Vehicle Dynamics
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Lecture – 08
Slip, Grip, and Rolling Resistance

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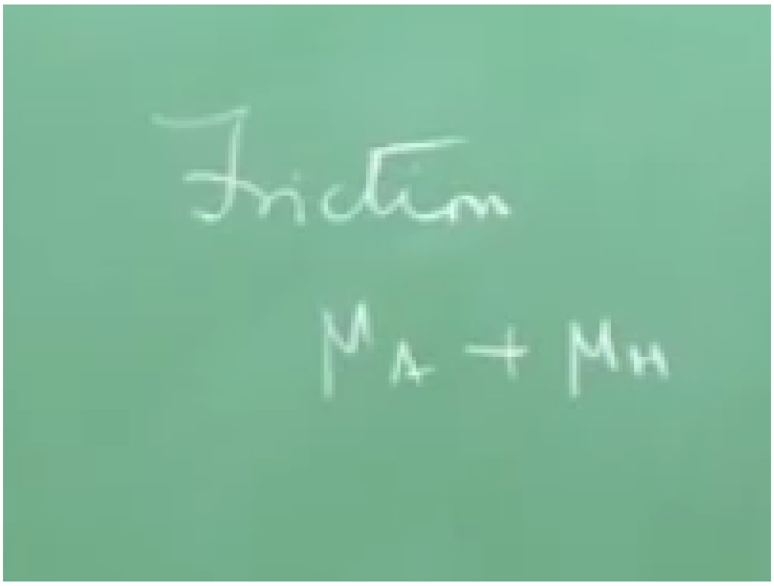

In the last class, we were looking at the friction between the elastomer, the tire and the road. We found that friction is not as simple as what you can see in a metallic friction but consists of 2 parts and we said that is a mu addition + mu hysteresis, in other words we said that the hysteresis of rubber plays an important role in friction. We also looked at the road and relations and how the macro aspect of the road surface and the micro aspect of road surface, both of them are important for tire friction.

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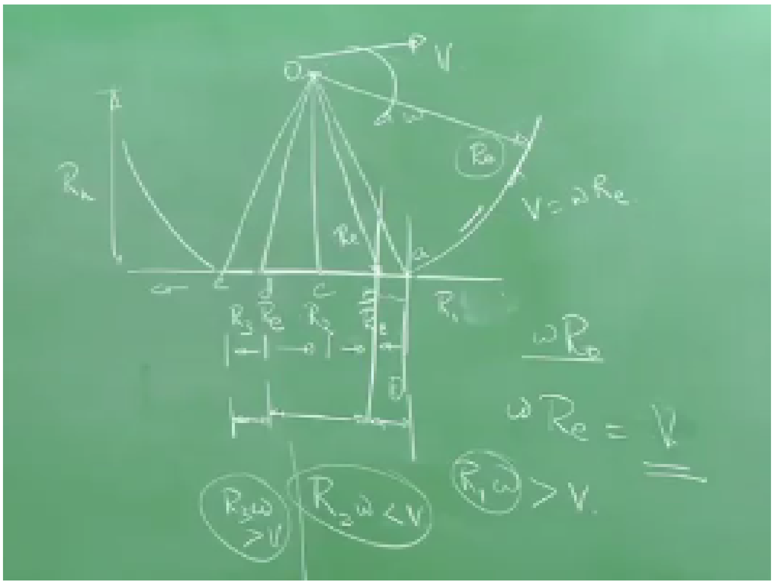

Now, we will leave this for a minute or maybe for half an hour come back to this and before that, let us look at what happens as the tire rolls? Now, we are now in from the micro between the road and the tire we are going to the macro, how actually the tire as it rotates it behaves. We had already seen this, we started this we said that as the tire rolls, there are 3 different radiuses of course when it stands also, there are there are 2 different things.

But, when the tire rolls, we said that there are 3 different radiuses. Of course; one is what we called as; if you remember right, R0 the undeformed radius of the tire which means that that is the tire radius; undeformed radius of the tire. We also said that when the tire enters the contact patch it has a reduced radius, okay it has a reduced radius and that in between the 2 actually, we have an equivalent radius which I think we called it as; let us, let me call that as Rh.

I think we called it as h, we call it as Rh. In between R0 and Rh there is what is called as an equivalent radius; radius which is when multiplied by the omega angular velocity of the wheel gives you the velocity V of motion. As I told you again in the last class, we can look at the velocity of motion of the wheel the stationary ground or you can look at it as if this is stationary and the road travels with a velocity of V, either way it is; it is fine for us.

We will use one or the other as the circumstances demand but the theory is the same, it is just for understanding purposes, we will be looking at it from 2 different perspective okay. We already saw this and we added that there are 3 zones in the contact patch. There is one zone, let me call that between a and b, where the radius is > Re, in other words that is the radius Re and there is a region where it is > Re, then there is a region where the radius is < Re, that is this zone.

