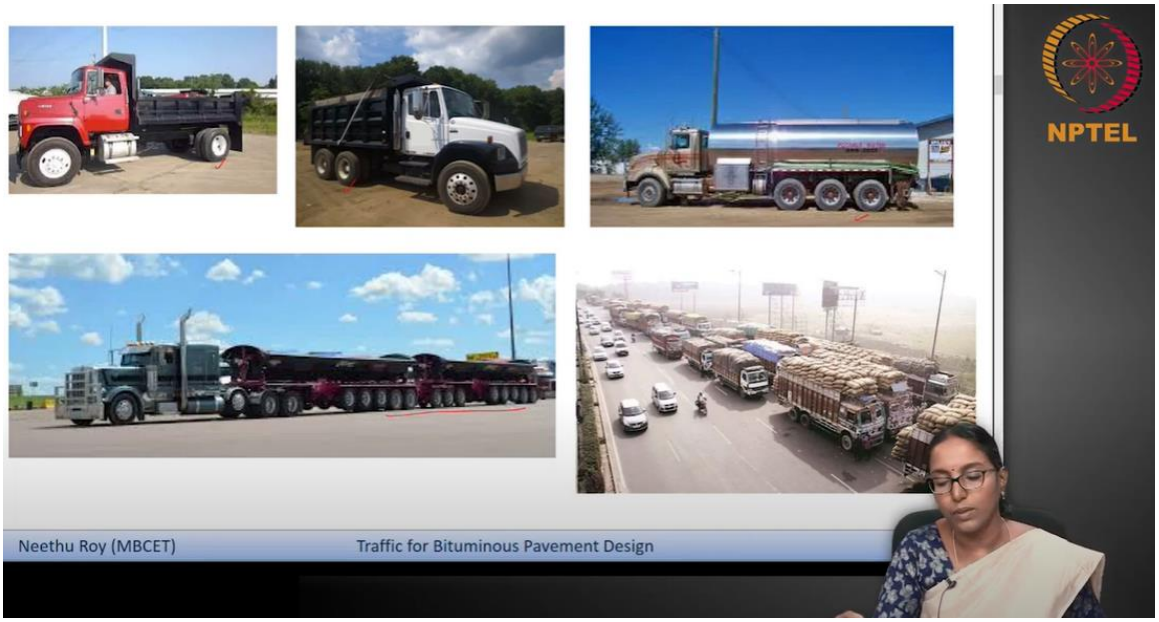


So, as far as the Indian classification is concerned, as per the IRC 3 1983, the vehicles or the traffic for pavement design is generally classified into 3 categories. One is the single unit trucks and then the semi-trailer unit trucks and the tractor trailer units. And they are named as shown in this picture. The type 2 truck is a single unit truck wherein there is a single axle in the front and there is a single axle at the rear. So, this is called a type 2 truck. Similarly, the type 3 truck here is a single unit truck wherein there is one axle in the front and there is a tandem axle at the rear, which is counted as 2 axles. So, altogether it is a type 3 truck. Whereas, in the case of a semi-trailer kind of vehicles, they are named as Type 2-S1, which indicate that the front unit of the vehicle has 2 axles and the rear unit has another axle. So, it is called as Type 2-S1. Whereas, in the case of a fully detachable trailer unit kind of a tractor trailer arrangement, this is named like Type 2-3, wherein the front unit has 2 axles here and the rear unit has 3 axles. Likewise, you have a Type 3-3 and so on. So, this is the classification of trucks as per IRC 3.

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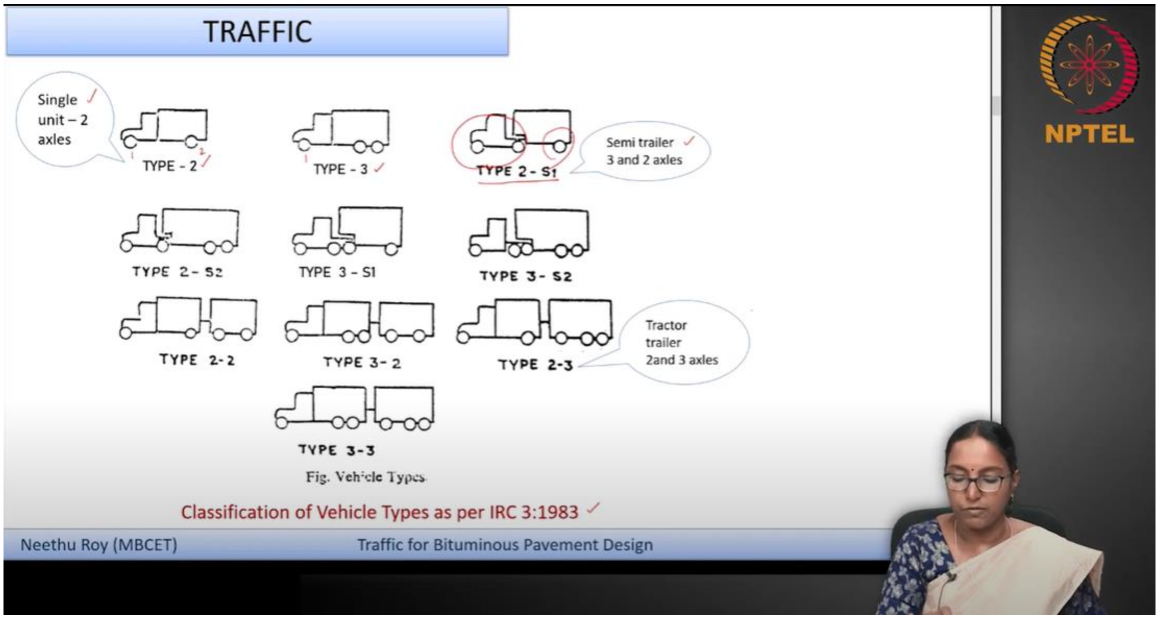


And so again, I have shown here, the naming of the axles. You see here, this is a single axle with a single wheel on both sides. So, there are 2 wheels and a single axle. Whereas in this case, you see that in this single axle, there are 2 wheels on either side. So, there are 2 wheels on the left side and 2 wheels on the right side. So, altogether there are 4 wheels, we call it as a single axle dual wheel assembly. And this is a tandem axle dual wheel assembly because you have 2 axles, this is axle 1 and axle 2 which are close by. And on either side of each axle, there are 2 wheels. So, there is 1, 2 here and 3, 4 here. So, altogether there are 8 wheels in a tandem axle dual wheel assembly. And you have the tridem axle also, but in the IRC 3, the original classification, this tridem axle is not considered. So, in the tridem axle, you see that there are 3 axles and in each axle, there is a dual wheel on either side.

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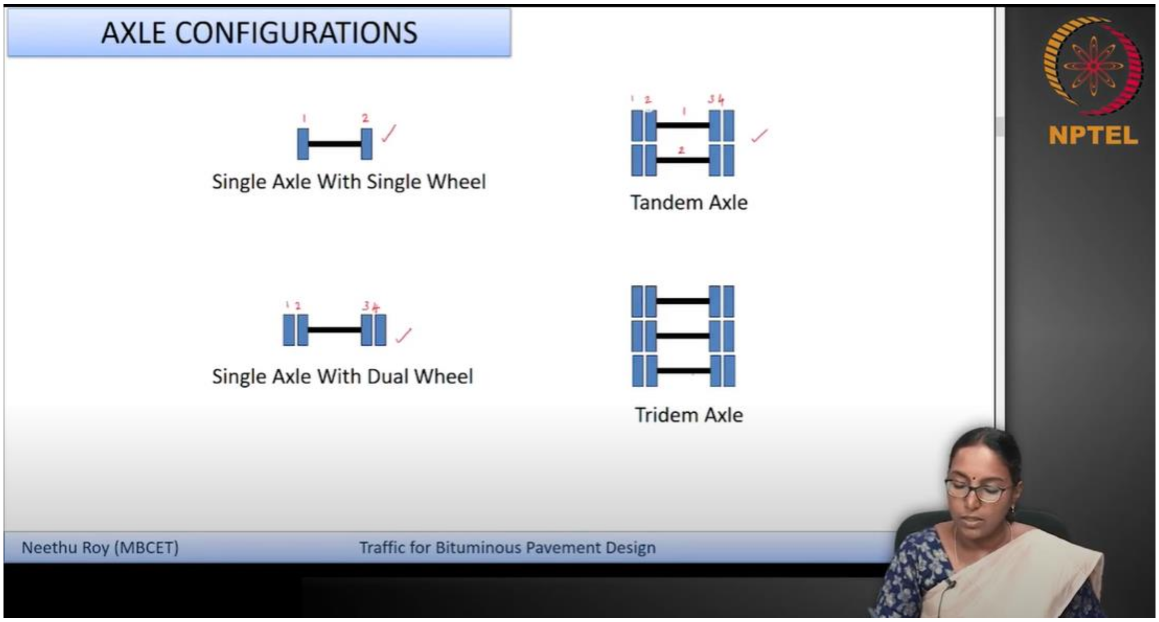


So, this is the permissible gross weight or the maximum axle loads that is given by IRC 3. As you can see here for the type 3 truck, the gross weight is 24 ton with the front axle weight of 6 tons and the rear tandem axle having a permissible weight of 18 tons. Now, this has been amended in 2018. As you can see here, the tandem axle for rigid vehicles, trailers, etc., the gross weight is given as 21 tons and you can see that the triaxial or the tridem axle, 3 axle trucks are also included in this category. So, this is already discussed by Professor Murali. So, in this heterogeneous traffic condition wherein you have different classes of trucks having different axle configuration with different load magnitudes and with different number of repetitions, how this traffic has to be considered for the pavement design.

