Traction Engineering
Professor Hifjur Raheman
Agricultural and Food Engineering Department
Indian Institute of Technology, Kharagpur
Lecture 06
Mechanics of Wheel and its Tractive Performance

Hi everyone. This is Professor H. Raheman from Department of Agricultural and Food Engineering, IIT, Kharagpur. I welcome you all to this Traction Engineering course. Today is lecture 6. I will try to cover the mechanics of wheel and its tractive performance.

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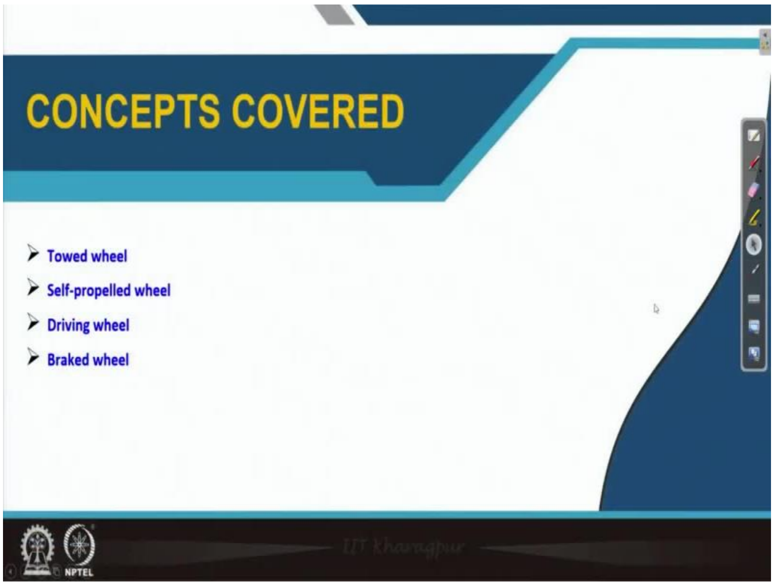

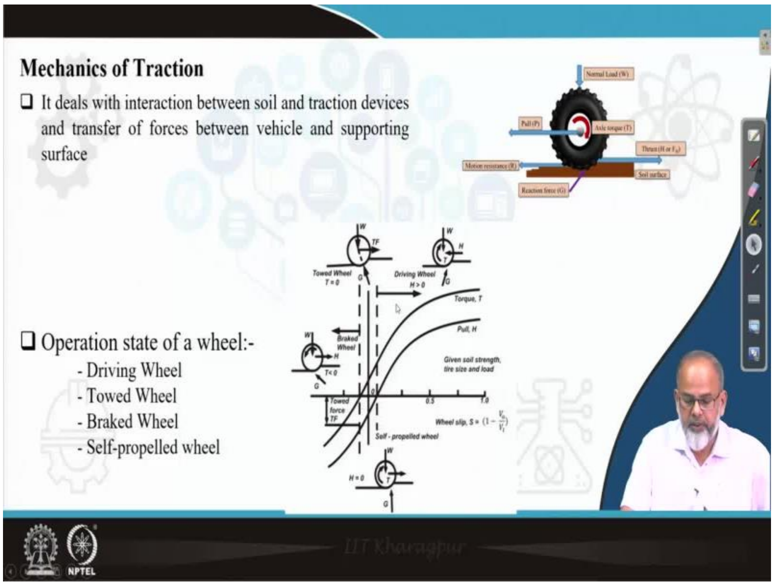

So as you know, the concepts which I am going to cover the towed wheel, self-propelled wheel, driving wheel, then mechanics of traction. As you know mechanics of traction is nothing but interaction between soil and the traction devices and the transfer of forces between vehicle and supporting surface. So, based on that we divided the wheels into four types- driving wheel, towed wheel, braked wheel, self-propelled wheel. And this figure we have already discussed in lecture 1 and 2, now I will try to give you in details, how the forces are acting.