Again, there is a region where it is > Re, right. So, there are 3 regions in the contact patch, so in region one, since the radius is > Re okay, V that is calculated omega into that R okay greater; let us call the radiuses here as R1 okay, of course this is a function of S, let us, just leave that S, let us say R1 okay that is the changing radius as I move from a to b. At b, of course it is our Re, let me call that as c, let me call that as d okay.

And the radius at d is again Re, right. Let me call that between the 2, the radiuses to be R2, which is actually a function of this length S, let me leave that for a minute and let us say that in this region it is R3 and again function of S. So, here between a and b, R1 multiplied by omega is > V. In this region, R2 multiplied by omega is < b and in this region R3 multiplied by omega is again > V, right.

So, that gives us a very interesting picture, as to what happens in these 3 regions. So, there is; **"Professor - student conversation starts"** so, how did we get this result? So what is this R, I am talking about and what are these results? Right, that is the question. Now, as it told you, let us say that this is the R0, you know which is undeformed radius right, so we will see what happens to a circumferential element in a minute is what we started in the last class, we will see that in a minute.

Because there were some questions on this, I am repeating it. So, at this point; at this point I hit the contact patch, right so, omega R0 is the tangential velocity at that point right. So, as the points in the contact patch move, right we also saw how contact patch actually is defined in the last class, so you have to have all those concepts what we taught in the last class in your mind. So, as I move from this point to a to b in the contact path.

In other words, as the contact patch moves above me between a and b, that region of the contact patch, the radius is > Re okay and here again the radius is > Re, between the 2 the radius is < Re, this is all I am saying nothing more than the less. So, since this > Re, V being omega Re, this region between a and b, R1 omega is > V. Similarly, R3 omega is > V.

Similar; I mean in the same fashion; we can say that R2 omega is < V because R2 is < Re. So, there are regions where the tendency for the tread to slip okay, will be different in these 3 regions the tendency to slip will be different, right. On one hand, the tread wants to go, if as I told you last class, if you are going to sit here okay, that tread wants to go faster in one region; faster which means it has a tendency to slip.

In another region, the tread goes slower okay and another region the tread goes faster. So, there are 3 regions in which the tread head goes wants to go faster or slower but let us for a moment assume that the friction is fantastic. Let us going to stick and that it is not allowed to go faster or slower because as it hits the ground, it is going to as I said; it is going to go stationary were stand there, it is not going to move.

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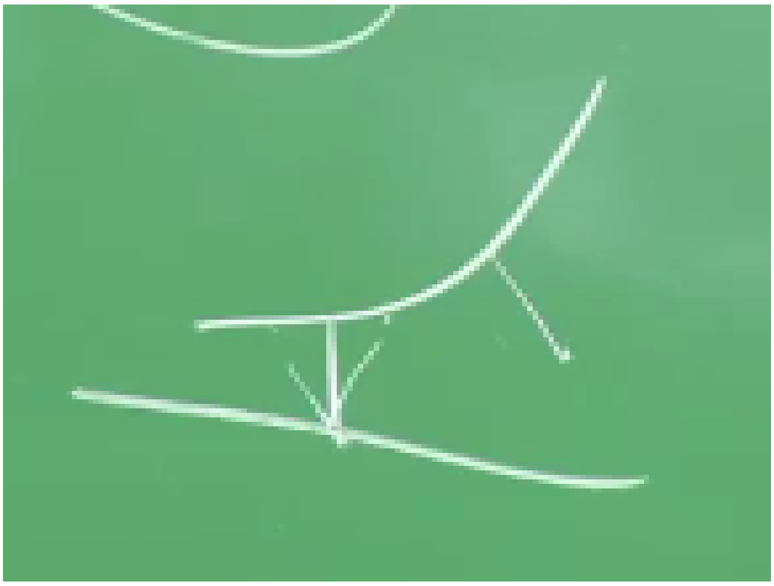

So, it is a question of that treads being pulled in one direction or pulled in the other direction okay, so here in this region what happens is that, the wheels go slower, so the tread; the tread which was like this; let us put it like this, let us say that I am just exaggerating the picture here in this region okay. Now, tread which was nice like this, let us take a tread at this point; a tread I am representing is it by a stick.

Let us assume that that is a tread block, I am representing this as a stick, so here as it sticks to the ground okay that is the carcass, when it sticks to the ground it wants to go faster okay but it is sticking to the ground. So, there is a tendency for it to be pulled in one direction, as it comes here, there is a tendency to be pulled in the opposite direction and when it comes here this tendency to be pulled in the other direction.