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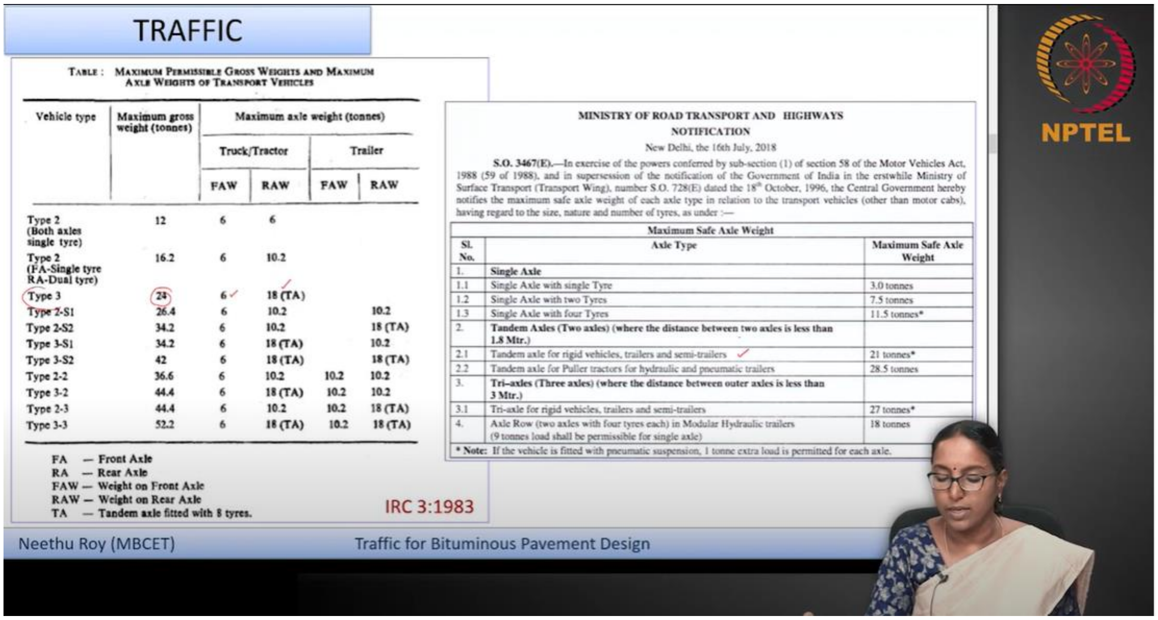


So, the aspects to be considered are, the loading magnitude, the axle and the wheel configuration and the number of load repetitions. So, there are 3 approaches to do this. First one is a fixed traffic approach, the second is a fixed vehicle approach and the third one is a variable traffic or a variable vehicle approach. We will see this one by one.

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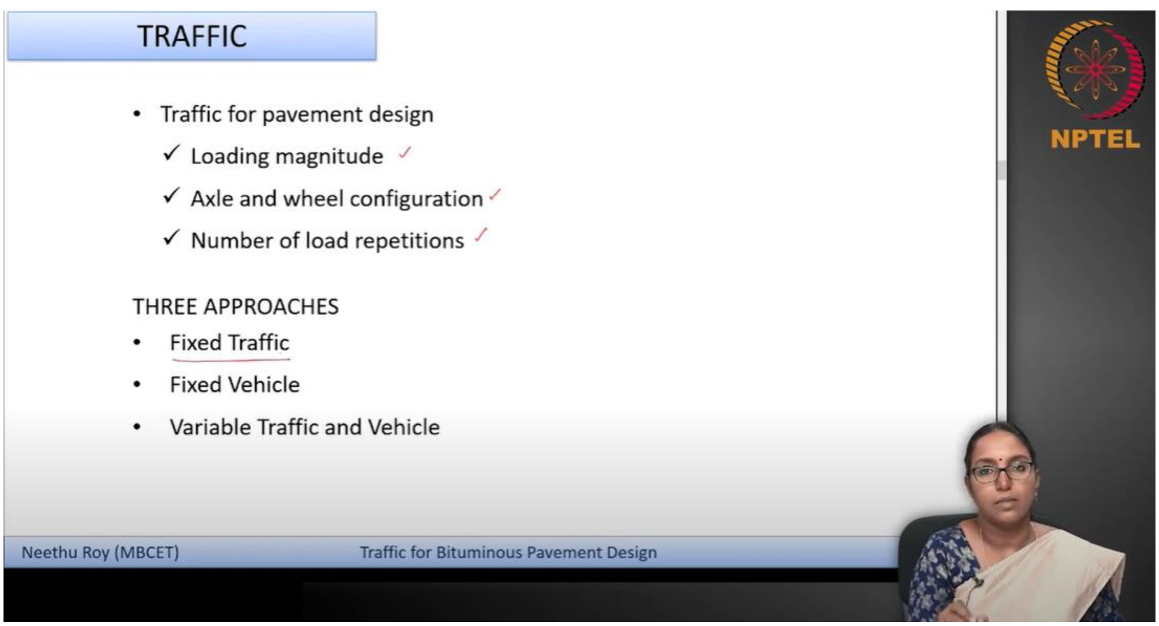


So, the first one is a fixed traffic approach. So, here what we consider is the damage to a pavement by one repetition of a single wheel. So, you can see that this is a single axle on one side, there is a single wheel. So, if you have a single axle with each wheel on either side, this picture actually depicts one side of the axle. So, you see that there is a single axle single wheel here. Similarly, a tandem axle with single wheel and a tridem axle with single wheel is drawn here. And likewise, the dual wheels on the single, tandem and tridem axle is shown in this picture as I have already shown. Now, this approach wherein the damage caused by the repetition of a single repetition of a single wheel was essentially adopted for the design of airport pavements in the past and also for traffic or highway traffic which has light traffic but with heavy trucks. So, we have different number of such single wheels of which the heaviest wheel load anticipated in the traffic over a design period was used for the design. Now, this approach was okay for the airport pavement design till such time when there were the introduction of dual wheel vehicles or aircrafts especially during the world war. So, this concept of equivalent single wheel load was introduced. Now why because, you wanted to use the same concept of designing the pavement using a single wheel load but introduced this dual wheel assembly into that. So, the idea was to convert this dual wheel assembly to a single wheel load and that wheel load to be used for the design. So, this equivalent wheel load is called a equivalent single wheel load or ESWL but the number of repetitions of this ESWL is not considered in the design. So, we will discuss even though this approach is not used for highway pavements but this concept of converting a dual wheel to a single wheel will be worth studying.

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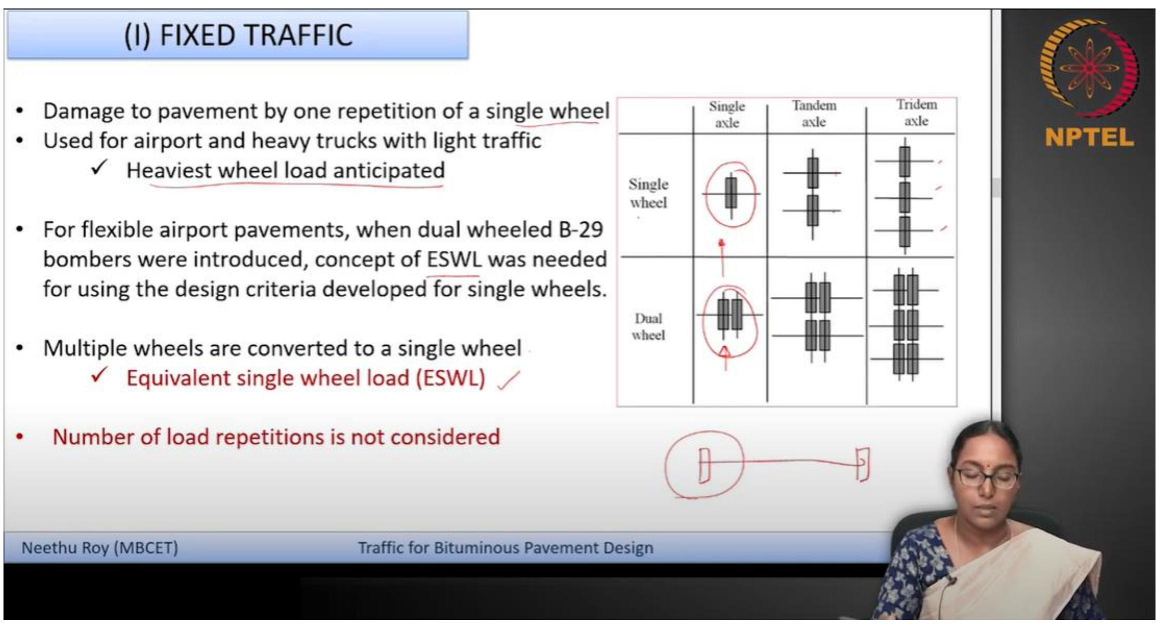


So, equivalent single wheel load is that single wheel load which will produce the same kind of an effect as due to the dual wheel load. So, this equivalent single wheel load will depend upon what is the criteria that you select to compare the single wheel load and the multiple wheel loads. So, you have different approaches. Huang studied the effect of various factors on which this ESWL is based and based on the Burmister's two layer theory, he assumed that the two dual wheels as well as the single or the equivalent single wheel have the same contact pressure but they have different contact radii. Whereas, Gerrard and Harrison considered the single, dual or a dual tandem. He tried to convert the dual tandem also to a single equivalent single wheel. So, all these are assumed to have an equal contact radii with different pressure. So, accordingly you have different methods based on what is the criteria that you use to convert the dual wheel to a single wheel. So, you have equal vertical stress criteria, vertical deflection criteria, tensile strain criteria and so on which will be discussed in this lecture.

