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A very warm welcome to all of you. I am Rajan Choudhary, a Professor in the Department of Civil Engineering at the Indian Institute of Technology, Guwahati. Instructor for the NPTEL MOOC course, Pavement Construction and Technology, funded by the Ministry of Education, Government of India. Today, we will be discussing lecture 23 under module 10, where we will discuss the aspects related to pavement roughness and its measurement. At the very beginning, I would like to acknowledge the use of text, information, graphs, and images sourced from various textbooks, codal standards, journal articles, reports, newsletters, and public domain searches. Now, as the word itself indicates, it is the smoothness or the roughness of the surface that is very important.

So, if I call a pavement rough, I can say that the pavement is not smooth. So, in a similar fashion, we measure the quality of this pavement in terms of its roughness and what is usually conveyed by the pavement roughness. If the pavement roughness or unevenness is a key indicator used to describe the irregularities of the pavement surface, We have seen in previous lectures how, during the construction of individual layers, the surface levels were ensured; then the unevenness or regularity was ensured, and finally, once the pavement surface is ready, the final wearing surface, which will be available for the user, also needs to be ensured for the roughness aspect. So, pavement surface roughness or unevenness is a key indicator used to describe the irregularities of the pavement surface; specifically, we are talking about the wearing surface on the top when this exercise is done.

That adversely affects the ride quality of vehicles because good smoothness or good evenness can be achieved, or lower roughness can be achieved if good practices are ensured from the subgrade construction itself. Only then is it possible to achieve a good riding quality or a smooth surface on top. Otherwise, if a surface is smooth, it adversely affects the ride quality of vehicles and the comfort of the road users. So, we will discuss these aspects related to pavement roughness. Considering the IRC SP 16-2019 special publication, which contains guidelines on measuring road roughness and its related norms.

So, we can say that an increase in road roughness leads to higher road user costs because it will definitely increase vehicle maintenance costs, fuel consumption, and the time for travel, as it will reduce the speed that can be adopted on that particular surface. And, in addition to this, it will make your ride uncomfortable and often draw criticism from the users. So, the functional requirements are not met if the surface is rough. So, for the user,

it is a very important aspect to have a smooth, good surface. So, roughness typically refers to surface deviations that are present from a true planar surface.

With characteristic dimensions that influence ride quality, because here the role of the vehicle will also come into the picture. Conversely, smoothness represents the absence of such deviations, which means that if this surface is smooth, we can say it is less rough or that the unevenness is less. As a critical indicator of pavement performance, even a newly constructed pavement, in addition to its structural requirements, should meet the functional requirement that the surface should be smooth enough. So, as a critical indicator of pavement performance, we can refer to what we discussed in previous lectures about the structural evaluation, where we talked about the residual life. So, that is one way to evaluate the pavement performance.

This is another way in which we are trying to judge the performance in terms of riding quality. So, a critical indicator of pavement performance is that the terms roughness and smoothness are often used interchangeably. Now, from where this roughness arises, as we mentioned, it is from the bottommost layer of construction, where we start doing the construction of subgrade layers, followed by our granular layers, bounded layers, and then our wearing courses. So, at all these layers, regular measurements in terms of the surface levels or surface irregularities have to be maintained so that finally, on the top, you can get a smooth surface. So it says road roughness mainly when it can arise either from built-in irregularities during the construction itself, caused by construction defects, or from surface distortions if there are certain distresses present.

During the course of construction, if the traffic is not controlled and the construction vehicles are using those underlying layers, then those layers can get distorted. So, these distortions later get reflected at the top. On the top layer is the form of roughness. So, this can either be from built-in irregularities caused by construction defects or from surface distortions that develop over time due to consolidation; if they are not properly compacted, then consolidation or densification takes place, or displacement of the pavement materials occurs if the pavement materials are not strong enough. They may get displaced, resulting in a distortion of those materials, which will cause roughness on the top.