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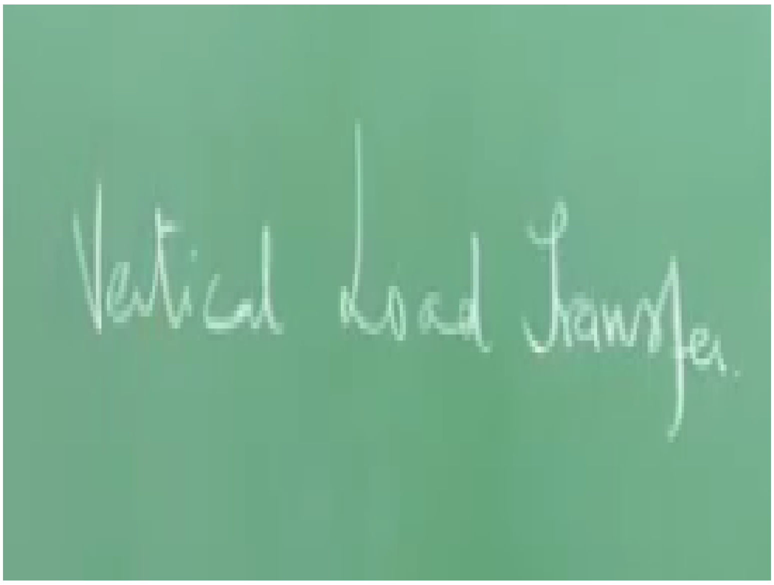

So, let me put that as a force okay, let me pull that that pushing or pulling whether it is going to be pulled like this or like this, we will put that as a force in a minute right, okay. **"Professor - student conversation ends"**. Now, before we go further and go and lie down there, there are questions as to how actually load is transferred; load transfer in a tire? This is very important to understand okay, vertical load transfer.

This is a very nice; I would say concept physics that comes into picture as to how actually the load is carried by the time, a lot of misnomers, so let us understand that you know very carefully, right. There is a tendency to believe number one, not all of you; I am sure all of you do not have this kind of beliefs but some of them as I see it; **"Professor - student conversation starts"** Yes absolutely, so in other words the question is; the question is that does the velocity actually change.

Or in other words, R keeps on changing, so when R keeps on changing okay, that instantaneous velocity also keeps changing, in other words amount of slip is not the same; give me a minute I will explain this and come back to this question, I know there will be a lot of questions it is very conceptual okay, so we are going to go very slowly, right. **"Professor - student conversation ends."** Before we go into this aspect, let us look at load transfer.

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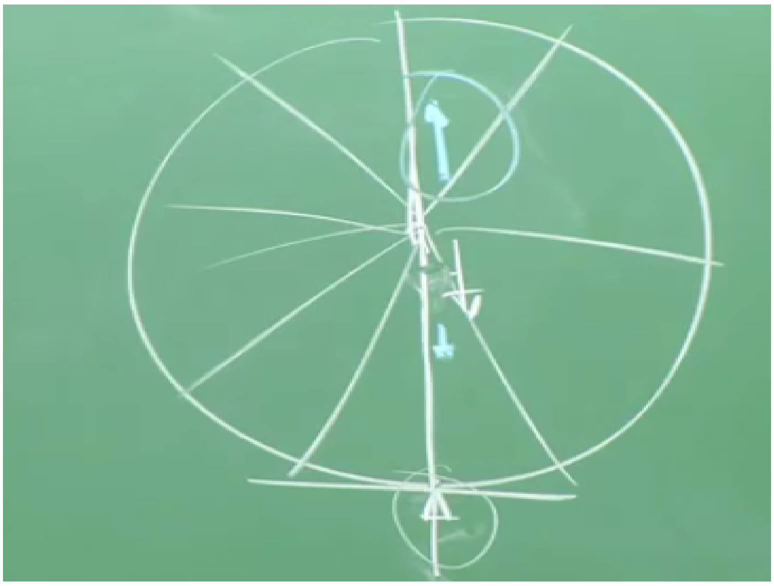

We have not talked about how the vertical load transfer takes place in a tire right okay. All of you drive bicycles okay, let us first understand how actually the bicycle wheel carries the load. Now, let us; you see that every day, it looks like very simple what is there? You would say that okay that is the bicycle wheel; I am just putting the spokes okay on the wheel, what is there? There is going to be a load like this, this going to be a load like that.

And it is all over, that is the free body diagram okay and the wheel is in under equilibrium, what else is there to talk about this. Unfortunately, lot more because the spokes as you know is a very thin piece of steel okay, if you subject that spoke to compression, what is that? This is going to take this, it is going to buckle, so the spokes are assembled with tension okay, they are going to be actually assembled with tension, right.

So, when the spokes are not; let us say that they are not on the ground just take the wheel out then there is a tension in the spokes which are opposite to each other and they would cancel each other okay. So it is not that the wheel will run away in one direction or the other, they are in equilibrium because of the forces that are in built into these spokes clear okay. Let us just consider a very simple situation, forget about all other spokes.

Now, this spokes is under tension, just we will consider one for clarity, that spokes is on the ground so there is a compression onto the spokes, so what really happens? Is that the tension here is reduced okay, the tension here is reduced. Let us depict that with an arrow okay that is all is the tension but this guy who was sitting there at the top his tension is not reduced, so his tension is high.

With the result, if you look at the forces okay which are actually acting on the axle, you would notice that this guy is the one actually which is responsible for the support of the wheel, in other words the wheel hangs from the top and that is not just pushed from the bottom. So, the hanging here, this hanging here is one which holds it; which holds it, so there are a number of forces that is the load that is acting.