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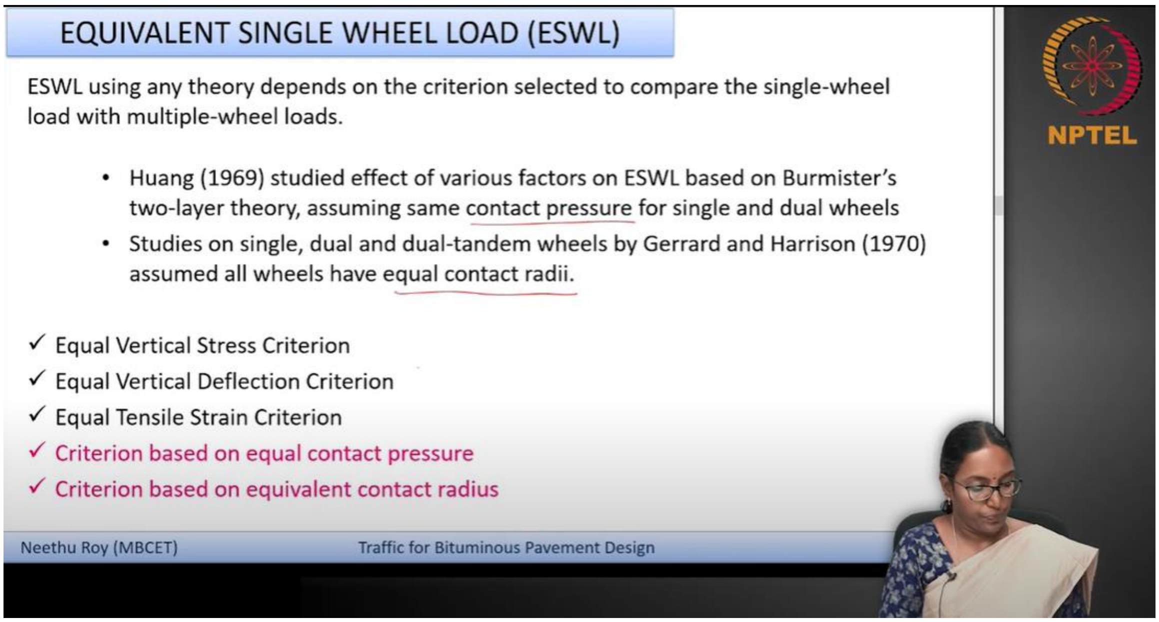


Now, the second approach of considering or analyzing traffic is the fixed vehicle approach or the fixed axle load approach. Here, the damage to a pavement structure by the number of repetitions of a standard vehicle or a standard axle is considered. So, what essentially you are trying to do is convert all the type different classes of axles or different classes of vehicles to one standard vehicle or a standard axle and find what is the number of repetitions of that particular standard axle. So, the common axle that is considered, the axle load that is considered for this purpose is a 80 kN single axle dual wheel or it is an 18 kilo pounds single axle dual wheel as you see here. So, you have a single axle with two wheels on either side and the total weight on it is 80 kN so that on each wheel the load is 20 kN. So, in order to convert this load class or any load class to the standard class, you use something called an equivalent axle load factor or a load equivalency factor EALF or LEF. So, the idea is that you are comparing the damage that is caused by the axle that is in question to that caused by the standard axle. So, you can get the EALF as the damage caused by the damage per pass of the axle in question to that of the damage per pass of a standard axle.

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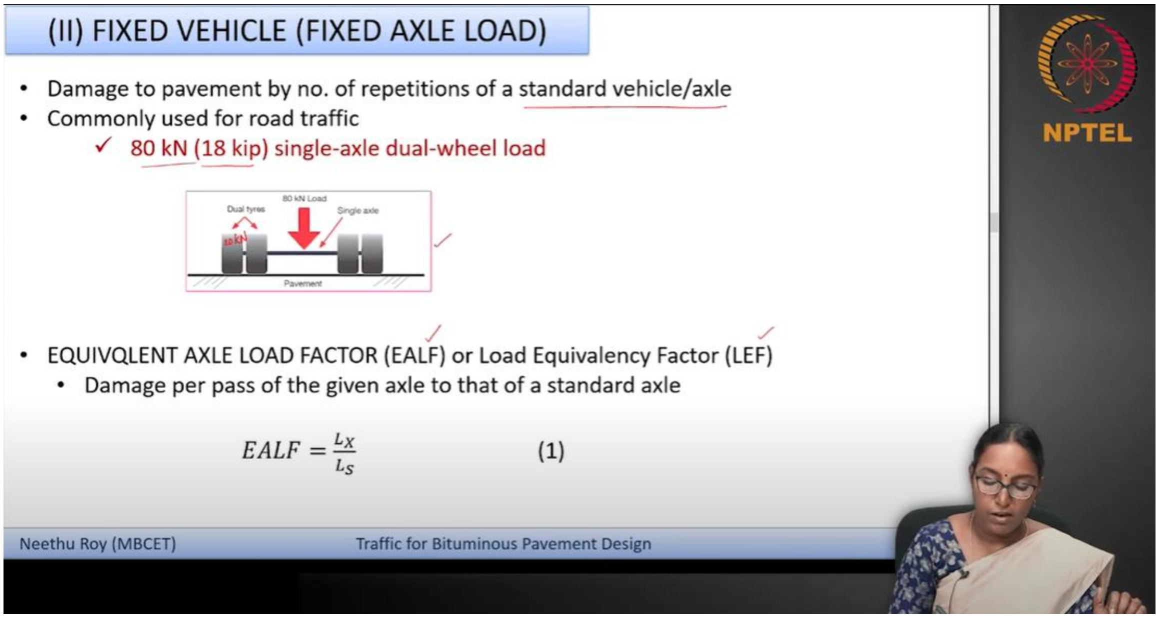


So, once you get the equivalent axle load factor for the different class of vehicles, you can multiply it with the number of repetitions of that particular class and this can be summed up for all the classes of vehicles so as to get the equivalent single axle loads over the design period. So, this is how the fixed vehicle approach utilizes or analyzes the traffic and either you can go and find out the equivalent axle load factor for each class of vehicle or an average vehicle damage factor can be considered for all the classes of vehicle put together. So, these two approaches of using an average factor for each vehicle class or an average factor for all the classes put together are called the truck factor and the vehicle damage factor respectively. So, these will be discussed in the coming lectures.

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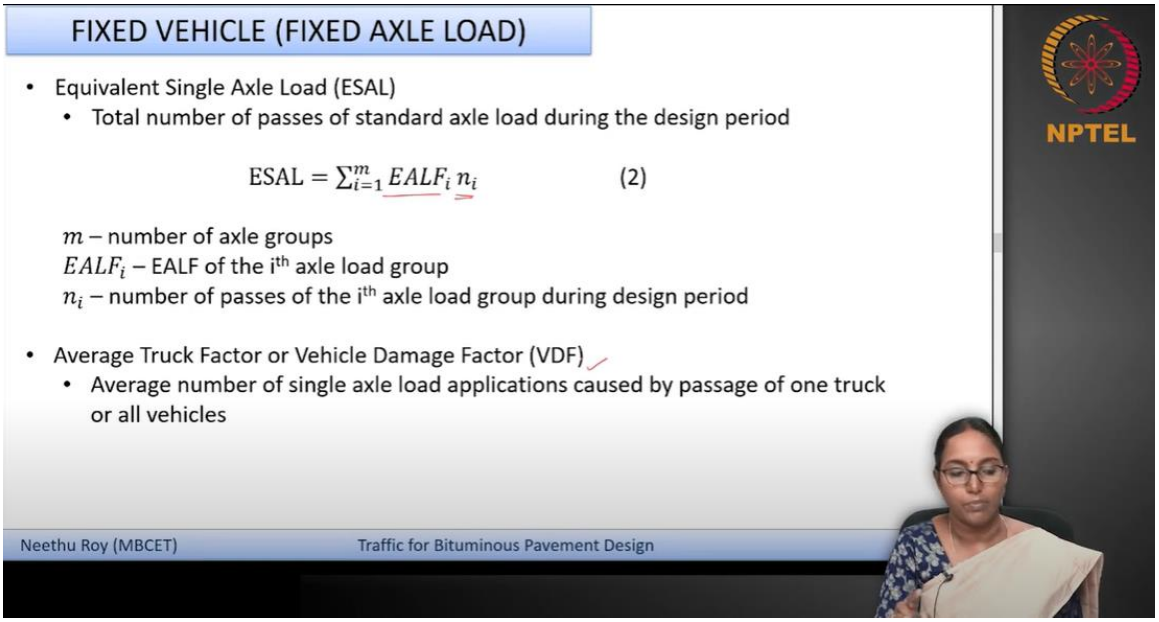


So, just a comparison of what we discussed just now, one is a fixed traffic approach and the other is a fixed vehicle approach. As we can see here in figure A here, the pavement thickness will depend upon that single wheel load or the critical wheel load that you consider and as the wheel load increases you see that the pavement thickness requirement also increases. Now, this will be different for different subgrade support values or different subgrade strengths. For each subgrade strength, this relation between that single wheel load and the pavement thickness will be different. So, as you can see here this dotted line indicates a pavement structure with a subgrade of a particular strength and the solid line is for a subgrade of another strength but as the wheel load is higher the pavement thickness requirement will be more. So, here, as I said, you are actually finding the one critical or the design vehicle or the load which is the most damaging one will be used for the design and all other types will be ignored and if there is a dual wheel, you will convert it into a equivalent single wheel load. So, this approach was largely used for the design of airport pavements. Whereas in the fixed vehicle approach, as you can see here, the number of repetitions of a standard axle or a standard vehicle is considered and as the number of repetitions increases your pavement thickness also increases and this relation between the number of repetitions and the pavement thickness, of course, will vary from pavement to pavement or for different subgrade strengths will be different as you can see from the two lines plotted here. So, the idea is, you are actually finding the pavement thickness requirement for the number of repetitions to failure for a standard vehicle and you are finding the damaging effect for all the vehicle classes in terms of the standard vehicle. So, if there are the different classes of vehicles, they are converted to the standard vehicle by using the equivalent wheel load factor and this is the approach that we use for the design of highways. So, this is essentially the difference between a fixed traffic approach and a fixed vehicle approach.