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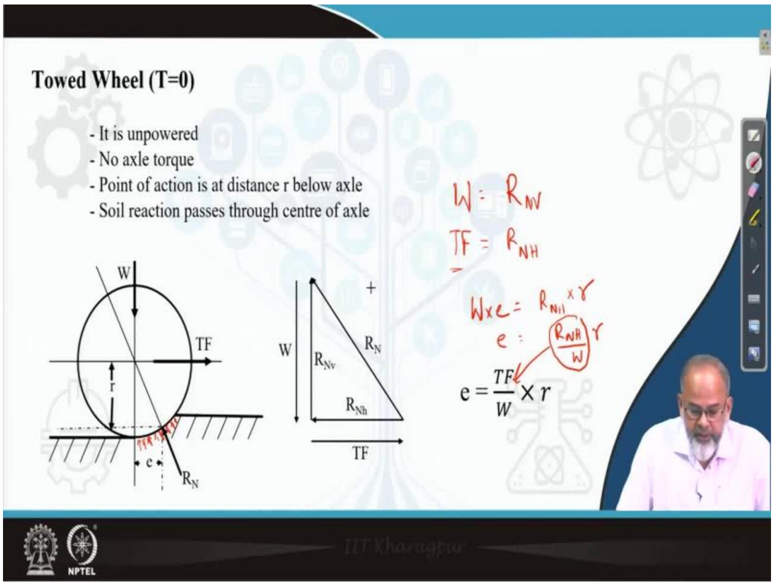

So, when a vehicle is moving, it is applying a load to the wheel at the axle and at the same time the soil will try to apply the reaction force to the wheel at the interface, interface means the soil-wheel interface. So load, from the vehicle will act on the axle, the reaction from the soil will be acting at the soil will interface.

Now when you consider a towed wheel, the simplest thing is there is no torque, torque is equal to 0 and it is unpowered. Since, torque is not there, so it is unpowered, so no axle torque. So, there will be soil reaction, weight will be coming on the wheel, weight is denoted as W. So, W is acting then correspondent W there will be soil reaction at the periphery, at the interaction, interface, sorry, at the interface.

So, resultant of this soil reactions at the interface is denoted as RN. So, the RN will have two components, one is the horizontal component, the other one is the vertical component, which I have shown in this figure, RNh is the horizontal component and RNv is the vertical component. And R is acting at a distance, so that the vehicle is in equilibrium, the tyre is in equilibrium.

And since no external moment is acting and neglecting the friction, what we can do is if you solve this then

$$W = R_{Nv}$$

and the force which is required to tow the wheel forward that is denoted as TF. So

$$TF = R_{Nh}$$

So, towing force is nothing but the summation of horizontal forces acting opposite to the direction of motion.

And weight is summation of the vertical forces, the magnitude is same, but the reactions are there in the opposite direction that means RNv is opposite to W and RNh is opposite to TF. Now if you take if the point at which the soil reaction is acting is at a distance e. So, then if I take moment some of the moments will be equal to 0.

So,

$$W \times e = R_{Nh} \times r$$

$$e = \frac{R_{Nh} \times r}{W}$$

$$\frac{R_{Nh}}{W}$$

which is denoted here as towing force by W. So this is nothing but ratio of towing force to weight coming on the wheel. Now, the moment we apply a little torque, so, that will be shearing force acting on the interface.

In this condition, there is no shearing force. In a towed wheel there is no shearing force, but in a power wheel or a self-propelled wheel, there will be torque acting.

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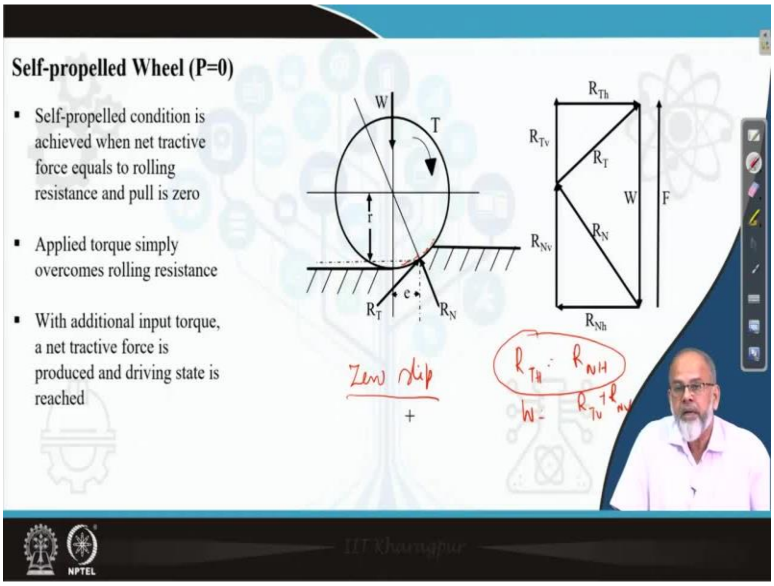

Now, if you look at this figure, you can see, there is a torque acting, weight acting on the wheel and because of the torque that we will be shearing action, so a tangential force will develop on the interface and the resultant of that tangential force is denoted as RT. So, at the interface there will be two kinds of forces acting, one is RT, the other one is RN. RN is the soil reaction, which is radial soil reaction.