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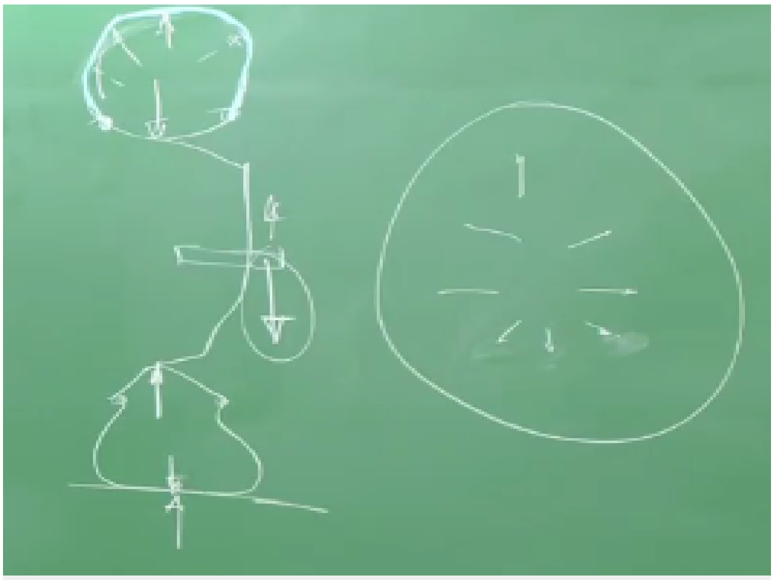

And there is a spokes which has an initial tension, it is a ground, so the equilibrium demands that the whole wheel hangs it, hangs the axle from the top. This is exactly what happens in a tire but who plays the role of the spokes in a tire, it is the sidewall of the tire. So, let us draw the sidewall okay, let us say that that is the sidewall of the tire okay, they are; say let us say sitting in a rim, all of you have seen a rim, okay.

And then again it goes like that and then that is the rim and then there is a sidewall of the tire. In other words, let us say it sorry; let us say that, that is the tire and that is the bead what is called as the bead okay you would have seen that all those things and that is the; this is the tire, right. Now, this sidewall is now going to act like a spokes, here the tension is in the spokes is given when we assemble the wheel.

Here, the sidewall gets the tension from the pneumatic pressure okay, so the pneumatic pressure in other words that the inflation pressure; you go to a shop and you fill it up 32 psi is the pressure you say you keep it, so that pressure is what gives the equivalent tension in a spokes to the sidewall right, so is it clear that gives the tension. Now, let us see what happens okay, that is the axle.

Let us look at what happens to this whole situation. Of course, the first thing you would say that look that is the inflation pressure that is how it acts, it acts throughout okay. There is an inflation pressure like this okay acts on the rim, let us say that it is a tubeless tire, if tube tire does not make any difference that is what is the inflation pressure and that is the ground reaction, clear, this is how it acts.

The first thing you have to understand is that it is the load bearing as nothing to do with the compression of the air inside, in fact this issue was settled long ago in the early 60s, if you remember right, there is a paper in 1962, which very clearly showed that the pressure; the pneumatic pressure does not vary more than 1%, <1%, so it is not; it is not that this air okay carries the load, right.

Air, of course acts as a cushion it is a; there is a different thing which gives that springiness and so on, so it is not that which carries the pressure then what is that which carries the pressure? In the same fashion as we explained the spokes okay, if you now look at the side of the tire; pardon me, that it is not a very good circle, now inflation pressure acting all through this pressure, now this; that is how it acts on the ground, right.

There is a difference between in the tension, again the same fashion here, so that now reduces. On the other hand, this pressure gives more or this is more than this now and so the sidewalls have the tension okay, to pull the rim and through which it pulls or gives the reaction to the axle, so in other words, the vehicle load is reacted upon by an upward force; the downward vehicle load reacted upon by the upward force which comes from the top.

Again, as in your bicycle wheel, a passenger car tire or a truck tire or whatever it is, is actually hanged from the top; it is hanged from the top, it is not that they are supported from the bottom. So, the whole load actually goes through this sidewall onto this most important component called the bead okay which transmits it to the rim and that gives the force for the rim to support the load, is that clear; any questions, okay.

So, this is an important concept on how load is transferred or held by the tire okay. We will come back to this rolling tire again. This is a phenomenal concept of pneumatic tire. Because as it rolls, the whole load; you know the different points in the tire is now held by different parts of the tire because this is not a stationary, this is stationary figure but imagine that actually it is rolling okay as it rolls.

So there are different parts which come and which is under tension and which holds the wheel.

