Analysis and Design of Bituminous Pavements

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Lecture - 31

Reliability in Pavement Design - Part 01

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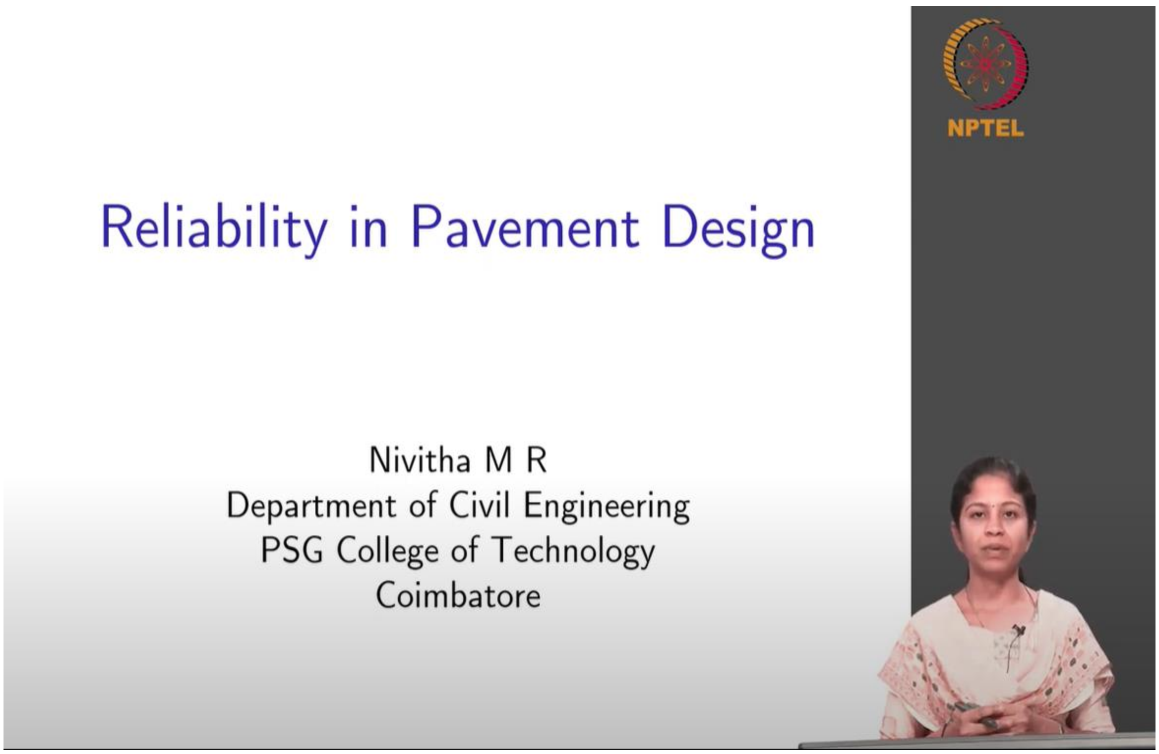

Hello everyone, in this lecture we are going to focus on reliability in pavement design. So what is the term reliability? We would have heard this term in a different context. So reliability is usually used to say how sure we are about something or how reliable is our assumption about a particular process. It is usually associated with the process or a system. So a process or a system will have one or more inputs and there will be a process and we will have one or more outputs. So usually when we define the process theoretically there will be a lot of assumptions that we are making about this particular input parameter or the set of input parameters. Then we go through the process.

For the considered input parameters we will be obtaining some output. But usually what we observe is that these input parameters are not those specifically that we have considered, but due to the natural randomness associated with any process, there is going to be a lot of variability in these input parameters. Hence the output that we get is not going to be the same one that we had got before. But it is going to vary because of the variability in all these input parameters. So considering this scenario how sure are we about our output? That is kind of defined by this term reliability.

Since I said this term has a lot of definitions and a lot of interpretations, let me formally introduce what reliability is to you. So in this particular lecture, I will be focusing on the overview of reliability. We will define what reliability is, how it is essential or how it is important in the pavement design process, and how it is considered in IRC 37. In the next lecture, I will talk about how reliability is considered in AASHTO 1993 design procedure because this particular design procedure starts with assuming a reliability level. So how is it considered in AASHTO 1993? Then we will talk about reliability in AASHTO 2004 or which is commonly called the ME-PDG design procedure. Then there are certain other reliability approaches wherein we can have advanced considerations for all the variabilities that we observe especially with respect to input parameters. So we will see some of those reliability approaches also and then we will summarize.

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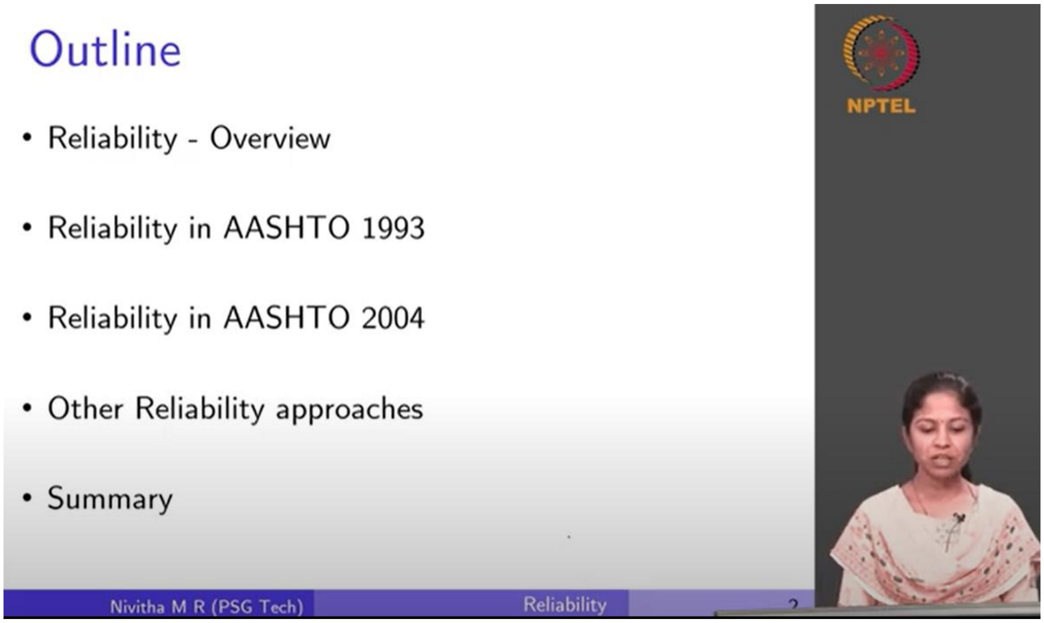

So this is the outline for this overall topic on reliability and as I mentioned. In this specific lecture we are going to talk about the overview of reliability.