Now, if I resolve these forces, which I have done it in the right corner, so RN has a horizontal component RNh and it will have a vertical component RNv. Similarly, the tangential force which is developed because of the shearing action of the wheel with the soil. So, it will have two components which have denoted as RTh, the other one is RTv. So, if you look at the forces, which I have drawn here, then there you can see RTh and RNh, they are opposite to each other.

So now, W is acting vertically downward now, if you resolve these forces what you can get is $R_{Tv} = R_{Nh}$ and
$W = R_{Tv} + R_{Nv}$.

So, this RTh is the thrust which is developed that will be sufficient to overcome the rolling resistance. It will not develop any pull and this condition we have taken us zero condition which you have already defined, zero slip.

Zero slip refers to the condition at which the thrust is developed because of the application of torque and the thrust which is developed that will be equal to just overcoming the rolling resistance that means the wheel will start moving just starts moving.

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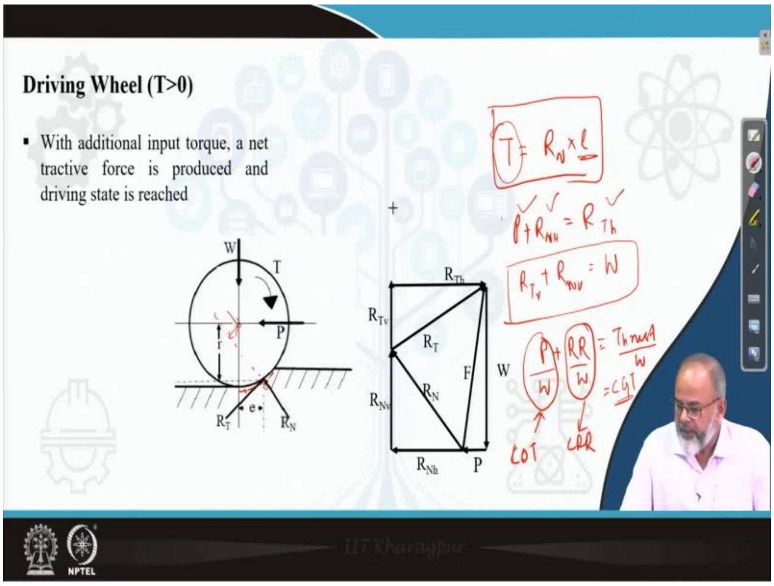

Now, we will move to the powered wheel or the driving wheel. Here two things, we will be seeing, one, there will be torque which is denoted as T and there will be a pull applied P. So, torque is indicated here, torque, and there is a pull here. Now, because of the torque there will be again shearing forces acting at the interface and the resultant of that shearing force is RT and the soil reaction RN coming from the wheel to the ground and W is acting downward.

Now resultant of RT and RN is indicated as F. So, now, if I resolve this soil reaction RN into two components, one is your RNh is the horizontal component and the other one is the vertical component RNv. Similarly, for the tangential force, which is acting because of the shearing action RT can be resolved into two components, one is the vertical component RTv, the other one is the horizontal component RTh. Similar to the self-propelled wheel, you can see RTh and RNh, they are opposite to each other. And in addition to that, if you look, P is also acting in the same direction as that of RNh. So, resultant of RT and RN, which I have indicated as F, and where the RN will act? Because there is no, here the torque is acting, so if you consider that then to balance this torque the RN should act at a point, so that if I extend this line that will give you, that it is not passing through the centre.

In case of a towed wheel, since torque was zero, it was passing through centre of the wheel, but in case of a driving wheel, since torque is acting you have to oppose that torque, so torque will be equal to RN into this distance, centre distance, the line of action is the centre. So, suppose that is denoted as l. So, RN should act at a certain point, so that moment R will try to balance this torque. Now, resultant of RN and RT denoted as F.