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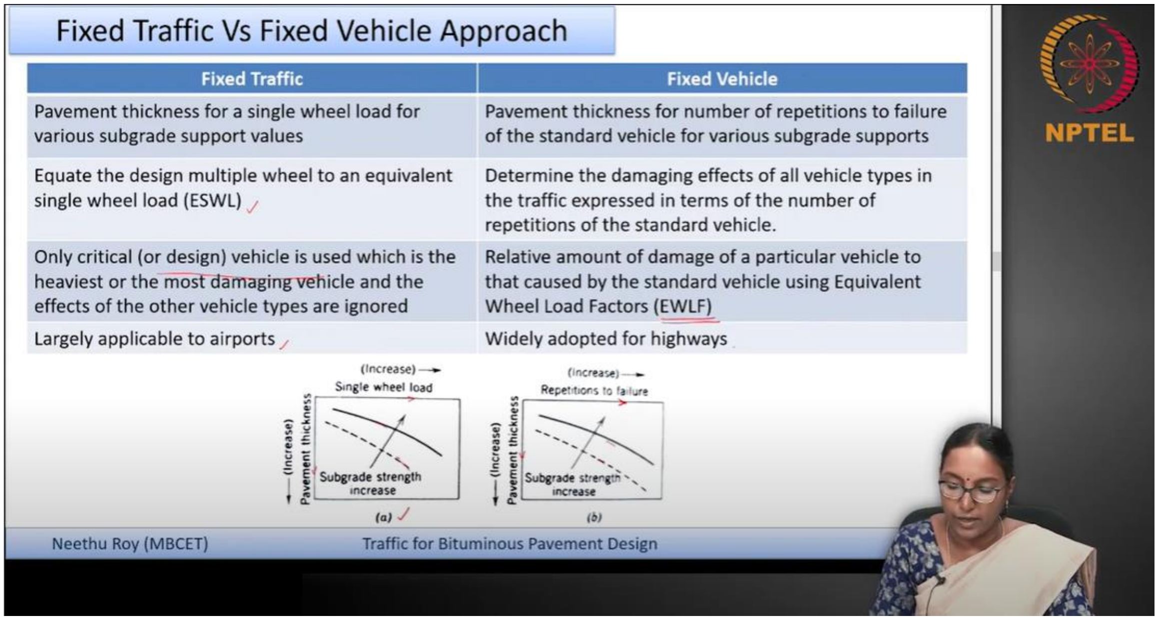


Now, moving on to the third approach which is the variable traffic and the variable vehicle approach. Here, in the traffic as well as the number of repetitions of each of these vehicle classes will be considered individually. So, the actual traffic as such is used for the analysis. There are no equivalence factors which are used to convert each one of the traffic or vehicle classes to a common class or a common load. So, essentially, the loads will be divided into a number of groups and for each load group the stresses, the strains and the deformations or the deflections under each load group will be determined separately and that will be used for the design purpose. So, this is the method that is to be used in the mechanistic method of design. But the problem is the computational difficulty that arises by considering all these vehicle classes and the axle loads separately.

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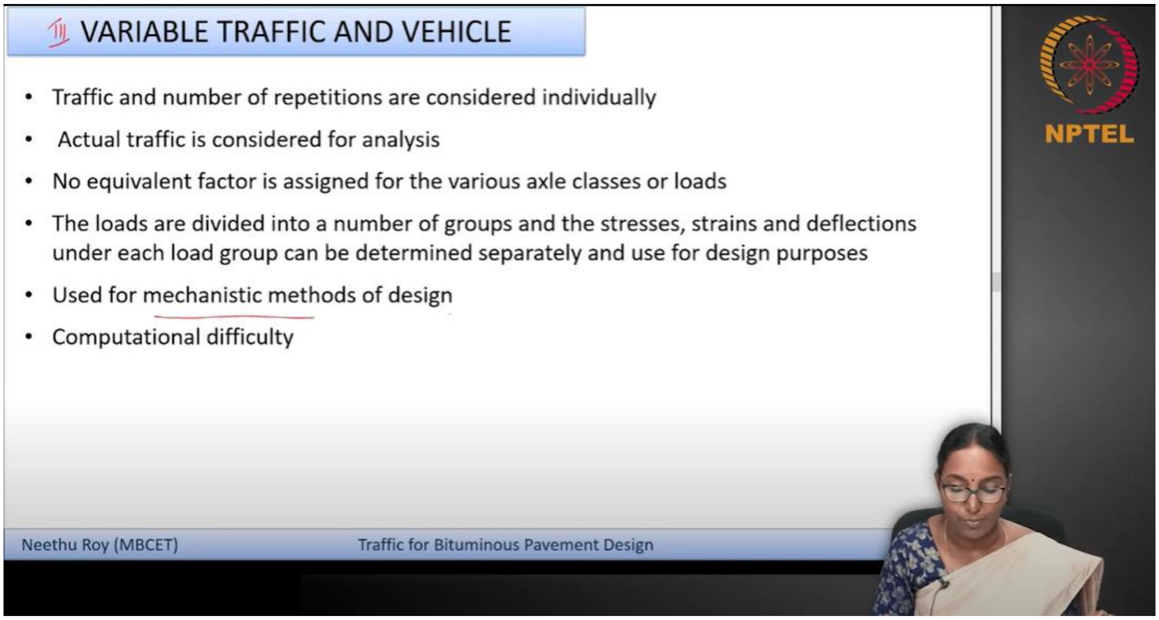


Now, let us go back and start discussing about each one of these methods. The first one as I said, is the fixed traffic approach wherein one wheel load is considered, the heaviest wheel load is considered for the design. So, in this approach, it is worth studying the aspect of converting a dual wheel to a single wheel or you call it as a equivalent single wheel load. So, you have dual wheel assembly with P and P as the loads and a pavement of thickness say Z. Now, you want to find out what is that one wheel load which is called the equivalent single wheel load for the same pavement thickness which will produce the same effect as that of the dual wheel assembly. So, this conversion of a dual wheel to a equivalent single wheel load we will discuss in this lecture. So, as I said, based on what is the criteria that you use for this conversion you have different approaches.

The first one is a equal vertical stress criteria by Boyd and Foster and then you have an equal vertical stress criteria by Boussinesq's theory by Foster and Alvin and then there is a equal vertical deflection criteria then equal tensile strain criteria. So, in all these criteria, what we assume is that the single wheel as well as the dual wheel assembly will have the same contact radius. Suppose a is the contact radius of the dual wheel, then the equivalent single wheel load also will have the same contact radius but the pressure exerted by these two will be different. Whereas in this approach, the fifth one, the criteria is based on a equal contact pressure that is the radius of the dual wheel assembly as well as the single wheel will be different whereas both of them will have the same contact pressure q. And the last one is rather than using a same contact area or a pressure this is based on an equivalent contact radius which will give you the same effect as that of the dual wheel. So, these are the various approaches by which an ESWL is computed we will see this one by one.

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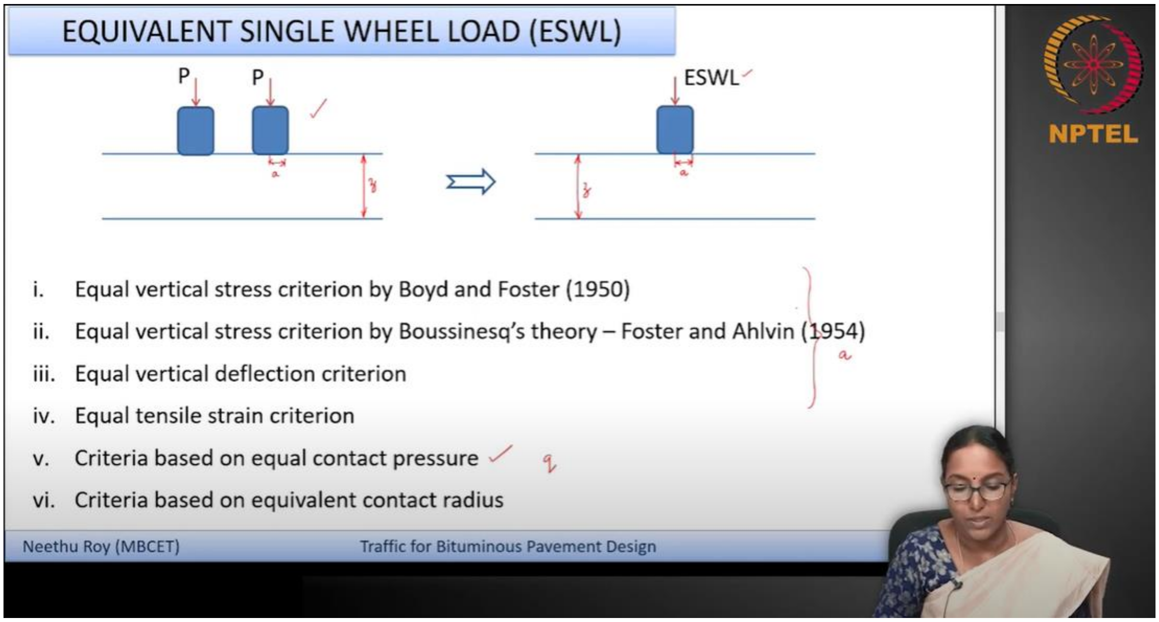