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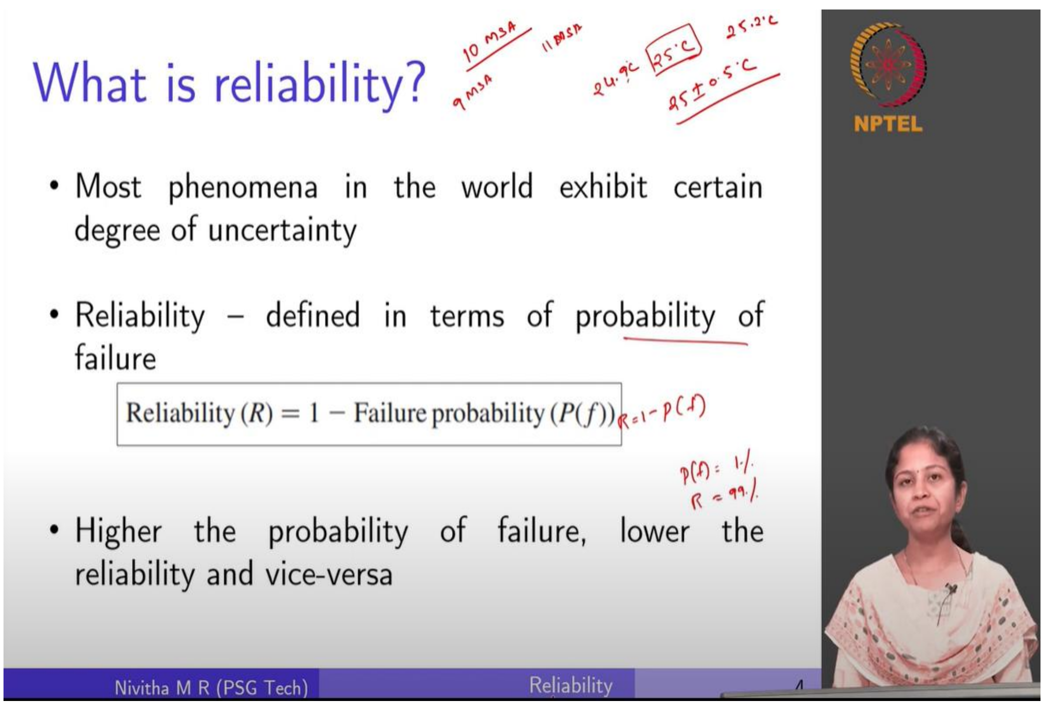

What is reliability? As I said most phenomena in this world will have some degree of uncertainty. We are not exactly sure what we are going to get. Let us say we are performing a test. The test temperature is specified to be 25°C. How sure are we that this 25°C is exactly going to be maintained throughout the test? There might be slight variations in atmospheric conditions. Because of that let us say that equipment is equipped with some temperature control device. So it will adjust the temperature to meet the 25°C. So there may be a few instances of time that this temperature may be 24.9°C or 25.2°C. So there is some variability around this value that I have considered.

That is why if you see most test procedures will specify 25±0.5°C. They consider in for the variability. Let me, let us take another example that is more related to pavement design. Let us say that I am designing my pavement and it is supposed to take 10 million standard axle repetitions of my standard axle load. So we colloquially say it as 10 msa. So let us say I design my pavement to carry a load capacity of 10 msa. Now, will it carry exactly 10 msa? So when I have the first repetition after this 10 msa is exhausted will it fail? We will define what failure is again but will it fail? So let us say there is again defining what failure is going to be slightly complicated for pavement but let us say we are able to define some definite point of failure for a pavement system. So if I can define something like that and if I am able to capture the number of load repetitions at which it is going to fail and we can certainly say that it may not be exactly 10 msa always. It is going to be slightly less or slightly more. So why do we see that variability? So it can fail at 9 msa or it can fail at 11 msa or something less or more. So why do we have this variability? Right now if we recollect the pavement construction process, so we have a design as I said earlier. We have a lot of input parameters that we use in design. So let us say we have a modulus, we have a thickness, poisson's ratio, then we have traffic parameters and so many input parameters.

When we are designing, we give one single point value to all these measurements. And based on that, I am computing my critical strain values and for those critical strain values, I am computing the number of repetitions to failure. So what if there is some variation in one of those input parameters? So obviously the critical strain is going to vary and so is the number of repetitions to failure. So now there are a lot of input parameters and each input parameter can vary over a range. So my critical strains are also going to vary over a range and my number of repetitions to failure which is my output is also now going to vary over a range. So every process in this world has a lot of uncertainty and the more the number of parameters that are involved and higher the degree of uncertainty with each of it, the lower is our ability to correctly predict the point of failure. So that is why reliability is usually defined in terms of the probability of failure. So we know what is the probability of failure and if I can say that as P(f), reliability which is nothing but 1 minus the probability of failure. It is shown in equation below.

$$R = 1 - P(f)$$

See if a system has a higher probability to fail, then it is considered to have a lower level of reliability. If I have designed a process which has only 1% as the probability of failure. So I have considered all the scenarios let us say, and I am able to say that 99% I am sure that it will deliver the desired performance. Then my probability of failure is only 1%, my reliability is going to be 99%. So when I am very, very sure that the probability of failure is low. I am saying here that I am very sure that is what I call as reliability. When my probability of failure is less, my reliability level is high, okay and vice versa. So that is why we say higher the probability of failure, lower the reliability and vice versa. Now let us look at some standard definitions as to how this reliability is defined.