So, F is again resolved into two components, one is your vertical component W, the other one is the horizontal component pull. So, now, if you look at this diagram then simply you can write as

$$P + R_{Nh} = R_{Th}$$

$$W = R_{Tv} + R_{Nv}$$

That means, this is the weight and this is the pull, this is the rolling resistance, and this is the thrust. So

$$Pull + Rolling\ resistance = Thrust$$

If I divide W on both the sides, weight of the wheel, then it becomes

$$\frac{\mathrm{P}}{W} + \frac{\mathrm{RR}}{W} = \frac{\mathrm{Thrust}}{W}$$

P by W, RR by W and thrust by W. This P by W is nothing but coefficient of traction COT, RR by W coefficient of rolling resistance and thrust by W is the coefficient of gross traction.

$$COT + CRR = CGT$$

This is what we have discussed before and now, I proved this through the application of forces.

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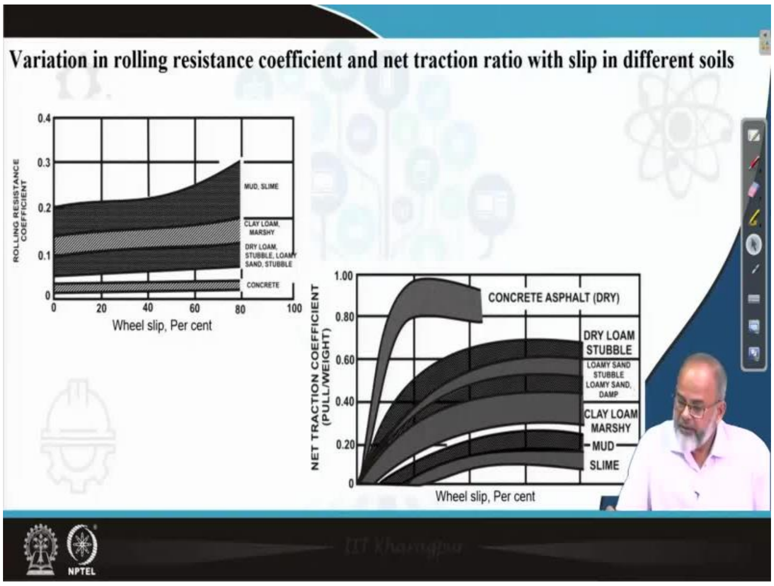

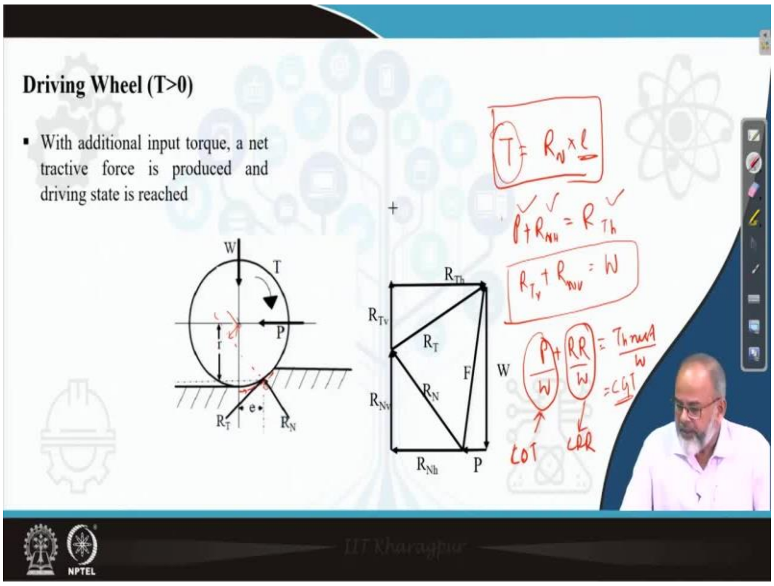

Now, let us see what are the different performance parameters now, how it is varying with slip. As you discuss that performance parameters are your coefficient of traction, coefficient of gross traction, tractive efficiency, then power delivery efficiency, these are the performance parameters. So, now we will see how the coefficient of rolling resistance is varying it wheel slip.

The left corner figure if you look at this has been plotted this CRR has been plotted for wheel slip for different soils, starting from concrete surface is the hardest surface, then at dry loam, then clay loam or the marshy land, then the mud, these are the four soil conditions, which is indirectly representing the strength of soil. Concrete means very hard and mud is the softer soil. So, how it is varying with these soil conditions are indicated here.