So, these may be possible causes of having a rough surface or for the introduction of roughness on the surface courses. So, roughness is an important aspect of pavement surface, and the reason is that it impacts various factors. Few things are more important than the safety of road users. Now, this is another very important aspect: vehicle vibrations from road roughness can impair driver performance; they can increase driver fatigue, and if driver fatigue increases, it also increases the chances of accidents. As prolonged exposure may cause fatigue, if he is exposed to a rough surface for a longer duration of time, it will definitely lead to fatigue, and this will increase the likelihood of accidents.

The vehicle suspension also plays an important role in influencing this effect because the quality of the suspension will reduce this particular impact and also decrease fatigue. So, when the vibration frequency aligns with the vehicle's natural frequency while traveling on these unrelated surfaces with different wavelengths and frequencies, the roughness may appear to be reduced, but if it goes out of alignment, then the roughness is amplified. So, this is with respect to the suspension, and it also plays a role. So, it is highly important for the safety of the users because, otherwise, if fatigue is present, it is definitely more problematic and, in due course of time, it increases the chances of accidents. Roughness can also lead to a significant reduction in the loss of braking force or skid resistance; this is another concern, and this roughness may vary in your wheel path, which is another concern.

So, variation in roughness between wheel tracks further compounds the problem. If you have roughness that is different in the wheel pass, it further compounds the difference because you do not have good contact between your vehicle's tires and the road surface due to the roughness. So then it leads to differences in braking and sliding forces, which further expose the vehicle to unequal friction levels on each side, creating a serious safety issue. So, this roughness, which may be different on the wheel, may not be the same; however, this roughness will reduce the frictional resistance and will affect your safety during the movement. Now, vehicle operating cost is another important factor.

What does vehicle operating cost usually comprise? It comprises your fuel, oil consumption, tyre wear, maintenance and repair, and depreciation. So, these are some of the important things that come under vehicle operation cost. This significantly increases if the surface is rough enough or the pavement has high roughness. So, road surface roughness is a key factor influencing vehicle operation costs, as higher roughness increases fuel consumption at a given speed and reduces overall travel speed. This is because when roughness is high, the travel speed comes down, and then the fuel consumption increases.

So, it further increases the requirement for repair because the rough surface may frequently require repairs for different categories of vehicles. Another aspect is vehicular riding comfort; definitely, if you have a rough surface, the riding comfort becomes poor. So, a vehicle's riding quality is definitely influenced by travel speed; if you have a rough surface, you will be traveling at a lower speed. It is the dynamic characteristics of how the vehicular suspension systems interact with the spectral properties of the road softness, as I mentioned in terms of the wavelengths of different irregularities and their frequencies. So, assessing the ride quality and roughness through vehicle response depends largely on speed and vehicle dynamics.

So, how the driver will be affected or the user will be highly affected depends upon the surface roughness, the vehicle dynamics, and the speed at which it is moving. Vehicle speed, as we discussed, is definitely lower over a rough surface compared to what it can be

on smooth surfaces. So, various studies on the roughness-speed relationship have established a negative correlation: if roughness is greater, it definitely means that users will move at a slower speed. Now, how do we measure the roughness of pavement surfaces? Normally, two systems are used. We classify the different systems used for measuring pavement roughness into two broad categories: one is profilometric systems, and the second is response-type road roughness measurement systems.

So, first of all, what is the profilometric system? So, these systems measure road roughness based on the surface profile of the pavement. So, the surface profile is captured, and it is compared with respect to a planar surface. And then, considering a simulation of a standard vehicle driving at a standard speed, some roughness index is derived. So, they include advances, and specifically, what is included under these profilometers is that we have some advanced profilometers. You can see this is a laser profilometer that is attached to the front of this particular vehicle.

That captures profiles using lasers and accelerometers, as well as certain walking profilometers. So, this is typically known by the name dipstick. So, this is again one profilometer, which is a walking profilometer. So, you need to walk along with these profilometers. This particular category of profilometer is attached to the vehicle at the front or rear end, and then it captures the profile of the road.

