Fundamentals of Electric Vehicles
Technology and Economics
Professor Ashok Jhunjhunwala
Lecture 15
Drive Cycles and Energy used per km

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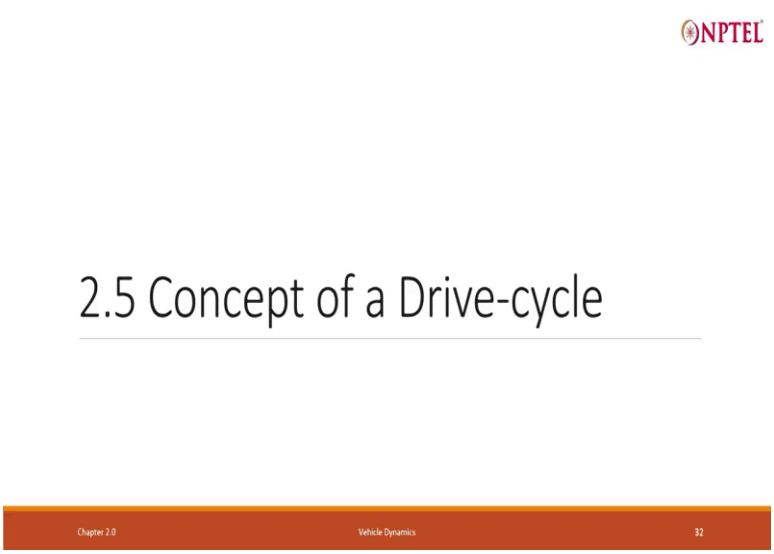

Before we proceed ahead, let us quickly capture what we have done so far on vehicle dynamics. What we did is that (())(0:29) vehicle when it is moving, we looked at all the forces that are applied to the vehicle the aerodynamic resistance, the rolling resistance, the gradient resistance and the force due to acceleration, when we accelerate it, that gave us the total force that is required for the vehicle to accelerate at a certain point and run at a certain velocity we are able to compute this for all kinds of vehicles 2-wheelers, 3-wheelers, 4-wheelers and even small trucks we are able to compute that.

What we did is that once we knew the force, we say well, we also know therefore, what is the power required because the force multiplied by the velocity gave us the power and when we took the power got the power, we could also integrate and find out the energy required that is something that we have done. At the same time, once we knew the force at any state, we also knew what the torque requirement is. And a different speed, what the torque requirement will be, what the power requirement will be, and we also got the energy required, this is what was a fundamental that we had to do to get things going.

After that, what we did in the last class, we introduced the concept of a drive cycle said this is fine. But, if I want to compare some manufacturers 2-wheeler to another manufacturers 2-wheeler, we can compare that, that how much energy does that 2-wheeler takes to carry out a drive and a similar drive how does the another 2-wheeler takes. So, the concept of similar drive came in and we sort of said that world over there are various entities, regulators, which define some standard drives, and you have to obtain the performance of the vehicle as per that drive and that drive is the drive cycle.

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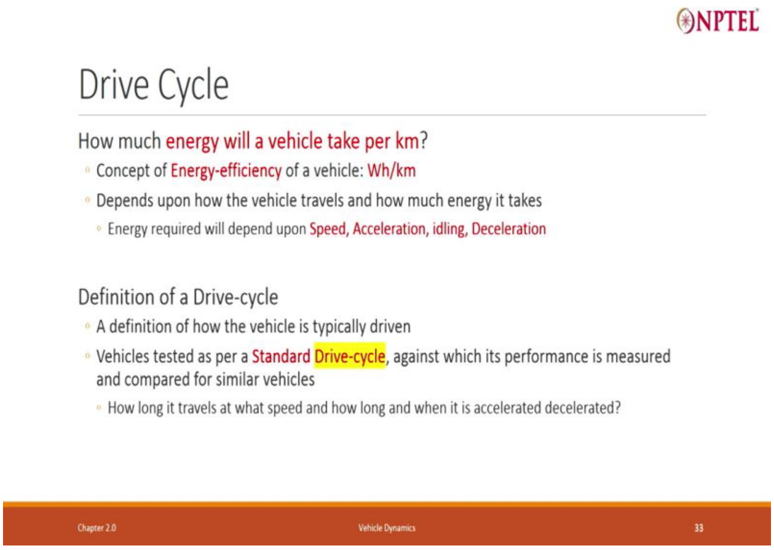

And, we introduced the concept of drive cycle and we said based on that drive cycle, we can compute what is the maximum power required, what is the torque, maximum torque required? What is the maximum energy, what is the energy required? What is energy efficiency watt hour per kilometer, we will figure out all these things.