So, in case of a concrete soil you can see it will with increase in wheel slip, the coefficient of rolling resistance is almost constant is not varying. In case of a dry loam, it is not exactly constant, but it is being varying very slightly and clay loam also. But in case of mud or slime, you can see coefficient of rolling resistance is increasing with increase in slip.

That means, in a soft soil there we will be sinkage of wheel, there will be accumulation of wheel in the front. So, because of that the, we require more power to overcome those obstructions that is why the rolling resistance increases, hence coefficient of rolling increases. So, what we conclude from here is coefficient of rolling resistance is a function of slip, is a function of soil condition.

Now, if we look at the coefficient of traction, COT, which is nothing but the ratio of pull is to weight, and how it is varying with wheel slip, this has been plotted for four different soil conditions, just like coefficient of rolling resistance, in case of a concrete, in case of dry loam, in case of loamy sand, we have added one more than clay loam, then we have mud.

So again, we are getting maximum COT, in case of a concrete surface and in case of mud we are getting the minimum COT. So, what happens while you are getting more COT in case of concrete because rolling resistance is less. So, rolling resistance less means the thrust which is developed, thrust minus rolling resistance will give you pull. So, rolling resistance is less so pull is more, even if the thrust is same pull is more in case of a concrete surface.

Whereas, in case of mud because of the higher rolling resistance so thrust minus rolling resistance will reduce the pull, hence COT is reduced this is one thing. So, what we conclude from this figure is COT is also like CRR is dependent on factors like soil conditions, factors like wheel slip. Initially, when we increase wheel slip for all the soil conditions, we can see the rate of rise was very fast, then after some slip, it starts almost remaining constant, but that rate of rise was very high in case of a dry soil like concrete surface.

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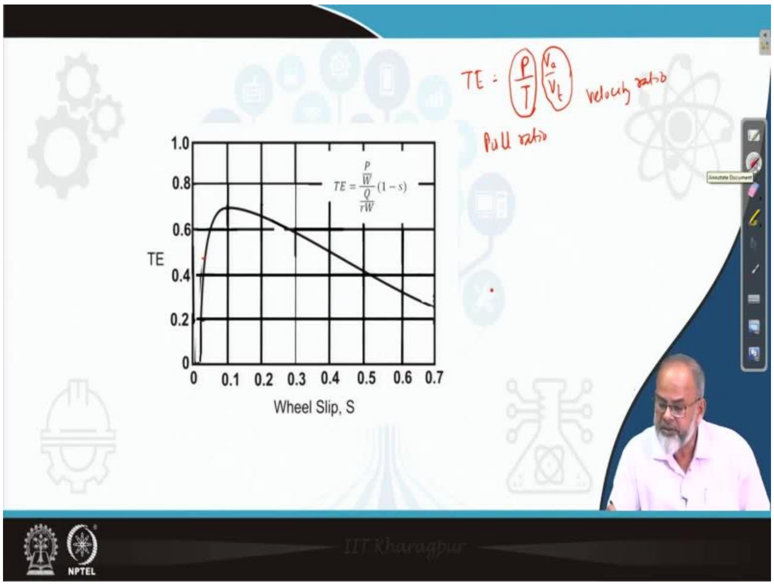

Now, tractive efficiency. Tractive efficiency is defined as the drawbar power to axial power. So, I have given the expression for that

$$TE = \frac{P/_{W}}{Q/_{r.W}}(1-S)$$

That means tractive efficiency is the ratio of two powers, one in the drawbar power, the other one is the axial power that ratio and it also depends on the slip.

Now, if you look at the plot, initially you can see it starts at a very faster rate up to this point and then afterwards initially it rises very faster rate, then after that is rises reduce, reaches to a peak, then it goes down. So, what happens, initially if I have to rise it sharply because there is distortion in the tire trade, afterwards when you further increase the slip there will be sliding of the trades. So, tractive efficiency or the output power is reduced.

If we further increase the slip, the entire wheel is going to slide, thereby, there will be lesser interaction between soil and wheel and the power which is developed is reduced. So, that's why, tractive efficiency reaches to a peak at a very lower value of slip, maybe around 10 per cent. Now tractive efficiency can be defined by two parameters. One is I can write then tractive efficiency is

$$TE = \frac{P}{T}(1-S) = \frac{P}{T}\times\frac{V_a}{V_t}$$

So, this $\frac{P}{T}$ is called the pull ratio and $\frac{V_a}{V_t}$ is called the velocity ratio, velocity ratio is nothing but the travel reduction or the slip, $1-\frac{V_a}{V_t}$ is slip. So, that means theoretical velocity, how much it is converted to actual velocity and thrust, how much is converted to pull. So, this is the product of these two.