The second is that they directly capture the profile of the road on the basis of that, and then, with the simulation model at a particular simulated speed, it measures how much the accumulation of the vertical movement will be with respect to the total travel time, which is given in terms of some index value. Second is the response type of road roughness measurement systems. So, this is another very commonly used system, and what is there? These systems evaluate road unevenness based on the dynamic response of vehicles. So, here you can see this is one that is known as the fifth wheel bump integrator. So, equipment under this category includes the fifth-wheel bump integrator.

This is the fifth wheel bump integrator, and the other is the automated road unevenness recorder; this is the one that was indecisively developed by the Central Road Research Institute, New Delhi. And then we have car axle-mounted bump integrator and axle row meter-based systems, and what these systems do is measure the response of this roughness of the surface with respect to the total length traveled. Now, further, we will discuss some of the important features of these response-type road roughness measurement systems. As I mentioned, this is the one that is very commonly used. You can see this is the fifth wheel bump integrator, which is towed by a particular vehicle.

So, it is a response-type road roughness measuring system that consists of a trailer mount and a trailer towed by a vehicle. So, this is a vehicle to which this particular roughness measurement system is towed, and it uses a standard pneumatic tire, which you can see

having a standard pressure filled up, mounted on the trailer chassis, and it has a heavy weight. So that the movements are not transferred to this rear chassis, which is there, and this is a trailer chassis supported by leaf springs; there are single leaf springs in this particular one. And dampened dashpots minimize vehicle-induced motion; any vehicle-induced motions are dampened in this particular case, and what is done here is a mechanical integrator that records the cumulative vertical displacement, which is the cumulative vertical displacement of the wheel relative to the chassis. So, this is what is done in this particular case, while a distance measuring unit tracks the travel distance.

So, we are monitoring the cumulative vertical displacement along with the length traveled. So, the roughness index is calculated as the ratio of the cumulative vertical displacement to the distance traveled. So, the lower this particular value, the smoother the surfaces; the higher this particular value, the rougher the surfaces, and this particular one is normally known as the roughness index, with the unit in terms of mm per kilometer. For this particular vehicle, the fifth wheel bump integrator has to be driven at a standard speed of around 32 kilometers per hour, and especially, this is moved along the wheel path of that particular lane for which we are measuring the roughness. And definitely, these are certain pieces of equipment that need to be calibrated regularly with high precision equipment, especially the profilometer-based equipment.

So, usually we do a calibration every 2 years or if a journey of already 5000 kilometers of measurements has been completed. So, whichever is earlier, the calibration has to be carried out regularly. The other category is the car axle-mounted bump integrator, again very similar to the fifth wheel bump integrator, but here the important part is that the bump integrating unit is mounted on the rear portion of the vehicle or the floor of this particular vehicle, and in this particular case, you can see the bump integrator fitted to the rear axle; this is the bump integrator which is fitted to the rear axle, and it is mounted on this particular floor of the vehicle. So, as you can see, this is placed here and it is fixed to the rear axle. Now, it records the differential moment between the rear axle and the vehicle body.

This is what is captured through this particular wire through the upward motion of a wire. Now, this particular upward motion is converted into a urine directional rotational moment of the integrator pulley. So, again, it simulates or accumulates the vertical motion that is taking place between the vehicle body and the particular one that is mounted on the axle. And along with it, the length is recorded, so again it gives the unevenness index or roughness index in mm per kilometer. And the other category is the laser-based profilometer systems; these are the most accurate systems, which are widely preferred for road roughness measurement.

These are high-speed systems that measure the pavement roughness response using laser beams, which are mounted either on the front end or can also be at the rear end. And

typically, there are two that capture the longitudinal profiles of both wheel paths. So usually you have two wheel paths, and in that case, you can capture this particular one; otherwise, when you are using the fifth wheel bump integrator, it is preferred that you move that wheel on the wheel paths themselves. In this particular system, vertical displacements are recorded through the sensors, capturing both the wheel paths and the profile; these corrected profiles are then simulated through a standard model at a standard speed, allowing you to directly obtain the unevenness index in terms of the International Roughness Index. So, there are two units: one is the roughness index, or unevenness index, which we get from the response-type road roughness measurements, and the second is the international roughness index.