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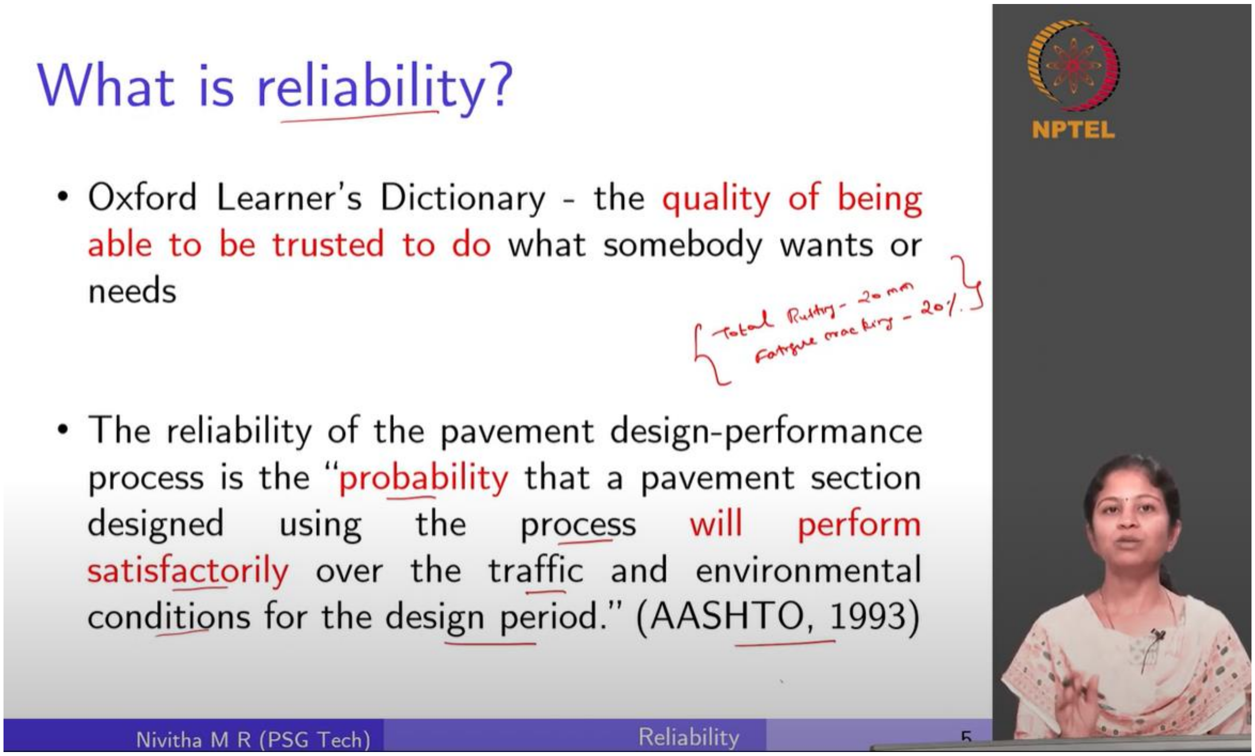

So if I look into Oxford's Learners Dictionary, this is what is the meaning that is associated with the term reliability. It is the quality of being able to be trusted to do what somebody wants or needs you to do. So again if I translate it to the same pavement design example, I design a pavement, I want it to operate without any failure for up to 10 MSA load repetitions, how much is it going to meet that promise. That is what reliability is. So if I am 100% sure that it will carry 10 MSA, then my reliability of that particular pavement design is 100%. But if I am only 50% sure, I know that there is going to be a lot of variability in my input parameters, I know that there is going to be lot of variability in the construction process, so thickness, modulus, everything is going to vary around, then I am not very sure that it is going to carry that 10 MSA or not. In that case, my reliability level lowers. So it is the quality of being able to be trusted to do how much trust I have in that particular pavement design process so that it will carry that particular load. So AASHTO has specifically given, again AASHTO has many definitions.

When I am talking about the AASHTO 1993 design procedure, I will go through all those definitions, but I have given one relevant definition to motivate reliability from the pavement design perspective. The reliability of the pavement design performance process. So it is a design which is associated with performance. We are expecting some degree of performance from this particular system. The reliability of pavement design performance process is the probability that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period. There are a lot of terms that we have to look into critically in this particular definition.

The first is probability. So the first thing is that a pavement section designed using the process based on a particular design procedure that is being followed here. It could be a standard procedure like IRC 37 or AASHTO 1993 or the recent MEPDG version of AASHTO. So there could be some particular design procedure. So using a particular design procedure, it will perform satisfactorily. So what is this satisfactorily? For what conditions are we designing the pavement? Let us say I want to limit total rutting to 20 mm and I want to limit fatigue cracking to 20%. Let us say this is what I consider as satisfactory performance and I am going to use the design process to meet these criteria. So this is what I consider during my design process and this is going to be my satisfactory level. Then it should meet these conditions over the traffic and environmental conditions. Again, we have different traffic on the road, we have different environmental conditions for the geographic location. Considering all this, it should perform satisfactorily over the design period. The design period is the period for which we consider that it is going to deliver this performance. It is the probability that it will do all these things. So that is what we call reliability.