So, the first one as per Boyd and Foster, is the equal vertical stress criteria. So, the idea is based on the stress that is imparted by each one of these loads at various depth of the pavement. So, this is the dual wheel assembly you see here and you are going to convert it to a equivalent single wheel load. So, the stress distribution from these two wheel loads is plotted here. So, you can see, this is the first wheel load. Let that load be denoted as $P_d$ and this is the next wheel of the dual wheel assembly again the load is noted as $P_d$. So, the load is $P_d + P_d$ and $d$ denotes the clear distance between the two wheels and $S_d$ represents the center to center distance between the two wheel loads. Now, this picture shows a pavement. So, this is the pavement surface and the depth of the pavement is marked like this and these two lines indicate the stress distribution. So, as you can see here, up to a depth of $d/2$, that is a clear distance by 2, we see that these stresses from the two wheels do not overlap. So, for any depth of the pavement which is less than $d/2$, the equivalent single wheel load is $P_d$ itself, because there is no overlapping effect due to the adjacent wheel. Whereas, when you consider the depths which is greater than $d/2$, you see that the stresses start overlapping and when it reaches a depth of $2S_d$, there is a complete overlap between the two stresses. So, if I consider any point say B here, there will be stress influence due to this load as well as this load. So, the equivalent single wheel load at this point will be twice $P_d$ or it is $P_d + P_d$, that is the effect of both the wheel loads. So, it is written here for any depth which is depth of pavement z which is less than $d/2$, the ESWL will be half of the dual wheel load and for any depth which is greater than $2S_d$ the equivalent single wheel load will be the total load which is $2P_d$.

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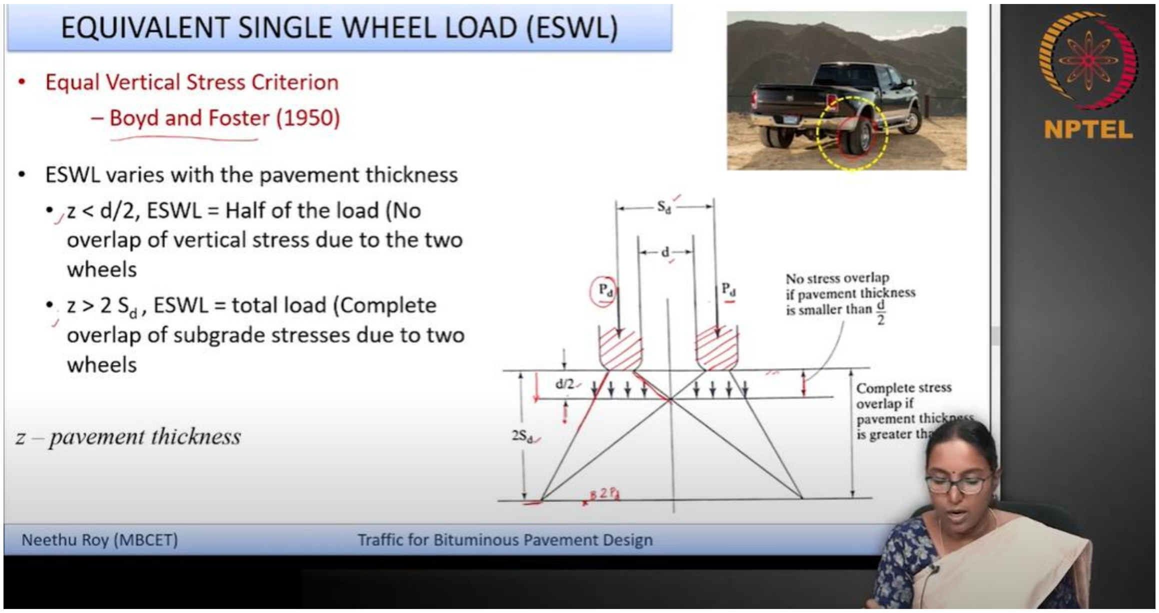


Now, for any depth of pavement which is in between these two values you can find, it from a linear interpolation of this data. So, how we can do is, you can draw a log-log plot as shown here. The y axis is in the log scale, the equivalent single wheel load and the x axis represents the depth of the pavement in log scale. So, you can get two points as we discussed now in this plot. So, this is point A which is at a depth of z equal to $d/2$, the equivalent single wheel load is $P_d$, that is, half of the dual wheel load. And then at a depth of z equal to $2S_d$, you get this point B wherein the equivalent single wheel load is the total dual wheel load which is $2P_d$. Now, you can join these two points with a straight line, so that, you can find the equivalent single wheel load for any depths in between, you can directly read the equivalent single wheel load from this graph. So, as shown in the picture any depth which is greater than $2S_d$ your equivalent single wheel load is $2P_d$ and for any depth which is less than $d/2$, your equivalent single wheel load is $P_d$. So, this, you can plot these two points in a log-log scale and you can find the equivalent single wheel load corresponding to any pavement depth. Or you can express this graph in terms of an equation as in the figure. You can directly use this expression also to find the equivalent single wheel load by Boyd and Foster method.

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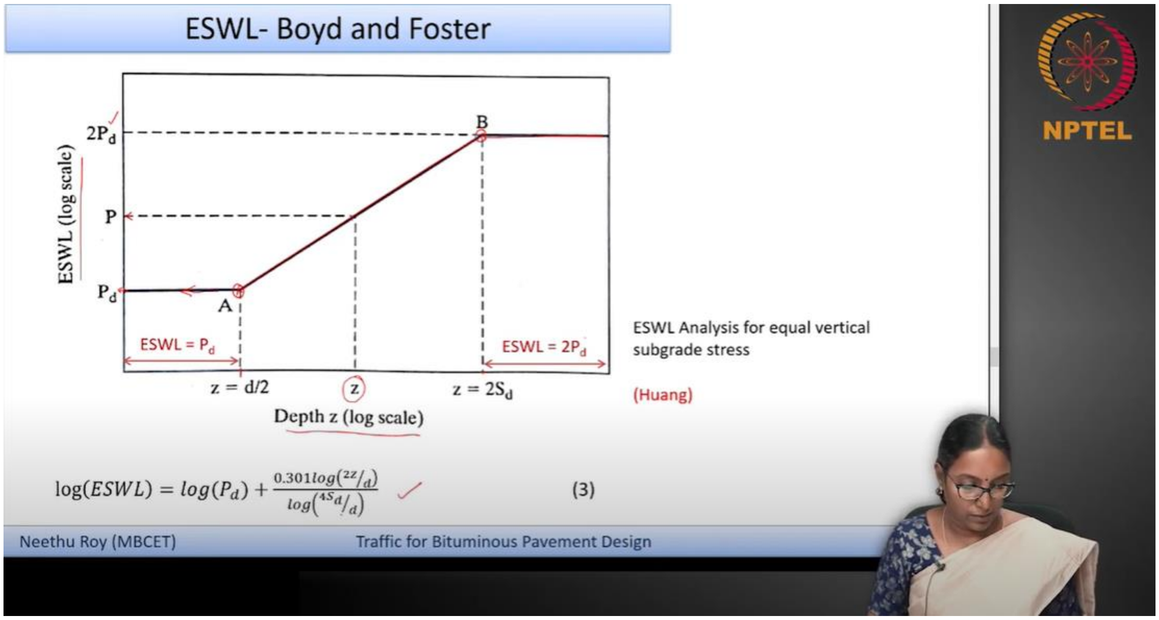


Now, the same approach can be extended to find the equivalent single wheel load for a dual tandem wheel load assembly. So, you see here, this is a dual tandem wheel, so this is the first axle and this is the second axle, so this is a tandem axle with both sides you have two wheels each so this is a dual tandem wheel. Now, using the same approach first of all, you need to find the distance between the center to center of the diagonally opposite wheels and this is marked as $2S_1$. Now, from a similar approach of the stress distribution, it is found that up to a depth equal to $d/2$ wherein d is the clear distance between the dual wheel assembly here, your equivalent load is P itself considering each one of these is carrying a load of say P. So, up to a depth of z is equal to $d/2$ your equivalent single wheel load is P itself. Now, when the depth reaches more than $2S_1$ where $S_1$ is this diagonal distance, the stresses due to all the four wheel loads will start overlapping so that the equivalent single wheel load is 4P. So, you can get two points A and B in a similar log-log plot, so this is depth z in log and the equivalent single wheel load in log and then you can join them by a straight line and for any intermediate depth z, you can directly read the equivalent single wheel load from this plot. So, this is how a dual tandem wheel load is converted to a equivalent single wheel load on a similar approach by Boyd and Foster.