So, this can be obtained for both the wheel paths, and the unit of this international roughness index is meters per kilometer. So, here you can see this is a laser for the left wheel path; this is for the right wheel path. So, as I mentioned, there are two units that are widely used in pavement roughness computations: one is the International Roughness Index, which has been preferred globally. It is a standardized and widely used measure of pavement roughness, representing the vertical response of a simulated quarter-car model. So, this is what the profile is for, which we have, the major longitudinal road profile that we get from the profilometers.

That particular one is subjected to or simulated through a quarter car model to get the vertical response, and this is simulated at a speed of around 80 kilometers per hour. The vertical response is computed for this particular model, and this is defined as the ratio of the circulated suspension motion or response to the distance traveled. So, whatever distance this is expressed as the reference average rectified slope. So, this response, which we get from a simulated quarter car model when simulated at a standard speed of 80 kilometers per hour with respect to the total length traveled, gives us the slope, which is reported in meters per kilometer or inches per mile. So, the one that is widely used in India is in terms of meters per kilometer.

So, from these profilometers, we get the values directly in terms of the international roughness index, having a value of meters per kilometer. Whereas, in the case of the roughness index or the unevenness index, which we measured with response-type road roughness measurement systems, such as fifth wheel bump integrators or car axle mount bump integrators, we measured the response of that particular system to the roughness, and this accumulated response with respect to the total length was directly observed. So, here we measure the dynamic response of vehicles to the road surface using some mechanical or accelerometer devices. So, what did we do? We did the cumulative summation or the summation of the vertical undulation deformations with respect to the length. So, it is the cumulative undulation per unit length.

Now, this is what happens in the case of response-type road roughness measurements, and as I mentioned, in that particular one, the unit is typically mm per kilometer. whereas in the case of the internet. Now, certain studies have established a relation between this roughness index in terms of the International Roughness Index and the Unevenness Index, and one is specifically given for IRI values of 17; 17 is a very high IRI value. So, it says the roughness index is equal to 630 times the international roughness index raised to the power of 1.12. So, this relation can be further used to calibrate these response-type road roughness measurement systems with the high-precision profilometers, and we can correlate the roughness index or unevenness index with the international roughness index using these expressions. Now, these different measurement systems can be implemented according to the precision we obtain from them. So, they are normally divided into four categories. These are class 1 precision profilometers; specifically, they can be used for calibration purposes or other profilometer methods. Response-type measurement systems, as we have an example of a fifth wheel bump integrator, can definitely provide responses in terms of subjective ratings.

I can drive on the surface and give a subjective rating, which can be on a scale of 1 to 5. For instance, if the surface is good enough, I can rate it as 1, or if the surface is poor, I can rate it accordingly. In this way, the manner of subjective rating is decided. So, the Class 1 profilometers are the instruments that have the highest standard of accuracy; specifically, they directly measure the profile and are used for calculating the International Roughness Index, as a series of accurately measured elevation points is important because the critical part is how accurately you measure the profile of the road. So, for this particular one, you need to have a short interval.

So, here it can be said that the elevations are measured at sampling intervals of less than 250 mm. So, you have these laser profilometers that can do this particular exercise with a precision of less than 0.5 mm. For very smooth pavements using even walking speed profilometers, this is a dipstick that is being used.

So, it is a dipstick. So, this dipstick can be used, and this is a walking profilometer. So, here is what they are sampling: you are measuring the elevations at intervals of less than 250 mm, and the accuracy is even less than 0.5 mm. So, these are high-precision profilometers, and once this profile is there with you, then through your cartographic simulation model at a simulated speed, you get the cumulative suspension with respect to the length, and you get your IRI values. So, this is an in-built one where you directly get your values in terms of the International Roughness Index.