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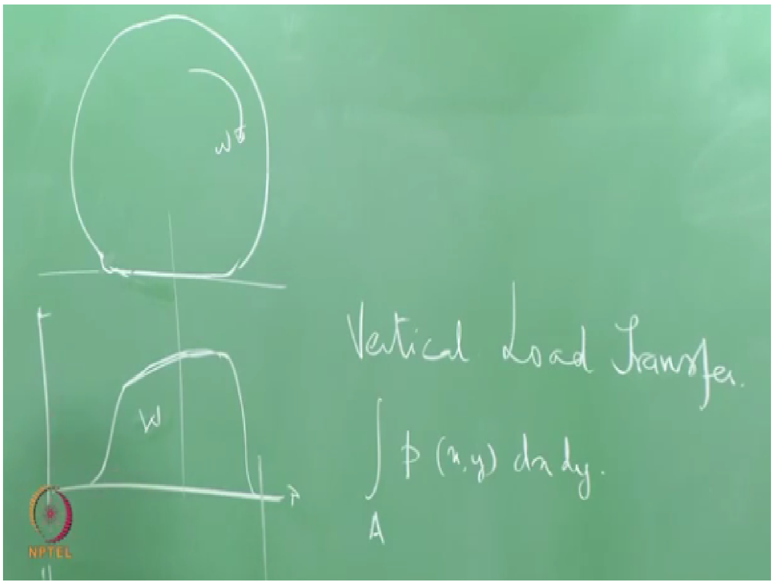

So, there is compression tension or a cycle which takes place, it is also responsible for hysteresis. Now, let us come back to this figure and let us understand what we meant by slip and what happens here? Now, let us say that, that is how the wheel rolls, right and that there is a contact patch which is developed under the road, we have seen that, that is what we had seen that as the reaction; ground reaction.

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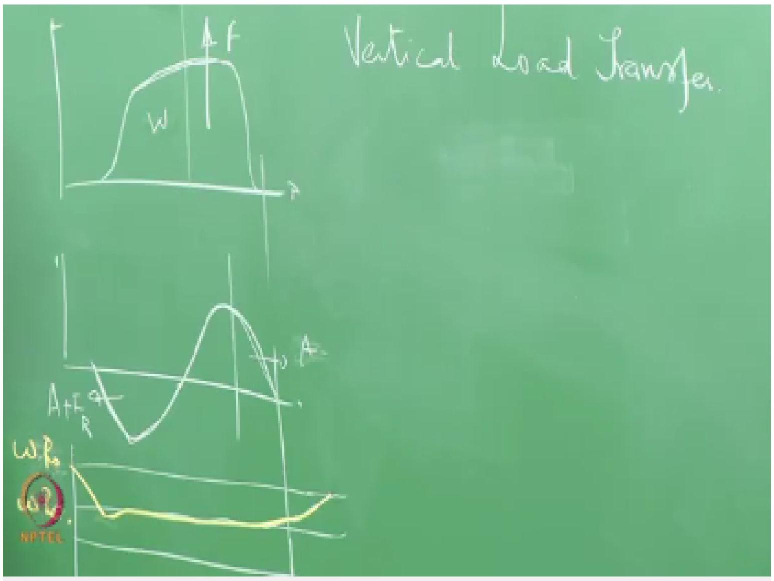

That some of this area under this contact patch, contact pressure multiplied by that is in other words, if I say that the contact pressure is P okay which is a function of x, y dx dy, if I integrate the whole thing okay is the total reaction of the ground okay that we are talking about, all right. As we had seen earlier, this is not symmetric for a rolling tire with the result that, there is an unsymmetric distribution results in a force that acts, which is responsible for rolling resistance.

We said that the unsymmetric distribution is due to the viscoelastic properties of the tire. Let us see what happens because of this variation in the radiuses. Obviously, this variation in radiuses caused a lateral force; causes a lateral force okay, so the lateral force in the first part up to A, it is like this in one direction and then starts dropping and then goes in the opposite direction and then goes up again.

So, in other words the lateral force developed depends upon the difference between the velocity of the wheel and the ground velocity, what is meant by ground velocity? We said that we can treat the motion of the wheel as if the wheel is stationary and the ground can move in the opposite direction, so it is the difference between these 2 that would cause; that would cause extension or a compression of these tread elements.

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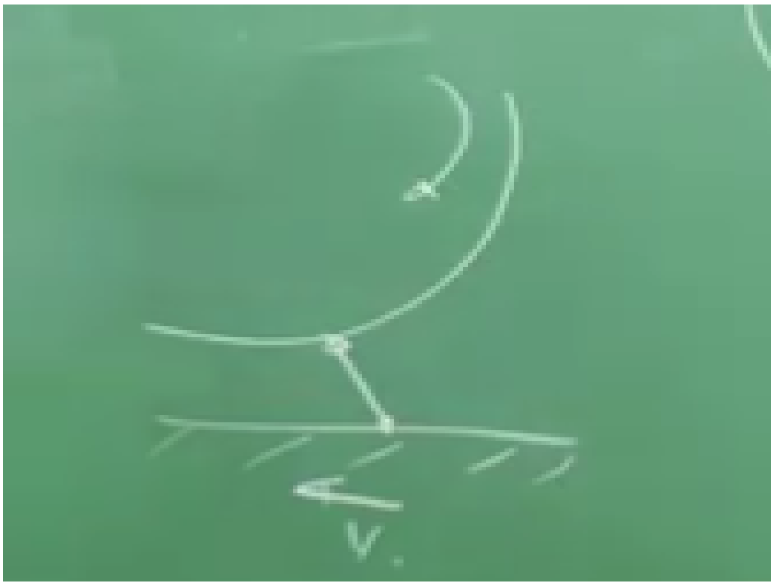

It is very important this; very important to understand that the tread elements can be extended or can be; or extended in either direction, I would say, okay extended in either direction. Just to under; before I go here; let us understand this carefully. Let us say that, that is the wheel okay and let us say that there is a tread element which is sitting that is the carcass rather okay, the treads are blocks which are extending from the carcass body of the tire, right they are extending.