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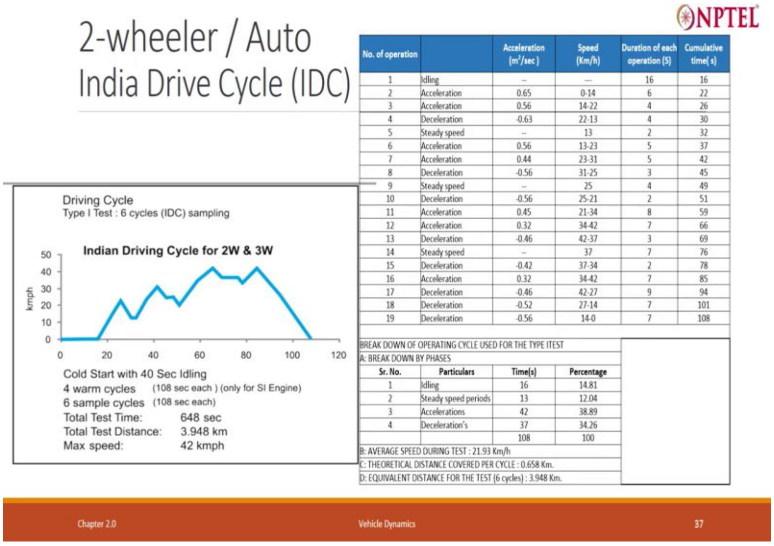

And we introduced this concept slowly and then we defined the 1st standard drive cycle the 2-wheeler drive cycle called India Drive Cycle, but different cities may have different drive cycles, why because in different cities, the roads may be of different kind, the slopes maybe thee or not there, in different cities you may have traffic moving at different speeds. But there is a India Drive Cycle which is widely used to compare one 2-wheeler with another pretty much around the country. And we defined this what this cycle, what drive cycle, what did we do, we sort of say every instant of time, what is the velocity at which it travels and next instant of time what is the velocity at which it travels.

So, we are able to also figure out what is the acceleration required and for how long does it try travel at that velocity or with that acceleration, we are able to figure out. And, once that table is created, that every instant and I sort if say we can take it every second, we can take it every half a second. We know exactly how the vehicle is moving. Once, we know exactly how the vehicle is moving that is what the drive cycle tells us, a standard drive cycles.

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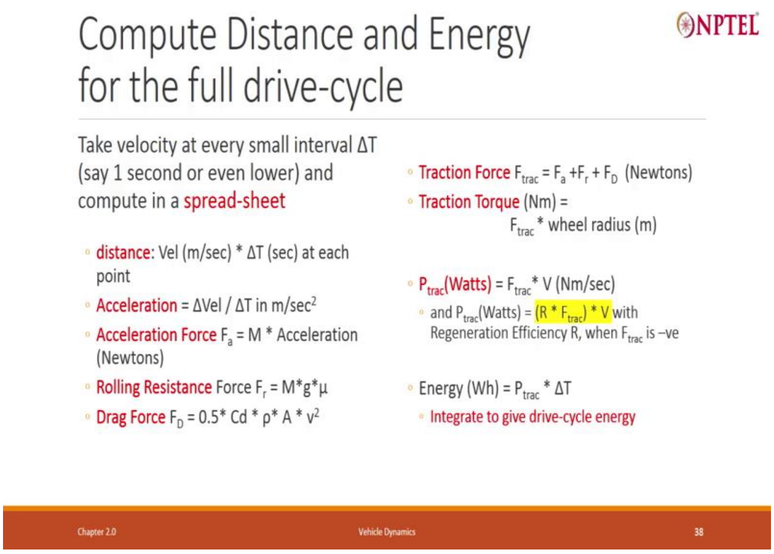

Then we start using whatever we had learned so far to create a spreadsheet, where we sort of say every second, what is a distance that you will travel, what will be the acceleration, what is the force required due to acceleration, what is the rolling resistance force, what is a drag force required and therefore, we added all this what is the traction force required and we computed also traction torque and then we computed what is the power required to move at that second and then we integrated the power and obtained the energy.

And we said this can be very nicely done on a spreadsheet. Now, if you notice in this what I have not done is the slopes, because the India Drive Cycle does not define the slope, but in one of the assignment problem that I gave you, I actually included the slope. So, the spreadsheet will change a bit will include one more force called the force due to climb, force due to gradient and you have to add that and do the needful.