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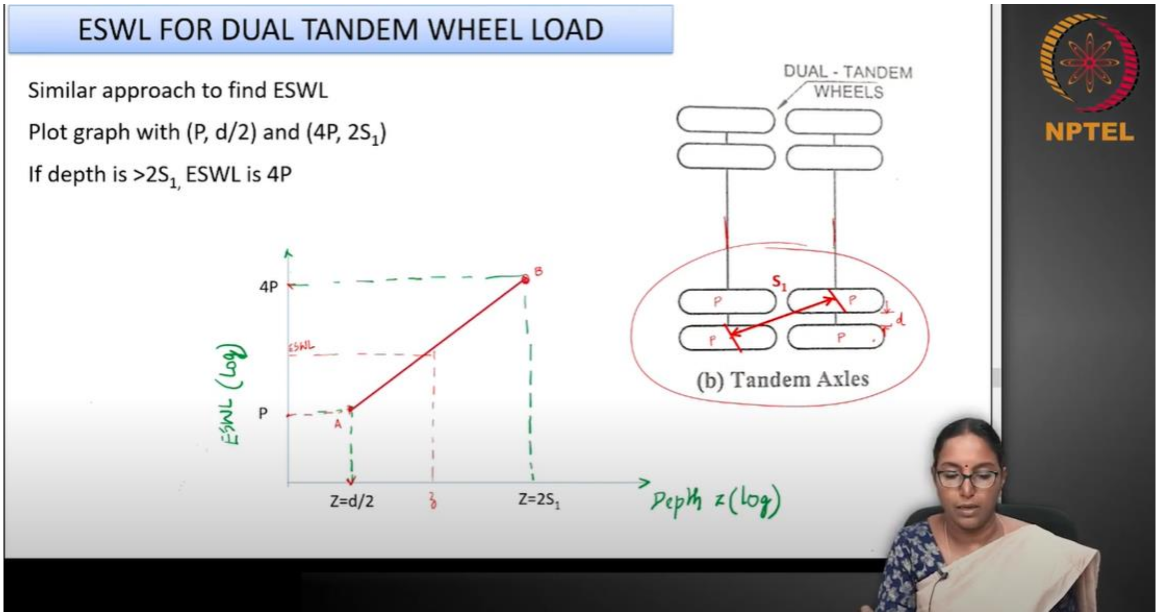


So, we can just discuss this one example, so this is example 6.1 from the reference text book. A set of dual tires has a total load of 9000 pounds and a contact radius of 4.5 inch each and a center to center spacing of 13.5 inch. You are asked to determine the equivalent single wheel load by Boyd and Foster's method on a 13.5 inch pavement. So, essentially you are going to find this by the method of Boyd and Foster for a pavement thickness of z equal to 13.5 inch. So, from the notations that we have been discussing, a is the radius which is equal to 4.5 inch and $S_d$ is the center to center spacing between the two wheels which is 13.5 inch. So, let us see the solution.

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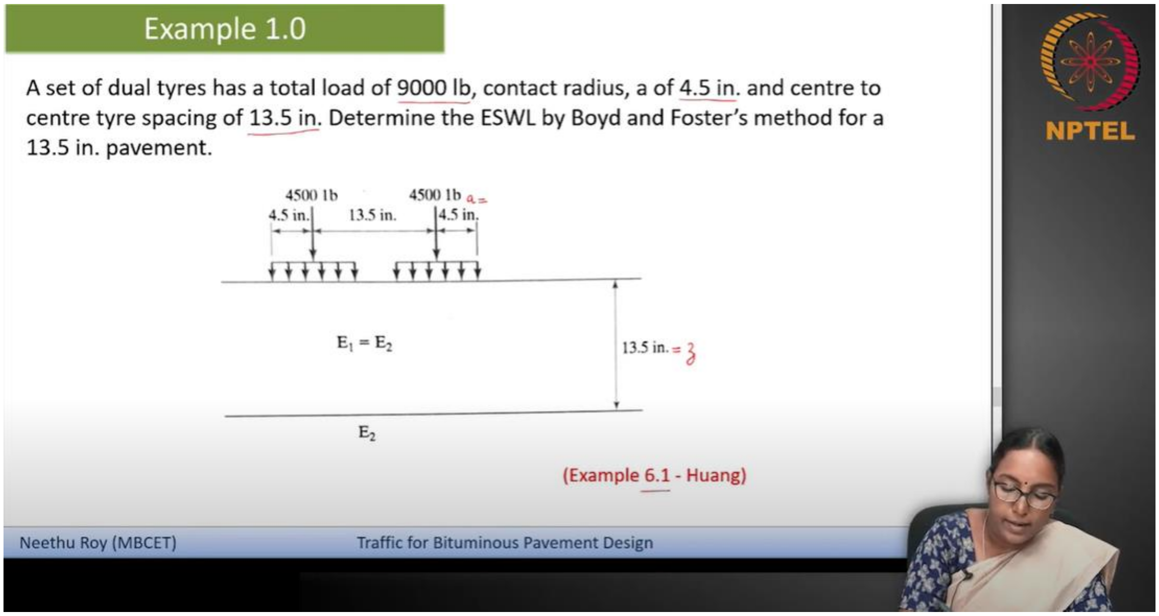


So, $S_d$ is 13.5 and $d$ is 4.5 inch. You can plot it in the log-log scale. So, this is $d/2$ which is 2.25 inch and corresponding to $d/2$, your equivalent single wheel load is half of the load which is 4500. So, this is the in the log scale, it is plotted in $10^3$ pounds. So, that is why it is marked as 4.5 here. So, you got the point A and then the second point is for a point of $2S_d$ which is twice 13.5 which is 27, the corresponding equivalent single wheel load is 9000 pounds, that is the total load. So, you got the two points A and B which can be joined by the straight line and for the 13.5 inch pavement, you can read the equivalent single wheel load from this plot as 7400 pounds. Or you can use the expression as we have discussed, you can directly substitute for z, $S_d$ and $d$ and $P_d$ you can find that the log ESWL is 3.87, you can take the antilog to find the equivalent single wheel load as 7413 pounds.

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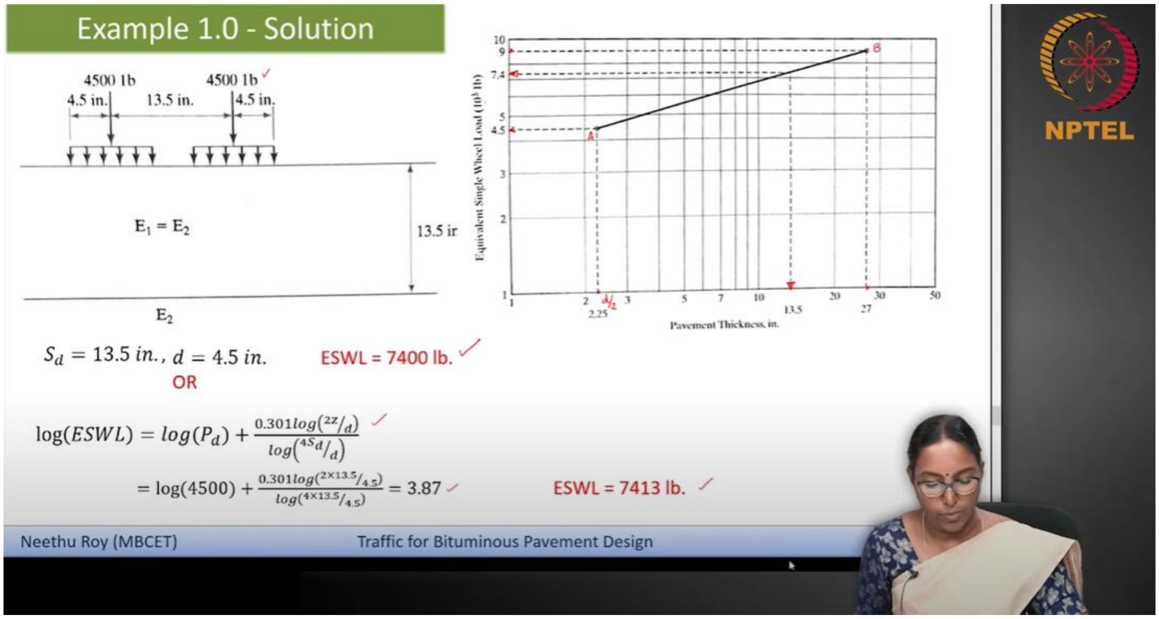


Now, moving on to the second approach, which is the equivalent single wheel load, the equal vertical stress criteria by Boussinesq's theory. The theory that we have just discussed is an empirical method wherein the stress overlap is assumed whereas you can directly use the Boussinesq's theory to find the vertical stress at any depth and that can be used to compare the dual wheel assembly and get its equivalent single wheel assembly or single wheel load. So, this is a plot which is already discussed by Professor Murali Krishnan during the stress analysis part, we are familiar with this. So, this is a Foster and Alvin chart for finding the vertical stress coefficient which is $\sigma_z/q$ where $\sigma_z$ is the vertical stress at any depth z and q is the contact pressure. This is expressed as $\frac{\sigma_z}{q} \times 100(\%)$ and the y axis is $z/a$ where z is the depth of the pavement and a is the contact radius and each of these plots is for different $r/a$ values where r indicates the distance from the center of the load to the point where the stress is computed or the horizontal distance from the load to the point where the stress is computed. Now, what we are trying to find is an equivalent single wheel load for the dual wheel assembly which will have the same vertical subgrade stress. So, the vertical subgrade stress due to the dual wheels can be equated to the vertical subgrade stress due to the single wheel. So, from the stress factor, suppose I get this stress factor for a dual wheel and get that multiplied with the stress or multiplied with the contact pressure of the dual wheel we will get the vertical subgrade stress due to the dual wheel assembly which is equated to the vertical stress due to the single wheel. So, as you see here, this is the stress factor for a single wheel which is estimated from this plot multiplied by the contact pressure because this stress factor is expressed as $\sigma_z/q$. So, you can multiply it with the contact pressure of the single wheel, so that you will get the vertical subgrade stress due to the single wheel. So, the vertical subgrade stress due to the single wheel is equated to the vertical subgrade stress due to the dual wheel. So, this is the expression.