However, for high-speed road profilometers such as laser profilometers, they can even give you better accuracy than what is mentioned under these class 1 profilometers. They can have sampling intervals less than 25 mm with a vertical measurement resolution of less

than 0.1 mm. So, this is how they go with very high resolutions, also in that case. So, we also have other profilometer systems that have precision.

Less than what is compared to class 1, which was there, and specifically, they say that the sampling intervals should have a maximum width of 500, and this particular precision should be less than 1 mm. So, this is again about the walking profilometers in that case. However, for high-speed road profilers, the longitudinal sampling rate is greater than 25 mm to 150 mm because these high-speed profilometers, which usually travel better than this particular one, have resolutions ranging from 0.1 to 0.2 mm. So, these are much better than what we are expecting. So, then comes the response type road roughness measurement systems; this is the precision 3 category that we have. So, all response-type road roughness measurement systems belong to this particular category, where you also have these car axle-mounted roughness measurement systems. So, where the dynamic response of the vehicles to a road surface is measured using any other mechanical or electromechanical process, this is the fifth wheel bump integrator that we have. So, the estimation of the roughness index for this response type of road roughness measurement systems is made using a correlation equation after calibration; therefore, this equipment needs to be calibrated, as I mentioned, because over time and with the travel they do for their measurement systems, we need to calibrate, and we can calibrate it with precision 1 and precision 2 equipment in that case.

And then comes the last category, which is subjective evaluations of the roughness, where physically driving on the roads allows for regular visual surveys to be made in this particular context. So this is another way. Usually, because this is not practically possible, it gives a subjective result. So, we will prefer to go to the commonly used class 3 and type of precision measuring roughness measurement systems for calibration, and as we have good laser profilometers now available. So, we also go with the measurements using these laser profilometers.

Now, what are the permissible limits? You have the unevenness index and the international roughness index values, so what are the desired permissible limits for different kinds of surfaces and different categories of roads? So here, as per IRC SP 16 2019, it states that the maximum permissible values of roughness for expressways, high-speed corridors, national highways, and state highways are specified. Because typical surfaces used in construction are measured from the top, it is important to consider bituminous surfaces such as bituminous concrete, stone matrix asphalt, or semi-dense bituminous concrete for a good surface when initially constructed. The surface is to be categorized as good, as we divide those sections into uniform sections; as we discussed in the previous lectures on structure evaluation, the sections can be divided into good, fair, and poor in that case. So, here if a section is to be taken as good, the roughness index should be less than a value of 1800 mm per kilometer and the international roughness index should be less than 2.55;

whereas if it is fair, it is in this particular range of 1800 to 2400 for the roughness index, and if it is poor, it is greater than 2400.

So, this is what happens when you have a high speed in the corridors that are there. And if there is another case, if you have, for example, roughness for major district roads and other district roads, you will have different kinds of surfaces there. You can have a surface dressing, an open graded premixed carpet, a mixed seal surfacing, a semi-dense bituminous concrete, and, in some cases, you can also have bituminous concrete in these lower categories of roads. So, we can also see that for expressways, national highways, and state highways, the requirement for the roughness index was less than 1800, but for lower categories, this requirement has increased, so now it is less than 2000. So, we again have these recommendations for good fare and poor, which have been given by IRC SP 16.

Which particular one can be picked up for what type of category can also be worked out, because now you have a good range of measurement systems available for monitoring the pavement roughness. So the choice of whether to use a fifth wheel bump integrator, an automated road unevenness recorder, or a car axle-mounted bump integrator is available. Any other advanced technologies, like a laser profilometer, can be used, depending on the size and extent of the road network to be worked on. Now, you will see specifically in terrain areas, plain terrain areas where roads are in average to poor condition, and the average traffic speed is normally in the range of 30 to 40 kilometers per hour. There, we can use this fifth wheel bump integrator because we saw that the equipment has to be run at a speed of around 32 kilometers per hour.