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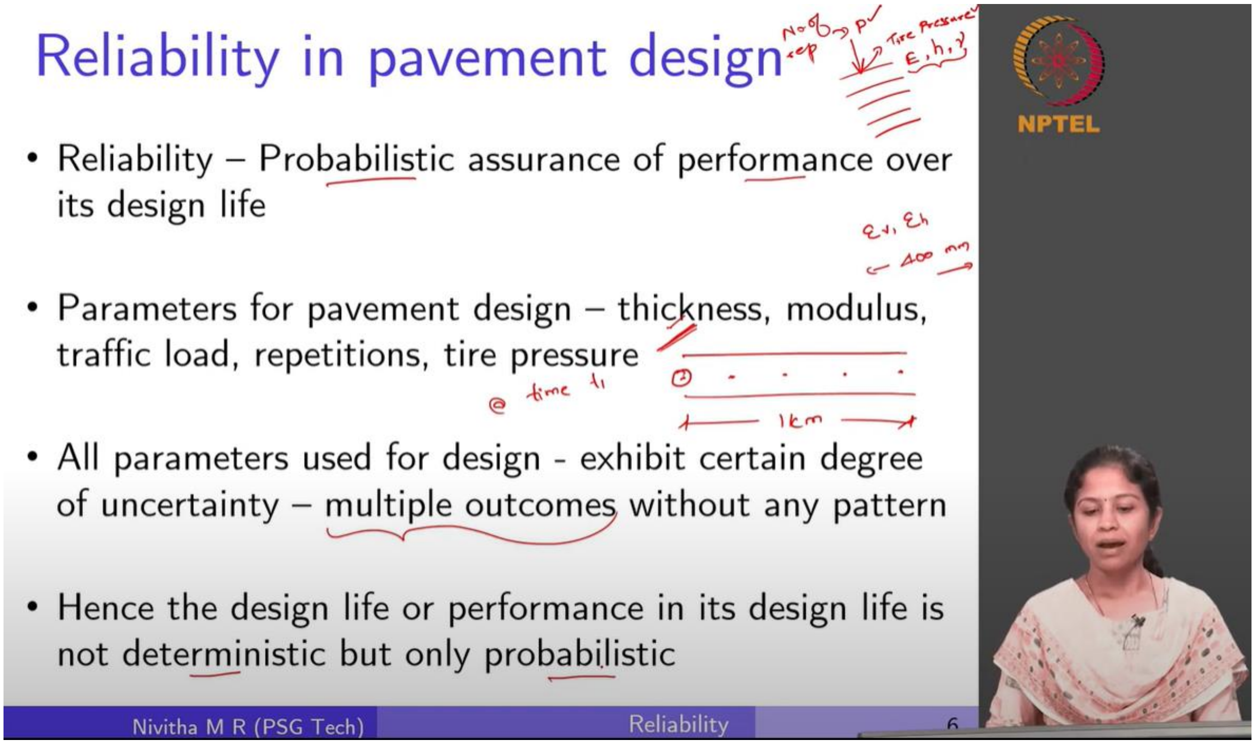

Now if I have to simply put this definition of AASHTO in one sentence, it is a probabilistic assurance of performance over its design life. We are associating a probability to it; we cannot say that we are 100% sure. So we always associate a probability with our design predictions. The probabilistic assurance again this performance is what we assume during our design procedure over its design life.

Now let us say there are a number of parameters that we use for pavement design. Let us typically consider our IRC 37 design procedure. Again we have different layers. So for each layer we specify a modulus value, we have a thickness value and then we have traffic load that is acting on it. We have a load parameter and then we also have the tire pressure of this and then we have the number of repetitions of this load value. These are some parameters that we typically use to compute our critical strain values. In IRC 37 design procedure if you look at it and we also use a Poisson's ratio value. These are the input parameters. Now how much is the variability associated with all these input parameters? We all know that all of these input parameters will have a certain degree of variability. These variabilities can be of different degrees. Let us consider 1 kilometer stretch of pavement. At a given instance of time t_1, let us say I am measuring all these parameters at some 5 points in this 1 kilometer stretch. So I am going to measure all the input parameters, modulus, and thickness. Let us say I am measuring Poisson's ratio, the load that is acting on the pavement for a given vehicle repetition and tire pressure. I am going to measure all these things at these 5 points for a given axle.

So most probably the tire, the vehicle load and the tire pressure might remain more or less identical. But if I am going to measure these 3 parameters which are the modulus, thickness and Poisson's ratio, we know that it is not going to be exactly the same in all these 5 locations. As I said, let us say we have a 400 mm thickness specified for 1 layer, it is going to vary some units on this side and some units on this side. So there is going to be a spatial variation in all these parameters at a given instance of time. Then there is also variation in these parameters with time.

Let us say we take the bituminous layer, as the pavement ages the binder is going to become stiff, there are a lot of phenomena that are going to happen in the bituminous layer. So it is going to become stiff and the modulus value is going to increase. If I measure this particular point at different instances of time, the modulus value is going to increase. So these are 2 different factors that contribute to variability. So we have seen the effect of climate on all these material properties.

We have seen that if I take a particular year, these values are not going to be constant over a year because of the influences of let us say if you take a bituminous layer the temperature parameters or if you take a granular layer the soil moisture related parameters, the modulus value is also going to vary. So there are a number of parameters that contribute to variability in all these input parameters. And these variabilities are associated with multiple outcomes without any pattern. There is no specific trend, let us say if it is a variation like this then we classify it under seasonal variation. But if I am going to measure it at these points, these 5 points, it is going to be random.

So there is no specific pattern that it is going to increase from these 5 different points provided the construction process is uniform over the entire 1 kilometer stretch. So all parameters used for design will have some inherent variability without any pattern and some pattern-based variability over the design period. Hence the design life or the performance of the pavement in its design life is not deterministic we cannot associate one single value to all this variability. It is going to be probabilistic. It is, it can be only said with a certain degree of probability and we cannot 100% certainly say that it is going to be this particular outcome for this process. So that is the concept of reliability that we are using for pavement design.