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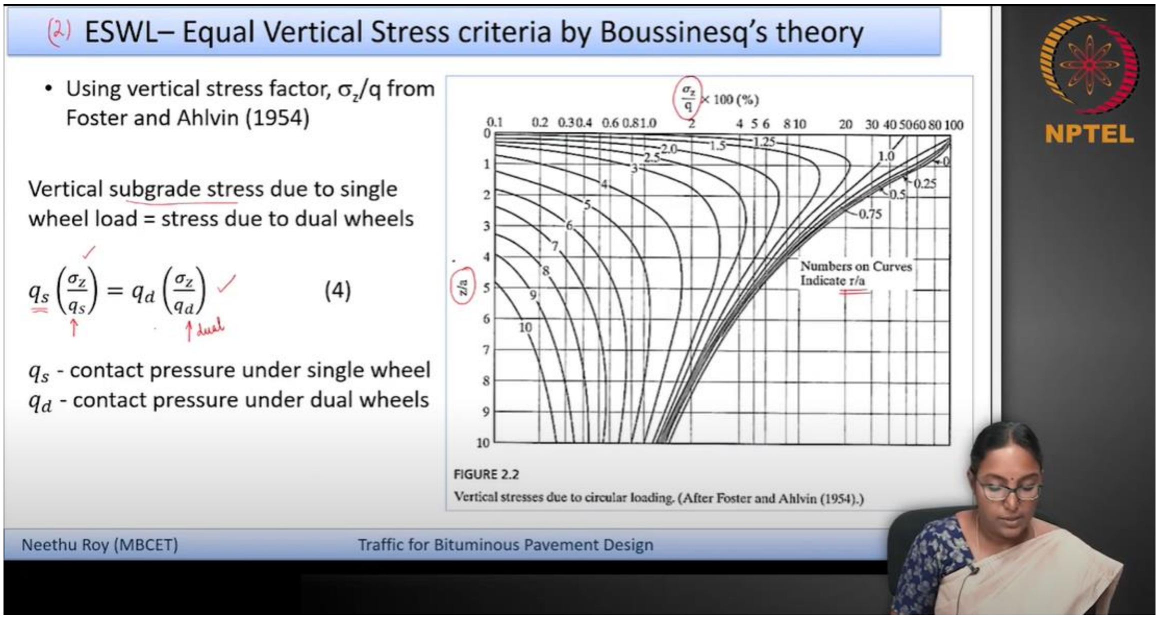


Now, how to find the vertical stress due to the dual wheel? So, I have just plotted, this is taken from Huang. Let us see how this vertical stress factor for a dual wheel can be obtained. So, the first figure here is the single wheel load, let $P_s$ is the single wheel load or your equivalent single wheel load which we are trying to estimate having a contact radius of $a$, then you are comparing the maximum vertical stress in both cases. So, in the case of a single wheel load we know that the maximum stress happens in the axis of the load. So, if z is the depth of the pavement the maximum subgrade stress will be at the point A which can be directly noted. Whereas in the case of a dual wheel assembly, so this bottom figure shows a dual wheel assembly. So, this is the first wheel and this is the second wheel having a load of $P_d$ and $P_d$ each one is having a radius of a. Now, if you consider these two loads here for a depth of z, you want to find out where is the maximum stress and what is the maximum stress. So, in order to do that, you have to consider three locations where there could be a chance of maximum stress. One is at the center of the first load, so this is one point and the second is midway between the two loads. So, this is point number 3 and the third point is a point which is midway between the first point and the third point, so this is point number 2. So, you have to find the stresses at point number 1, 2 and 3 and then see which one is the maximum and that maximum value has to be equated to the one due to the equivalent single wheel load. Now, the point here is how to get the stresses due to two wheels at the point 1. So, what you do is that, what is the stress factor due to the left load, let me call this as the left load and this is the right load. You can find the stress factor due to the left load at point 1 and the stress factor due to the right load at the point 1 and this can be superposed together or added together to find the stress factor at point 1. Similarly, stress factor at point 2 and stress factor at point 3 can be determined in the case of a dual wheel and of the three you can consider the maximum for this comparison.

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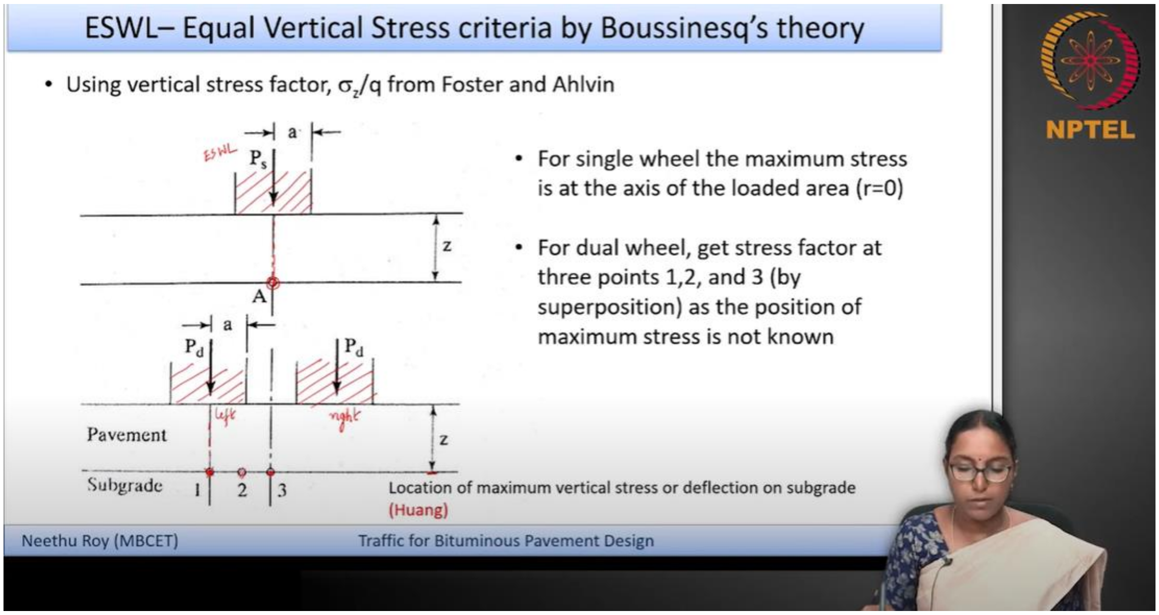


So, the maximum stresses due to the dual is equated to the stress due to the single and you can take the ratio of $q_s$ by $q_d$ which is the stress factor due to dual by stress factor due to the single load. And since they are assumed to have the same contact radius, the contact pressure is proportional to the wheel load. So, instead of writing this contact pressure, you can write it as $P_s$ by $P_d$ where $P_s$ indicates the equivalent single wheel load or the single wheel load and $P_d$ indicates the load on one of the dual wheel loads. So, what you have to do is get the stress factor for the dual wheel and the stress factor for the single wheel load. So, from this ratio you can get the equivalent single wheel load.

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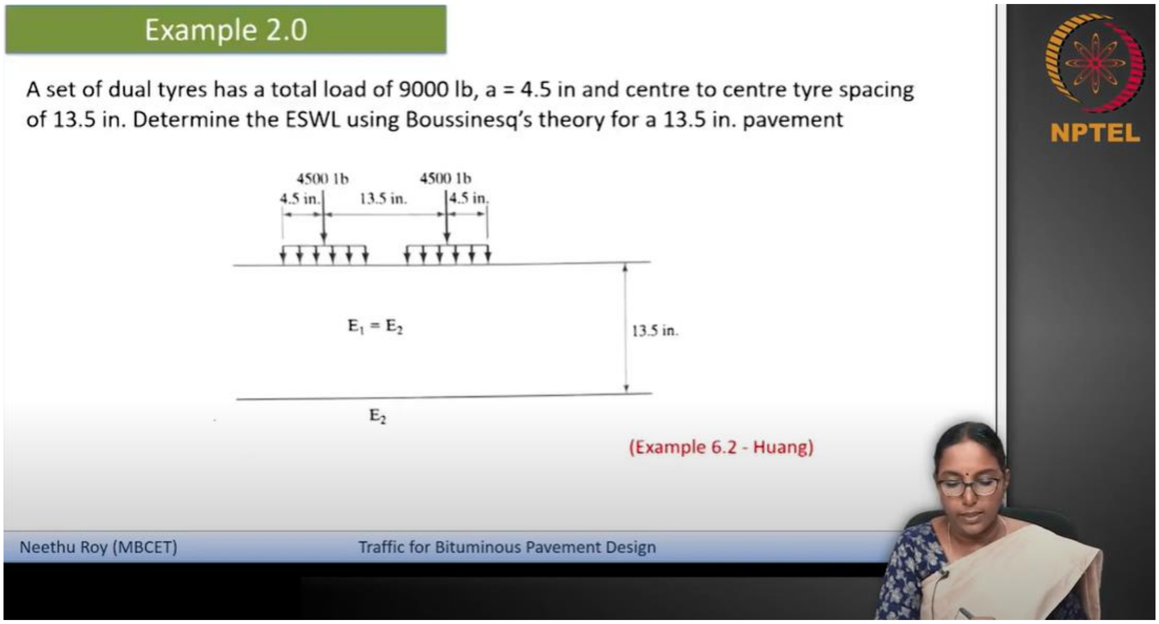


So, let us work out the same problem which was discussed earlier using this Boussinesq's approach of equivalent single wheel load. So, as already mentioned, this is two dual wheels of 4500 pounds and 4500 pounds with the center to center spacing $S_d$ of 13.5 inch and the contact radius $a$ as 4.5 inch and you are considering a pavement of thickness z is equal to 13.5 inch. And you have the modulus of this layer as well as the subgrade as equals which means that you are considering a homogeneous half space. So, this is same material throughout.