But if you look at this then the losses of power is a function of, losses of power means output power is a function of pull ratio, is a function of velocity ratio. Now, velocity ratio, the inability of theoretical velocity to be converted to actual velocity. So, as a result what will happen there will be slippage, the movement between the soil, movement between soil and soil, movement between wheel inside the wheel.

So, because of that there will be losses. Now, if I try to plot this in a different way, because this effect of pull ratio and velocity ratio which makes this tractive inefficiency and indirectly we can say, which makes this tractive inefficiency is not reflected in this figure. So, that is why we will try to put it in a different way, so that these losses can be reflected.

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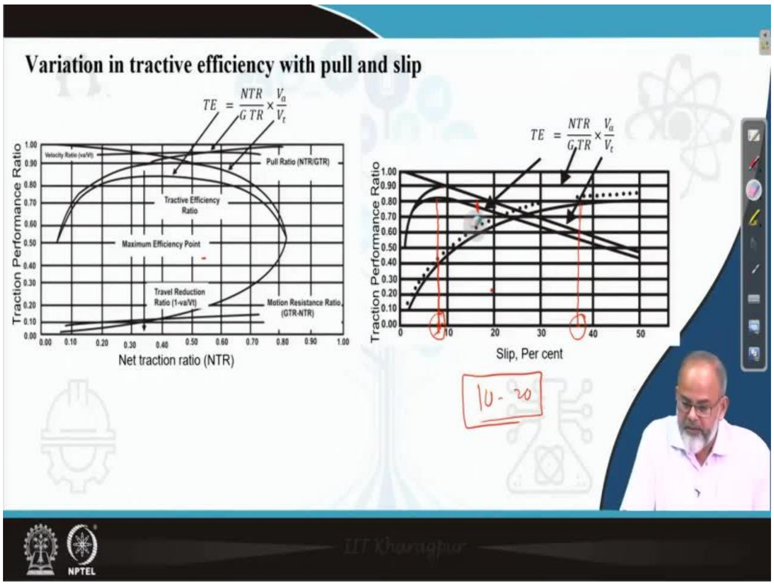

Now plotted traction performance ratio that means NTR versus GTR, Va versus, Va by Vt ratio, these are plotted against net traction ratio. So, this curve if you look at velocity ratio is this curve going down, then pull ratio, this one, so let us first and tractive efficiency is this curve. So, the tractive efficiency curve is always below these two ratio curves. And when you look at the velocity ratio it started nearly equal to one in a self-propelled condition, it is that condition have taken as 0, so velocity ratio is nearly one.

Then when we increase the net traction ratio, what happens the velocity ratio will go down that means, it will decrease, when you increase pull obviously there will be more slip hence, Va by Vt will reduce. Now, if you are looking at the pull to thrust ratio or the NTR to GTR ratio, it is nearly zero. The NTR never reaches too close to GTR. So, there is a difference, why there is a difference? Because the difference will give you the rolling resistance.

So, that is why NTR never reaches GTR and the ratio cannot be equal to 1, the differences roughly are on a concrete surface it is roughly around 0.15 like that. So, as you increase the net traction ratio the pull ratio increases and it never reaches to 1, as I said because of the rolling resistance. So, that means, both the values, both the ratios are lesser than 1.

So when you multiply this, then it is further reduce that is the reason why tractive efficiency is always lesser than the ratio of NTR by GTR value or the ratio of Va by Vt value. Usually, this kind of plot is plotted in the right side figure I have indicated, traction performance ratio versus slip, but I have plotted in a different way, so that you can verify or you can see the effect of Va by Vt and NTR by GTR ratio effect on different performance of the wheel.

Now this the conventional way, the right side figure is the conventional way by which the performance parameters are usually plotted. Now, what is the difference? If you look at difference, there is no difference, in fact, the only the x-axis we are taking slip, in the previous figure we are taking net traction ratio. Now, nature of the curve we can see it is same, tractive efficiency is increasing, reaching to a peak at slip value of around 10 percent.