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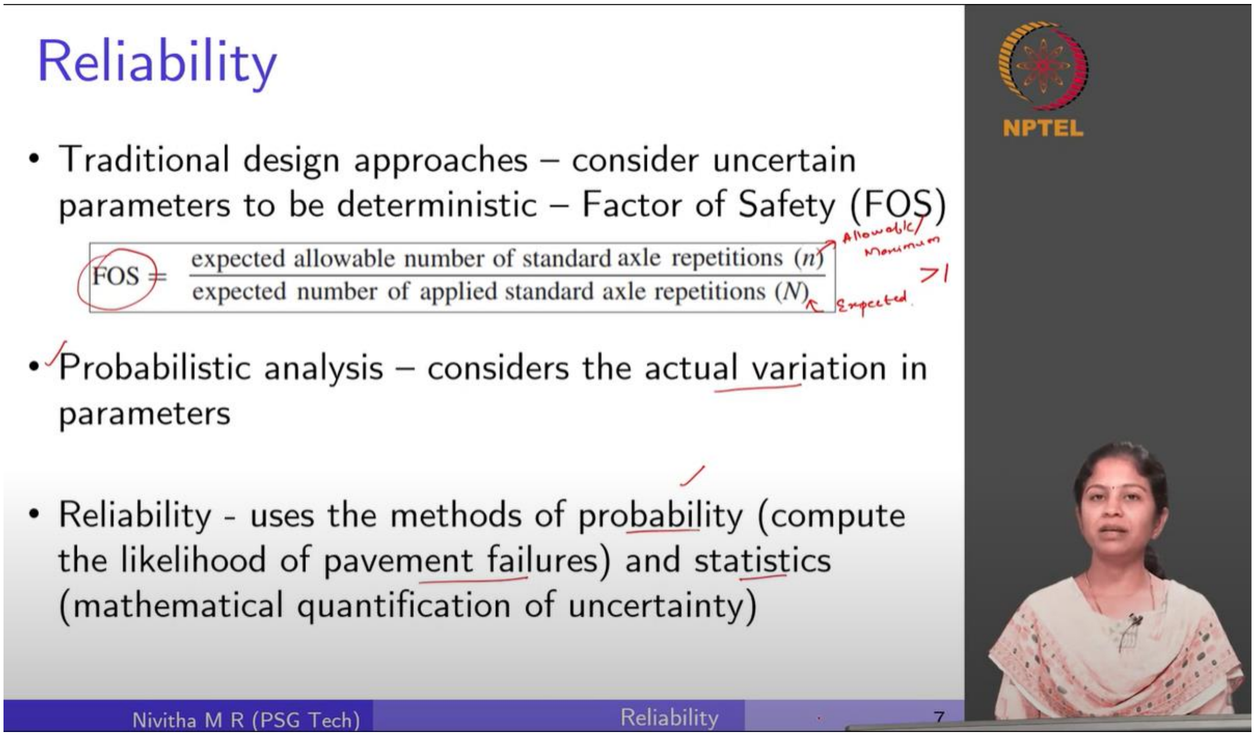

Now how do the traditional design approaches consider this kind of variability? It is usually done through a parameter called factor of safety. So many times when we design, we see what is allowable, let us say we require a particular strength, we see what is the required strength for our case, multiply by a factor of safety and say that we need a material that twice more strong than what is actually required at my location. If I am able to factor in all these variabilities and I am sure that if I am using a higher factor of safety value, then the system is not going to fail in my expected design life. So, we account for these kinds of variabilities by using a factor of safety parameter.

How is this factor of safety defined for pavement? It is the expected allowable number of standard axle repetitions to the expected number of applied standard axle repetitions. So, this is my allowable or the maximum value that my material can take and this is expected or which I am going to observe in my case. So, I divide this, and I get a parameter called a factor of safety and it should be always greater than 1. If we want to be surer that a system should not fail at all, then we resort to using a higher factor of safety value. But again, this factor of safety is only a number. We do not know what factor of safety should be used.

For a pavement of like you know high importance or where you think that the variability is large, we tend to use a higher factor of safety value and wherein we are sure that there is not much variability, we tend to use a lower value. But there is no specific guidance as to what factor of safety should be always used and there is no guarantee that if we use this particular factor of safety, then this pavement is not going to fail at all. It is only an adjustment that we make and that number we allocate that is based on our previous experiences. So, intuitively we feel that if it is of good quality construction and if it is designed considering many parameters, we tend to resort to a lower factor of safety.

It is only intuitively done and there is no guarantee that the pavement will not fail if you use this particular factor of safety. This factor of safety-based approaches has a lot of limitations in it. That is why probabilistic analysis is resorted to wherein the actual variation and parameters are considered and it is inbuilt into the design process itself. So, if we take a particular input parameter, what is the variability that is experienced by this input parameter? It is quantified and those values are actually taken into the design process. So, we can be more certain that the probability of failure will be less when the actual variation of material parameters is incorporated into the design process.

So, this reliability uses the methods of probability and statistics. So, what is this probability? We use probability to compute the likelihood of pavement failure. What is the probability that the pavement will fail? To compute that we use the basics of probability and we use statistics to arrive at the mathematical quantification of uncertainty. So, this reliability is built on the concepts of probability and statistics.

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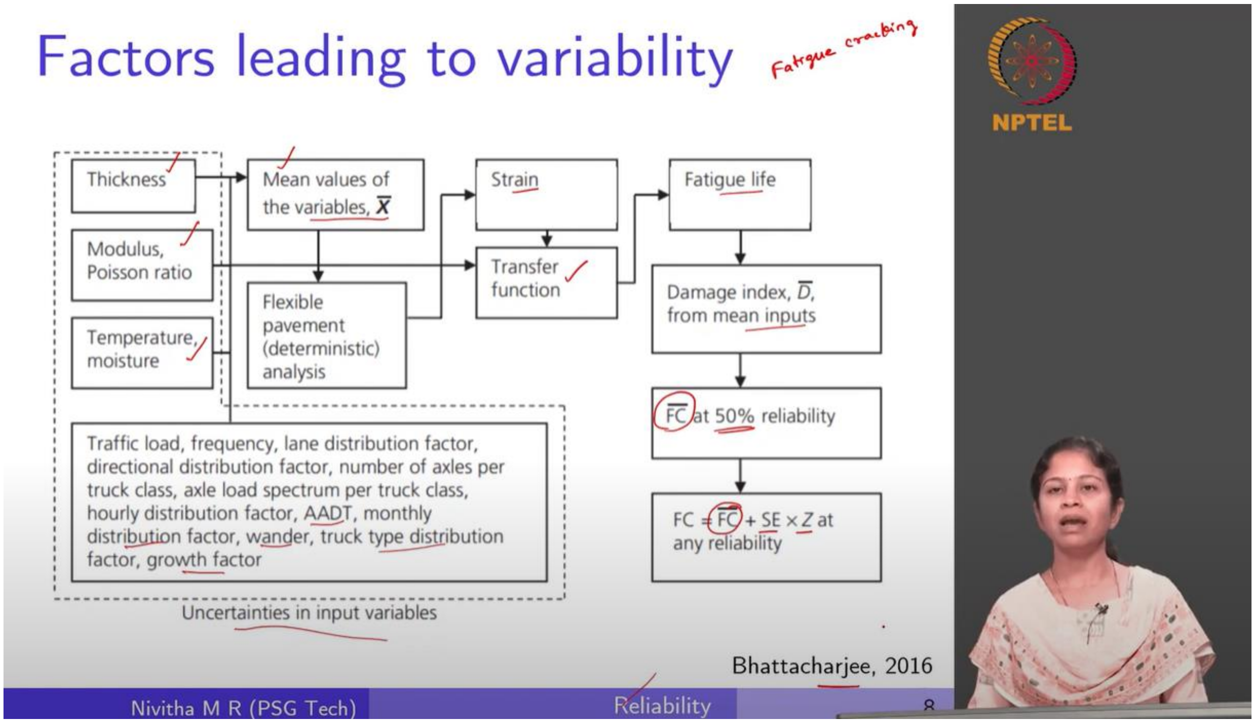