So, it is possible to run those fifth wheel bump integrators at speeds that are not very high. But if you have these high-speed corridors, the vehicles will be moving at higher speeds, typically more than 60 kilometers per hour, even in fair or poor conditions. So, the slow-speed precision equipment and the roughness measurement systems cannot be used. And there, what we will prefer is the laser profilometers or the ultrasonic sensor-based profilometers, which fall under the category of class 1 and class 2.

So, they are particularly used for high-speed corridors. Now, again, a guideline has been given for the selection of appropriate road roughness measurement systems in different operating conditions, as it states, when you have low speeds from 10 to 40 kilometers per hour, and the type of terrain, which includes plain terrain, rolling terrain, and hilly terrain, with respect to the country slope that is present. So, if you have a plain terrain, you can use the fifth wheel bump integrator, or an automated road unevenness recorder, or a car axle-mounted bump integrator. For rolling, it can also be used; for hilly terrain, it is a car axle-mounted bump integrator that is preferred, with multiple speed calibrations that have to be done. Because then it has to be run at different speeds, so calibrations have to be done for different speeds. Now, similarly, if you have a median speed range from 40 to 60, then here it says for laser profilometers; it also says for ultrasonic sensor-based profilometers.

So, these are profilometers; this is again a car axle-mounted bump integrator, or these are accelerometer-based roughness measurement systems. They can be used for higher speed; we always prefer to go for laser profilometers or ultrasonic sensor-based profilometers. So, these are the ones which you typically do not have in hilly regions, speeds more than 60 kilometers per hour, design speeds typically, and in addition to this particular one, they say how many runs have to be done for these particular measurements for different categories. So, it says if a single lane road is there, an intermediate lane is there, a double lane is there, and a multi lane is there, and if you are using this particular one because if I am using laser profilometers, it can capture the roughness of both the wheel paths, so I can go for one single run for one lane. So, for every lane, I will go for laser profilometers because they will be able to capture the roughness for both wheel paths, but if I am using a fifth wheel bump integrator, then it is a single run for each lane, and specifically, we will prefer the one that is more distressed or the outer lane, which may be preferred in each case.

So, these are accelerometer-based; one single run can be in each lane. Now, it says that for roughness measurement systems with a fifth wheel bump integrator, the fifth wheel should preferably follow the wheel path; this is an important aspect again. While making use of this, you need to work it out; you have to have better control because it should follow the wheel path with at least one measurement per lane. So, as I mentioned, at least one measurement per lane has to be there. In the case of a car axle-mounted bump integrator, the vehicle's outer wheel traverses the wheel path; in this particular case, it goes in the middle of it. However, in the case of a car axle-mounted bump integrator, it is always preferred that the vehicle's outer wheel traverses the outer wheel path.

As I mentioned, walking speed class 1 equipment is generally used for calibrating these particular ones, validating the roughness data. And for this, if you are using walking profilometers, you have to be very careful, and you will use them for small stretches because you will walk with those profilometers. So, for small stretches, we can carry out those exercises with walking profilometers, and then that particular roughness index can be compared with these response-type rolled roughness measurement systems to calibrate those systems. The roughness, again, in what manner the roughness results can be reported, is that there is a standard format requirement that if you are using any of these response type road roughness measurement systems, and if you have, basically, nowadays this kind of exercise is done at least when you have a two-lane road and a multi-lane road. So, it says that if you are working with the fifth wheel bump integrated, it mentions individual lane buys, and it can be in terms of the roughness index or converted to the international roughness index because IRC SP 16 gives requirements both in terms of your roughness index as well as in terms of your international roughness index.

So, this can be reported in both terms in that case, but for that particular one, you need to have the calibrated one. Now, for laser profilometers or ultrasonic sensor-based profilometers, individual lane-wise and average IRI are converted because both wheel paths are present. So, you can take an average in this particular case. Invoice individually. So, this is again a requirement that is provided with respect to how the results will be reported; the results will be reported either in terms of the roughness unevenness index or in terms of the international roughness index.

So, this is all about the roughness measurements of the different sections by using different equipment; specifically, we have the profilometers, high precision equipment, and also we have the response-type road roughness measurement systems. Thank you so much.