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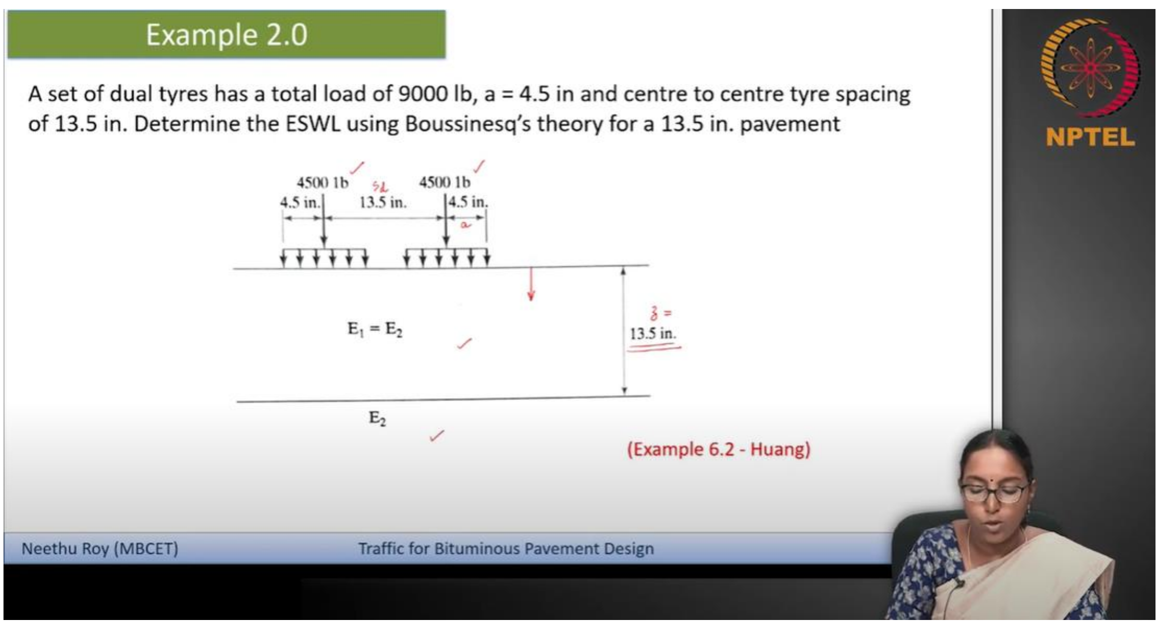

So, first let us analyze the single axle. Suppose you have only one wheel, the maximum stress happens at this point say $a$ and let us see what is the stress factor at this point. So, at this point, the radial distance r from that point is 0. So, the $r/a$ value is 0. So, let me consider it as a left wheel. So, $r/a$ value is 0. Now, for this assembly, the $z/a$ value is,( z is 13.5 and a is 4.5 because you are considering the single wheel as well as the dual wheel are having the same contact radius), so, your $z/a$ is 3. So, for an $r/a$ value of 0 and a $z/a$ value of 3, let us look at this chart and get the $\sigma_z/q$ value. So, each value written on the graph indicates the $r/a$ value. So, the last chart here or the last line here represents the $r/a$ of 0 and the $z/a$ of 3. So, this is 3. So, when you look at this point, you see that the value is somewhere here. So, it may be somewhere close to say a value of 14 or 15. So, here it is written as 0.143. You may wonder how that you can get a value of 0.143 from this chart. So, this is essentially taken from the KENLAYER analysis. You can use a KENLAYER which is already discussed in this course and you can use the KENLAYER to arrive at these factors. So, from that you have noted it as 0.143. So, if you are using the chart, you can directly straight away take that value as what you read from this chart as 0.14. So, essentially why it is 0.14 is that because the value is multiplied by 100 in percentage. So, whatever value you note here, you divide it with100 to get the stress factor. So, for this vehicle, for the single wheel at the center of the wheel at a depth of 13.5 inch, this is a factor which is 0.143. Now, let us consider the dual wheel assembly. So, when I consider the dual wheel assembly, I have to take 3 points. So, the first point is point 1, which is exactly at the center of one wheel load and the second point is, it is marked point 3. So, this is midway between the two wheel loads and the second point is midway between 1 and 3. So, this is point 2. So, I need to find out what is the stress factors at point 1, point 2 and point 3 due to both the wheels. So, this is the left wheel and this is the right wheel. So, this is entered in this tabular column here. So, these are point numbers 1, 2 and 3 and you have written the left wheel and the right wheel. So, let us consider point number 1. So, point number 1 for the left wheel, r distance is 0. So, $r/a$ is 0 and $z/a$ is 3 as already discussed and the stress factor is 0.143. And as far as the right wheel is concerned, the distance of that load to the point 1 is exactly 13.5 because the load acts here and to the point 1 the horizontal distance is 13.5 or the r distance is 13.5. So, the $r/a$ becomes 13.5 by 4.5, which is 3. So, for that $r/a$ of 3 and $z/a$ of 3, you can again get from this chart. So, you see here this is $r/a$ of 3 and this is $z/a$ of 3. So, it cuts here. So, somewhere this is the value which is 3. So, divided by 100, 0.03 is the value. So, you see here that this is the stress factor. So, the stress factor is 0.03. Likewise, you have to consider point 2. So, for point 2, your $r/a$ for the left load, it is 0.75 because this radial distance is this much and divided by a will give you 0.75. And for the right load, it is from the center of the load to the point 2 and divided by a will get it as 2.25. So, for $r/a$ of 0.75 and 2.25 and for the $z/a$ of 3, you get the stress factors from the chart which is written here. Likewise, for the point 3. Now, for the dual wheel, you have to sum up the left wheel and the right wheel. So, which is summed up here and at point 1, the stress factor is 0.173, at point 2, it is 179 and point 3, it is 0.176.

You have to take the highest of this. So, which means that the highest stress factor is coming at the point 2, which is 0.179. So, as discussed, the first if you consider only a single wheel, the stress factor comes to around 0.143. And if you consider both the wheels, you have to see point 1, 2 and 3 where you get the maximum and the maximum value that you get is 0.179. So, you got both the stress factors. Now, the stress factor due to dual divided by stress factor due to the single load multiplied by the single load, will give you the equivalent single wheel load as per this equation. So, I am discussing about this equation. So, $P_s$ is equal to $P_d$, that is one of the dual wheel into stress factor due to dual divided by stress factor due to single. So, this is how we compute using the equal vertical stress criteria by Boussinesq, you got the value of 5630 pounds.

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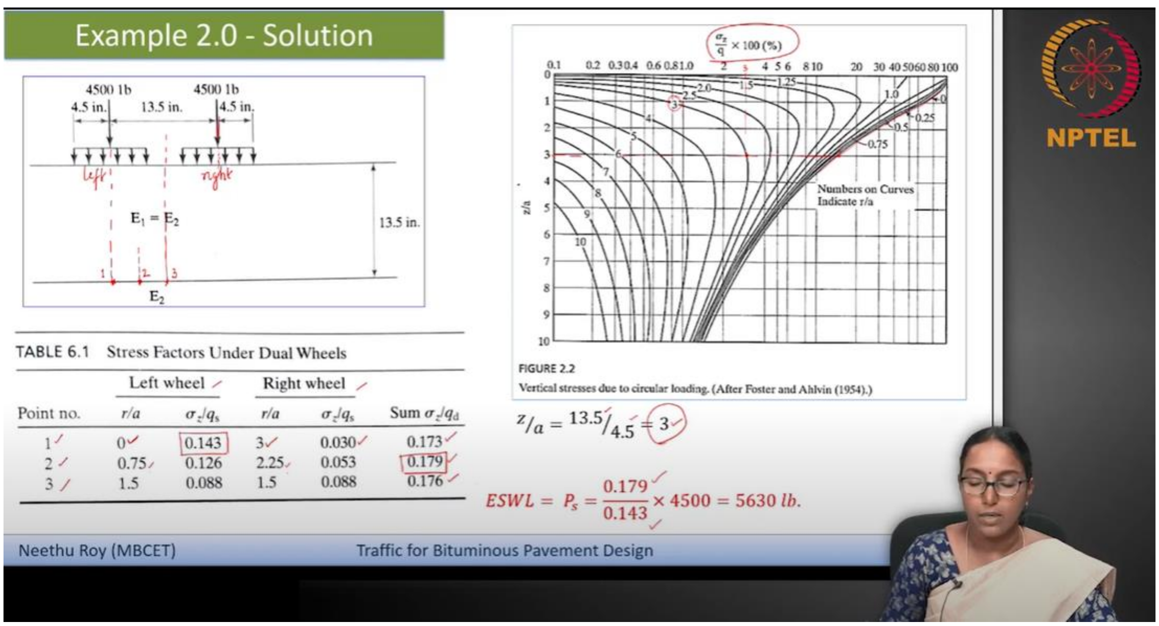


So, just an observation from these two methods that we have discussed just now, the equivalent single wheel load factor from the Boyd and Foster is more empirical in nature because we are assuming that the stress distribution will be overlapping beyond a depth of $d/2$ and so on. So, that essentially will depend upon the payment thickness that you are considering and the loading configuration. Whereas the Foster and Alvin method using this Boussinesq chart will be more theoretical in nature, but what is seen is that we have seen from the example, the same example that the Boyd and Foster method has given a larger ESWL value of close to 7400. Whereas, the second method has given a smaller ESWL value. So, whether you use the empirical method that is the first method that again is going to give you a safer design. So, these are the two approaches of finding ESWL.

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# Observations

- ESWL by Boyd and Foster was empirical in nature.
  - Depends on the pavement thickness and the loading configuration

- Method by Foster and Ahlvin using Boussinesq's stress distribution is more theoretical

- Boyd and Foster method gives an ESWL greater than the Boussinesq approach and hence on the safe side



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