Now let us see the factors which lead to variability in a design process. To illustrate that, I am considering this example from this particular reference. So, it is for fatigue cracking. Let us say that we want to predict fatigue cracking and consider it for our design process. Now, this again involves a number of input parameters as we have been discussing. It involves thickness, it involves modulus and Poisson's ratio, temperature and moisture, and the variation in modulus because of these parameters.

Then there are a number of traffic-related parameters, the load, frequency, lane distribution factor, the directional distribution factor, and the number of axles per truck class which is an approximation that we will be using. When I am explaining AASHTO, I will talk more about this. The axle load spectrum per truck class or in fact you would have discussed all these things in the previous lecture on traffic. The factors are hourly distribution factor, AADT, monthly distribution factor, traffic wander, truck type distribution factor, growth factor. So, there are a number of input parameters that we consider when we do a detailed design with the traffic input parameters.

Now considering all these, you can see there are uncertainties in all these input parameters. Now considering all these parameters, the mean value of the variables is used. So if I have a thickness, let us say I am measuring thickness at 10 points, I get all the 10 values, I take the mean value and I use it for my design process. And the flexible pavement analysis is deterministic. For a given set of input conditions, we get one critical strain value at the bottom of the bituminous layer and one critical strain value at the top of the subgrade for a given set of input parameters. So, it is a deterministic analysis.

Now I take that strain value and input it into my transfer function. So, in some cases, we will also need information on modulus and Poisson's ratio for the transfer function as well. Now from this, we are computing the fatigue life, and from that, the damage index is computed for the mean input value. So, all my inputs are one single measurement, though I have a range over which each of these parameters can vary. So for that input parameter, we are computing the damage index and computing the fatigue cracking.

So, this is said to be at 50% reliability because we are using the mean value. So whenever we perform a design wherein we use the mean value and carry out the design, our reliability is only 50% sure, which means we are 50% sure that it will not fail. But if we wanted any other reliability, then it has to be corrected. So, it is the fatigue cracking at 50% reliability plus standard error (SE) into standard normal deviate.

$$\mathrm{FC} = \overline{\mathrm{FC}} + \mathrm{SE} \times \mathrm{Z}$$

So, what is the standard normal deviate (Z)? I will show you in some time. Okay, so this is how the reliability is considered and it is accounted for other values apart from the mean input parameter. Two or three lectures down, we will carry out an analysis wherein we will consider the actual variability in the input parameters and see how we are able to define the reliability for that particular case.

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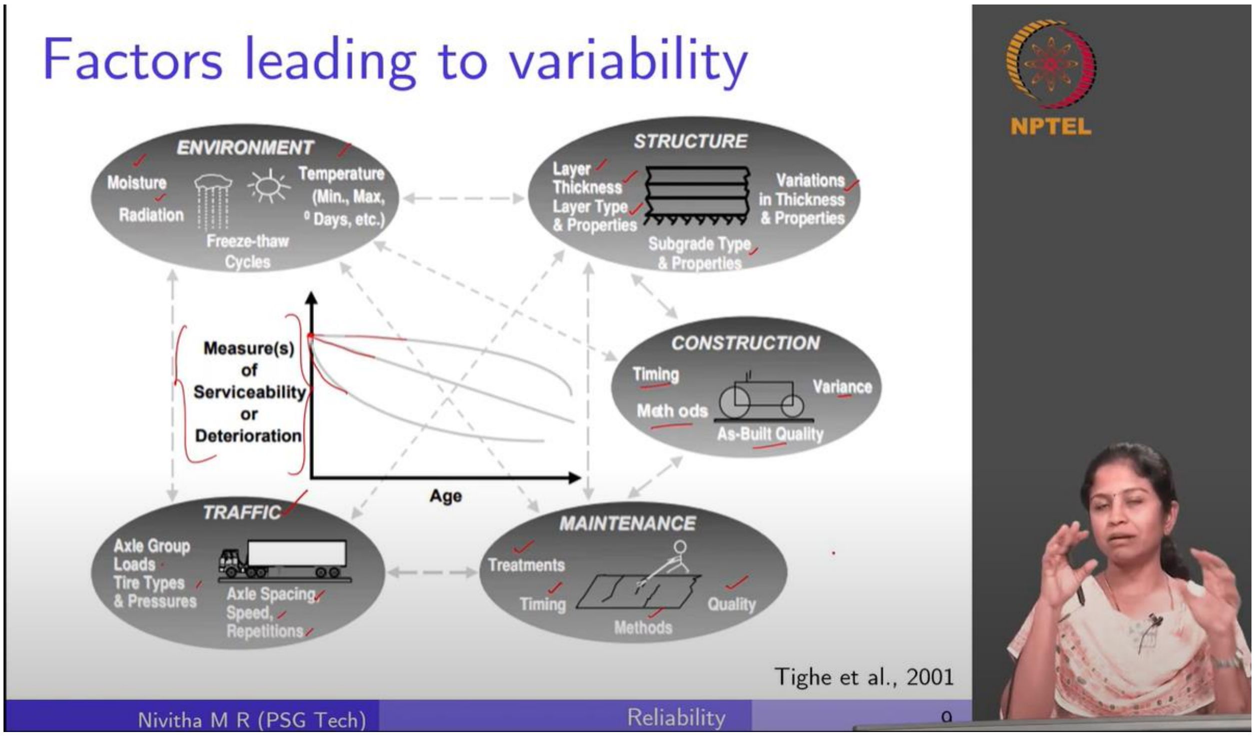

So now let us spend some time discussing the factors which lead to variability and the magnitude of variation that we typically observe in each of these parameters. Some parameters might not vary that much. So is it going to have a big impact on my design? For that we need to know what is the degree of variability or I could simply say it as what is the standard deviation if I collect a set of values for each of these parameters.