And they are the ones, which are touching the; which is touching the ground clear okay, so they extend and touch the ground, he is rolling, you can either assume as I said he is going to the velocity V or that stationary and this is going with the velocity V. Let us consider 2 extreme cases, yes; **"Professor - student conversation starts"** No it is actually there, in any; we will we will see that first day, we saw the tire we will again see it to the next class okay, you will have; you will have tread blocks okay and actually you have bells; tread blocks and all that okay.

For example, if you take a radial tire you have a; you have apply and you have bells and you have treads which are supporting, which are supported on that okay and we will see that again in the next class how it looks like okay. We will take a real tire and we will see it okay. So, we will do that in the next class. This is the longitudinal force okay, we will come back to this, if we look at this, we will look at extreme conditions and come back slightly difficult concept to understand.

But let us try obviously we can do this. That is a normal pressure; is a normal pressure okay. Now, let us look at 2 extreme conditions to understand it and then we will extend it to a simple you know normal conditions okay. **“Professor - student conversation ends.”** Now, let us say that we have applied a sudden break right? What happens when you apply a sudden break? The wheel now would not rotate; wheel would not rotate but the vehicle will be moving.

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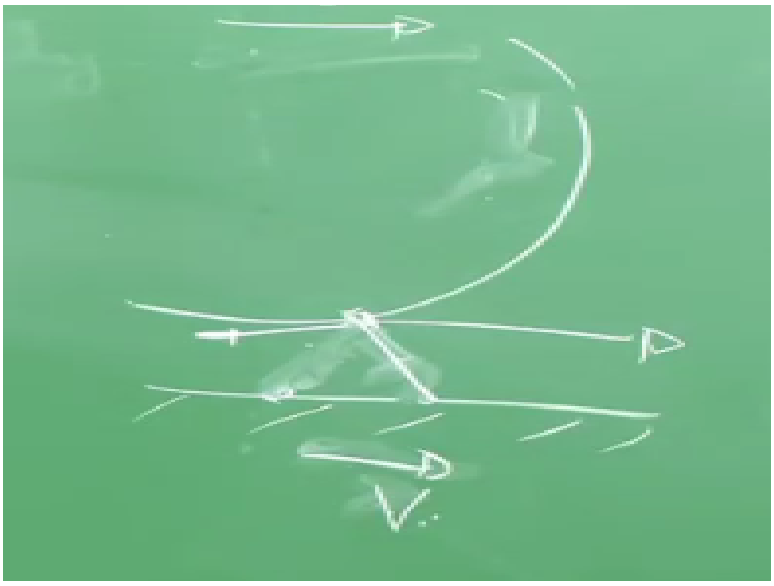

Let us say assume, that vehicle is; the wheel is completely locked but the vehicle is still say let us say that it is moving, right, so gone; that is gone. So, this would result in the ground moving in this direction as if this is stationary okay, so at this point there would not be any velocity because it is not rotating okay, so the ground is moving in this direction that is how that tread will be stretched.

Because he is going in this direction, this just does understand I said both of them are the same, so tread is actually stationary there, let us say the friction is so good that it is standing there right and this rotation is stop okay. So, this fellow is going there, what would the tread do now? Tread this now. it is an elastic material, it is now getting extended, so in other words, there will be a force on that tread, there will be a tension in the thread right.

So, one side for a guy ,one side the road is going to hold him, the other side the tire carcass is going to hold him okay, either side he is held and this guy is stationary, this guy is moving, so what will happen to the tread? He will now pull, he is not going to leave the other side okay, so he is now going to pull the tire; hey! do not go away, I am being pulled here, you know I am going to stop you.

With the result that if you now resolve this force in the longitudinal direction that would result in a longitudinal force that gets depicted as a braking force. So, it is this tension which is now causing; now causing that wheel to stop okay or in other words, that is what is the braking force, just the opposite happens when it is; when we are accelerating, it is easier to understand like that, so there is a braking force that is generated, right.

You can; same concept can be explained as if this is a velocity okay and that is moving, this part is stationary, that part is moving and again there will be a tension and that will be causing cost in this direction okay. Now, the other extreme is during or other part is during accelerating; in accelerating okay, there is a difference between this velocity and it will be in this direction and this velocity at the rim.

Let us not; now we have; we understand this, so there will be a difference in velocity between the 2 right, so with the result that there will be a stretching of the V; sorry of the tread and that stretching would give the force which is the traction force; which is the traction force, right. So, one side one stretching in one direction gives the braking force and the stretching the other direction gives the traction force.