Then it remains almost constant, sorry, it goes down, this one. Now, when I plot the pull versus the coefficient of traction, you can see, initially it rises then reaches to a peak. So, the slip at which you are getting maximum pull and slip at which you are getting maximum tractive efficiency, they are not same. If I draw a vertical line here then, if I draw a vertical line here corresponding to maximum tractive efficiency this is the corresponding slip.

Now, if I draw a vertical line here this is the maximum pull. Now the slip at which you are getting maximum tractive efficiency, the slip at which you are getting maximum pull, they are different. So, now choice is ours, whether you want more tractive efficiency or even more pull. If you want to make a compromise between these two so that neither pull is lost much nor tractive efficiency lost much. Then you have to find out a design value somewhere here, so that not much of a pull is lost or not much of tractive efficiency is lost.

So, you have to make a compromise. And this design value again depends on different soil conditions, what I have plotted here is only for one soil condition that is on a hard surface. So, depending on the soil condition, you have to decide whether the slip is to be maintained at 10 per cent, 20 per cent or 30 per cent.

But usually we never recommend for 30 per cent, we say that the slips should be between 10 to 20 per cent for all conditions so that the maximum compromise is possible with tractive efficiency and coefficient of traction. So, these are the two ways by which we can represent the performance parameters.

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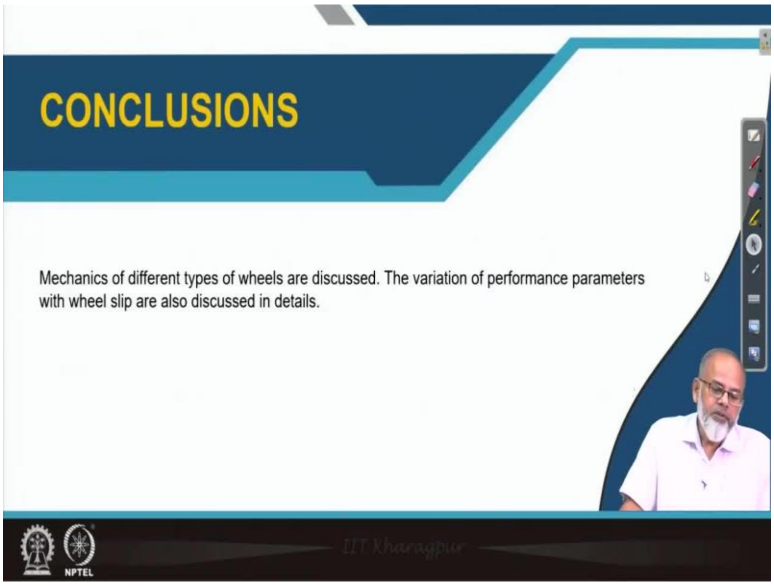

So, let me conclude then. We discuss related to mechanics of different types of wheels, then how these performance parameters are varying with slip, with the net traction ratio and how to represent in a different way, the tractive efficiency that we have discussed in this class.

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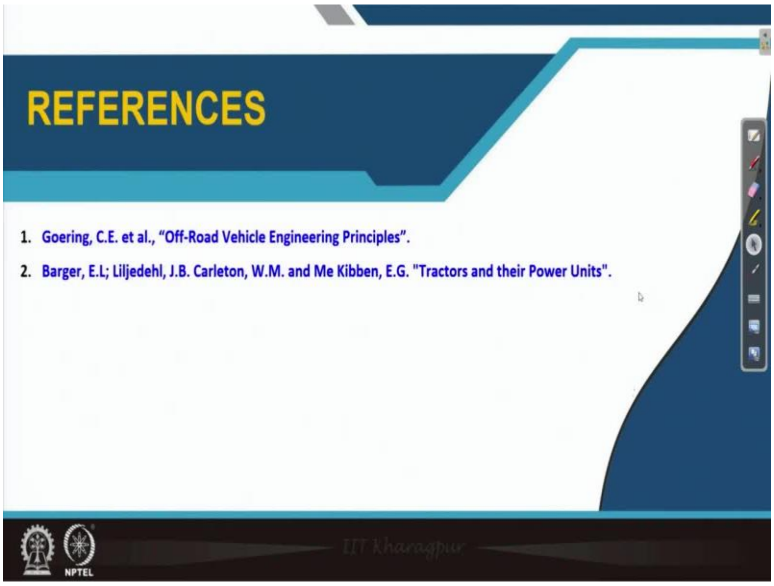

So, you can refer to some of these books for further increasing your knowledge related to this mechanics. Thank you.