So based on that we can say how much the variability associated with the particular input parameter is. If we look at let us say I am starting from traffic, we have an axle group, the load, tire pressures and even the types of tires, axle spacing, the speed in which they travel, the number of repetitions, so like that many parameters associated with traffic. Then we also have environment-related factors, we have moisture, we have radiation, we have a temperature, so these things are going to vary in a random manner. We have already seen the degree of influence exerted by each of these parameters on our modulus values. So once the modulus value changes obviously the critical strains are going to change and might allowable a number of repetitions.

Then we have a structure, so again as we said the type of layer, the type of material that we use, thickness, the properties of each layer, again it is going to vary, and the subgrade type and properties and all those things. Then we also have the construction practice wherein all these design parameters are translated to the field. So, we have the time during which it is constructed, and the methodology using which it is constructed. If I am going to use a very, let us say I am laying an asphalt layer, if I am using a paving machine that has precise control over the thickness and other things, then my layer is going to be more or less uniform. On the other hand, if I am resorting to other methods to lay or wherein I am not sure about the thickness that is being laid, I do not have any automated means, and then there is going to be a lot of variabilities.

So the construction methods also will play a big role. The as-built quality of pavement that we can observe here and the variance that is associated with the process. Similarly, if I am doing some maintenance operation on this, what are the treatments I am giving to a particular location, at what time I am providing those treatments, what are the methods I use and what is the quality of those treatments. So, these things are also going to vary. So my measure of deterioration of pavement, let us say this is the condition of a new pavement that is in an as-built state. If this is the serviceability of that pavement, it is going to deteriorate with age.

How does it deteriorate? It can deteriorate like this or like this or like this. So the manner in which the pavement deteriorates is the combined influence of all these parameters which are discussed here and the manner in which they vary. It is not only the variability of thickness but to what extent thickness varies or to what extent the modulus varies, which is usually quantified by its standard deviation right. So the measure of serviceability is the combined influence of all these input parameters which are given here. So if I have to specifically you know, like separate them into individual parameters, it could be given something like this okay.

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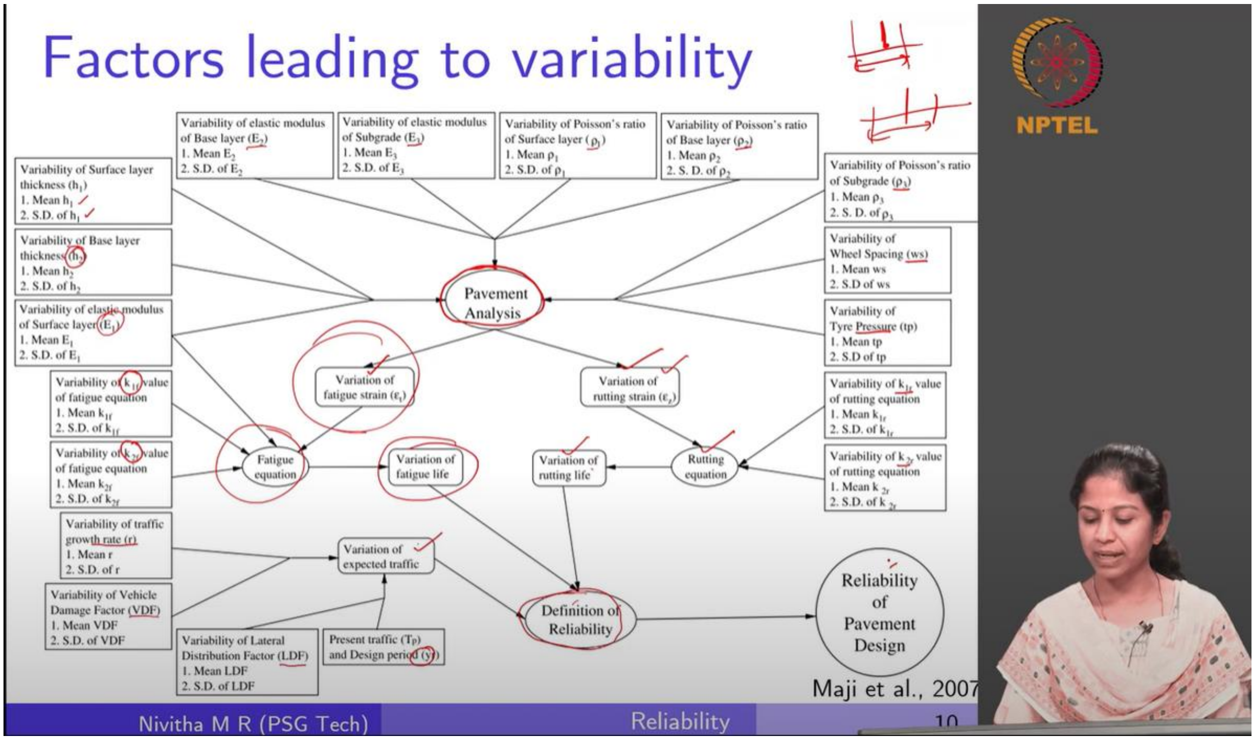

Do not worry about it, it is not that complicated. Once when you understand what each of these boxes is, you will be able to understand it is nothing but a summary of all the variabilities that I have been discussing so far. So if you look at pavement analysis, this is our crux. It is going to depend on a number of parameters. So what does it depend on? It is the variability of the surface layer. So I have a mean value and I have a standard deviation if I am going to collect a number of points at which I can measure h_1.

Similarly, I have variability of the base layer which I call it as h_2. So I am going to quantify that using a mean value and a standard deviation value. Similarly, I have variability of elastic layer modulus of surface layer, so E_1 value. Again for each of it, I will be able to associate a mean and standard deviation. Now if I use a fatigue equation, then we have some constants in the fatigue equation that you are aware of. So the value of the constant k_{1f}, again if you have another constant is k_{2f}.