So, it is this stretching however you view, it is responsible for all the forces that are developed on the tire. So, here we have assumed that there is no slipping of the tread as if this whole thing is held, this is just to understand this, you know when we put this into the vehicle into the wheel, it is going to be slightly different right, okay. So, in other words you may argue that why should it stand there when the forces are more than what the friction can withstand, it will start slipping.

Absolutely correct; right okay. Now, let us extend that here first what is that we learnt? We learnt that when there is a difference between the peripheral velocity and the velocity of the vehicle okay, a force is generated; number 1. Number 2; depending upon whether it is lower or higher, the direction of the force would also be different, this is what we learnt clear from this, any questions? Right.

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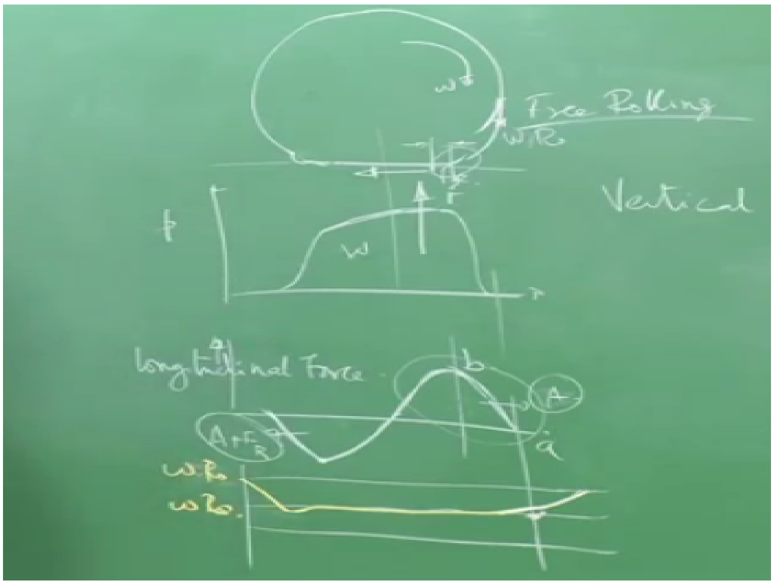

So, when I extend that concept to free rolling, this is free rolling and assume that the friction is good enough that there is no slip okay; here slip what we mean is slipping of this? When the force; say there is a tangential force; the tangential force is higher than the; what can be withstood by the frictional force then it would start slipping okay. We will come back to that figure again; we will be talking about that figure more often now.

So, when it hits the ground, so a force is generated in one direction, so all, this guy is under tension okay in one direction. Now, as he goes from b to c, this part b to c; the tension that is generated in one direction is now going to be relieved because there is the difference in velocities here would now come into play, they are different. Here, one side it is more, another side it is less okay, more acting in one direction less acting in the other direction.

So, you have now pulled it, the fellow when he reaches here, he is going to get relieved now, so the longitudinal force that is developed from a to b will be like this, then it is released keeps building and then again it goes in the opposite direction and so it goes back to 0, so that when the tread gets up from the tyre and goes out all those forces; longitudinal forces have to go to 0, right.

That is what happens, all the longitudinal forces or the longitudinal force because there it is outside the ground but interestingly, if you look at the some of the longitudinal forces okay this is in one direction and this is the other direction, some of the longitudinal forces is not equal to zero because even in free rolling, we have what is called as rolling resistance. So, that rolling resistance manifests as a difference in in these 2 okay.

So, if it is a; if the total force that is acting is a or here okay because as I told you please remember there is a compression tension, the curves are different so they are not the same and all that viscoelastic concepts now come into picture here because after all the tread is getting compressed, it is getting relaxed, compressed and relaxed and so on. So, all the viscoelastic forces now come into picture and that the loading curve is not the same as unloading curve.

So, if there is a force a in one direction, the sum of the forces here in this case which is behind the contact patch they have to be A+ rolling resistance force, so in sum there is a difference and in other words, that results in a rolling resistance force Fr. Now, what is the effect of that rolling resistance force? That is in other words, there is a force which opposes even in free rolling that is you are neither braking nor you are accelerating okay.

So, free rolling, no other force is acting okay. Even in that free rolling, there is a force which opposes the motion and has to be compensated from by a torque onto the V, so you neither accelerate nor break you need okay, a force that is acting, that is the rolling resistance force. **"Professor - student conversation starts"**. We are not; we will define it more carefully; slightly later. Right now, we will say that we are neither braking nor accelerating; we are going at a constant velocity okay.

But we have to define this carefully; we will do that now after some definitions. Right now, understand that we are neither braking nor accelerating in other words I am not applying a lateral force sorry longitudinal force I am not applying a longitudinal force okay, so either to brake or to accelerate, so this under; these conditions, the only force that acts is the rolling resistance force and rolling resistance force has to be compensated, clear, right.

Any questions; **"Professor - student conversation ends."** In some, as the tread elements goes under the contact patch, it is just not the normal compression alone which works along with that normal compression, there are longitudinal forces which also act, that is the sum and substance of what we have been talking about and these longitudinal forces are not just equilibrated on one side of the contact patch to the other and they have or they result in an uneven distribution of forces.