Then it is the variability of traffic growth rate r, variability of vehicle damage factor VDF, we all know what VDF is, the variability of lateral distribution factor, what are the present traffic that is observed at the given moment, and the design period that is considered. And we also have variability of modulus of base layer E_2 of subgrade E_3, again Poisson's ratio of surface layer, Poisson's ratio of base layer, Poisson's ratio of subgrade. Then we also have the wheel spacing right, we have if you take a dual axle we have wheels, so what is the spacing of these wheels and even the axle spacing you can consider here, variability of tire pressure. If you use the rutting equation, then we have two constants again k_1 and k_2 in the rutting equation. So, what are the constants for the rutting equation? If you typically consider a design methodology something similar to IRC, even in that kind of a design methodology we will have these many parameters and each of them will have a mean value and a standard deviation which means it is not one point measurement like this, but it is going to be a measurement over a range, it can vary anywhere between the range.

Now for this, considering all this variability if I input it in pavement analysis there is going to be variation in fatigue strain, and variation in rutting strain. So, this epsilon value along with the modulus and the constants is going to influence my fatigue equation and therefore my fatigue life is going to vary. Similarly, all these parameters along with the variation in strain are going to influence my rutting equation, so I am going to have a variation in rutting life. Later I will show you some plots wherein you can see that if I use the probability-based approach and if I consider the variability of all these input parameters my output is not going to be one life that I will be getting for my pavement system, but my pavement life can vary over a range as in the case of these input parameters. I will show you some plots, I will refrain from drawing a distribution at this point in time, let me show you some data and then we will see how this varies.

Then we have again the expected traffic rate that you can expect on your pavement, this also varies depending on the growth rate, VDF, lateral distribution factor, and all those things. Now considering the variation of traffic, variation of fatigue life, and variation of rutting life we will be able to define the reliability of that particular pavement system. So, that is what we get as reliability for the pavement design. If you want to carry out a very simplistic analysis still we will have these many parameters and the variability associated with all these parameters.

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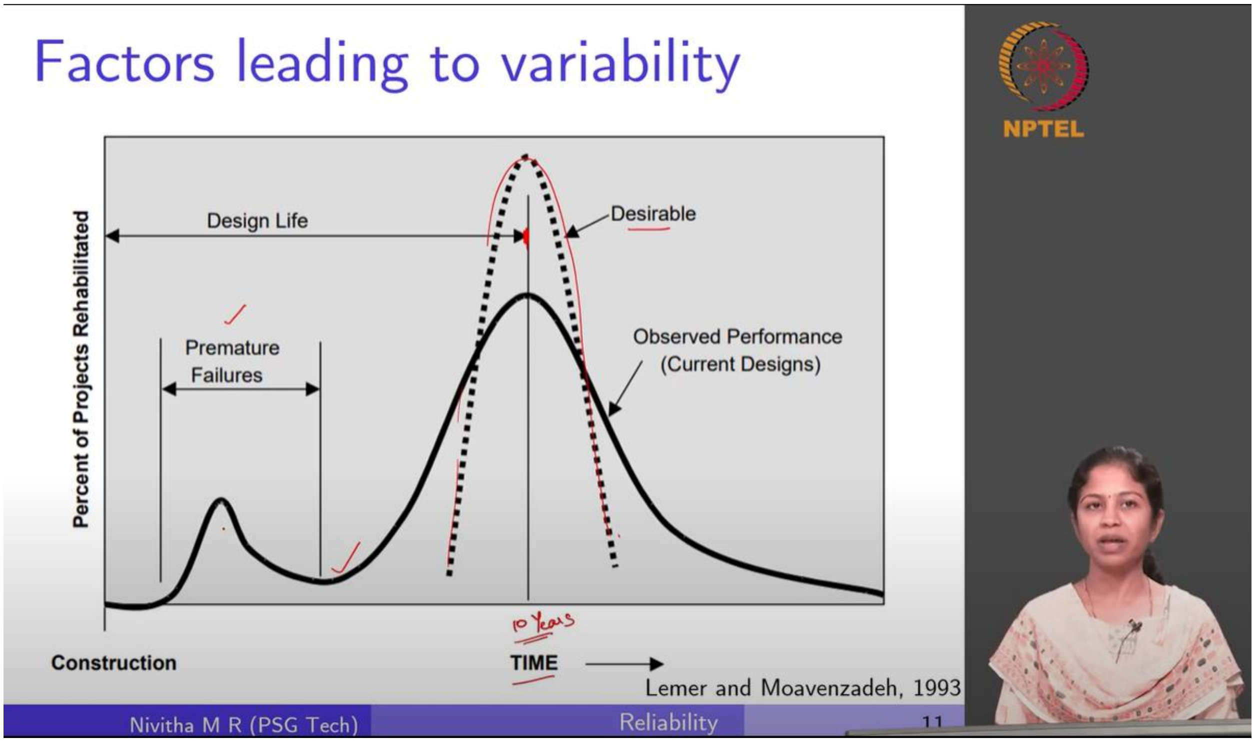

So, what is the outcome? What will happen because of the variability of all these input parameters? Let us say I have a pavement, this is my time, this is my assumed desirable design life. Let us say I design it for 10 years, let me take a specific example for the sake of discussion. I design it for 10 years, will my pavement serve exactly for 10 years as I said earlier it may not be right. So, it will be around this, so it is usually approximated with the normal distribution.

So, it will have a variation like this over this 10 years. But in reality, this is our desirable case. In reality, what we are going to observe on the pavement is something like this solid line which you can see here. There are going to be some pavements that will exhibit premature failures and some of them may work around the design life also. So, it might happen that we can have pavements that fail much earlier and some pavements which meet the design life for which they were designed. So, why do these pavements undergo premature failure? Because the assumed conditions in our design are not the same as the conditions which were translated into execution or we could have failed to consider some of the variability in the material properties during the design procedure right. So, if we are able to consider all those variabilities we may be able to minimize premature failures or make better approximations in the design process.