And that is what we call as rolling resistance. Now, let us go and lie down here and see what happens as I roll? As I now start rolling; let me call that you know; let us say that you are lying down like this, so as I now roll and as I come to the contact patch, the radiuses are going to decrease and I am going to get compressed because after all you know I am in a free surface or free stress free state, I am just lying there okay.

As I enter the contact patch because in other words, I am a part of the circumference obviously, so as I enter the contact patch, my radius is going to change, so I will get compressed right. So, in fact interestingly the impending contact is felt by me even before, it is not that so theoretically speaking we said the radius is the same here and so on. In actuality at the impending contact with the ground is felt by me before.

So, if my tangential velocity is slightly away is omega R0; omega R0, so as I approach the contact patch okay my velocity now keeps dropping in other words, I start becoming smaller; I start becoming smaller okay, so the velocity starts dropping even before I hit the ground. When I hit the ground, in fact for a very small distance I still keep contracting, I still keep contracting, so you will see; that is the graph you see, so that is the place where I hit the contact patch.

But my compression keeps extending till a small region in other words, till say that point. Let us for a moment assume that there is no slip in other words, friction is good enough for me to hold then usually, there is no variation in the velocity okay and at the end, you would see a small bump of rubber in other words, the rubber is under compression. This is because the rolling resistance has given me a force there and that force gives me that extra compression towards the end; an extra compression towards the end.

And that result in further drop of my omega R and then I rise after this and then goes; I go back to my original velocity. Strictly speaking; this is not a straight line there is a small variation as we had seen just now, there is a small variation okay but for all practical purposes, people draw that as a straight line, in actuality there has to be a small gradient, then there is a sudden dip.

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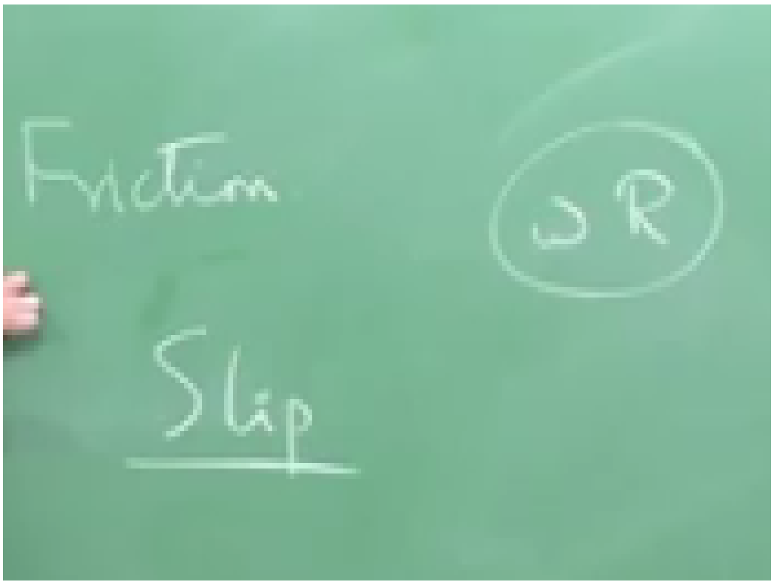

Because of a compression which exists at the end due to that rolling resistance force raised up, then go back again. In other words, if you are sitting on the circumference of a tire, if you are measuring your own velocity, that is how it would be, clear okay. Now, we have to enter into lot more technicalities. The first question; I know many of you have right now is that there is a limiting friction; you are talking about sticking that is not the reality.

In other words, as a race between the normal force determined by the contact pressure and the tangential force determined by this pulling and pushing and this is not a constant throughout the contact patch and whenever one exceeds the other in other words, the tangential force exceeds mu* n, it is going to slip; understood. So, that is what is going to also play a role here and we are going to see that okay for both braking as well as for acceleration.

We will take one case because the other case is just opposite, we will take braking we will explain this and define what is called as a quantity called slip. In other words, omega R and what is R? This is going to play a great role, okay in our definition of slip, clear. We will see that in the next class; remember that the R values are not a constant as you go along the contact patch. We will extend this concept in the next class and define what is called as the slip.

Our next goal after this; this is actually simple when compared to what happens during cornering because the cornering in; during cornering I have to develop a centripetal force and the centripetal force is also developed because of this kind of interaction between the road and the wheel and these tread elements, when I say tread it along with the belt and so on, they participate in creating that force.

And a combined situation where you have cornering plus braking, you have a tendency to brake when you corner; cornering and braking then there are 2 forces that are going to act. In other words, for this quantity called mu*n, there are 2 guys who are going to compete or who are going to; who wants that mu*n, after all mu*n is the same, so when there is cornering plus braking, then there is a longitudinal force as well as there is a lateral force.

Both of them now act and both of them want a part of this pi called mu into n, so this is combined cornering plus braking. So, we will first look at braking, look at cornering and then we will combine both cornering and braking and look at how the force actually gets distribute. We will see that in the next class.