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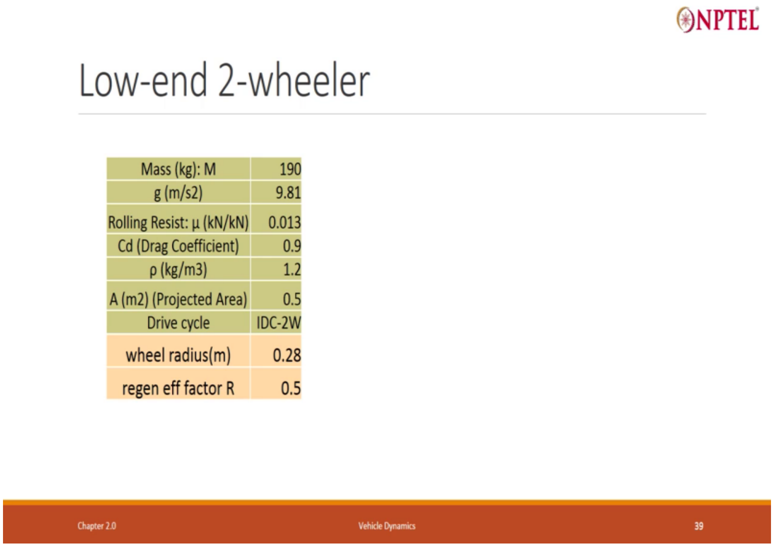

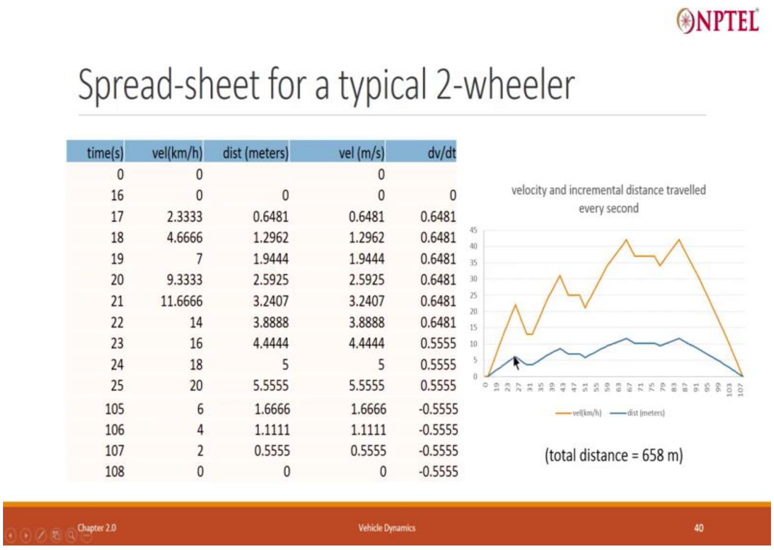

And based on that, we took defined a 2-wheeler; we had to define all the parameters for the 2-wheelers, something that we have been doing for the last so much time. And (())(6:30) we will do every second this compute and we actually computed and started putting the spreadsheet, in fact in the assignment I have asked you to build a spreadsheet, here we have only used the spreadsheet, we then are able to figure out the velocity at which every second how much it will travel, the incremental velocity, incremental velocity for incremental distance travel and similarly the distance, incremental distance that is traveled.

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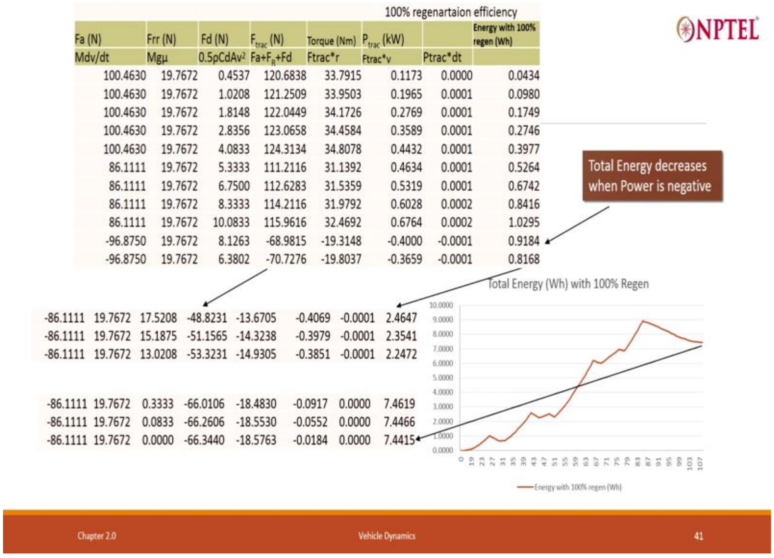

Once, we are able to figure this out, we then are able to also figure out the power, the power, the torque, the total force, torque power, and we are able to integrate and get the energy and we also introduced the concept of regeneration. If there is 100 percent regeneration, what is the energy consumed or is a 30 percent regeneration, what is the energy consumed? All this we are done it and we are able to then plot, what is the energy consumed and this is with 100 percent regeneration, you can see that while energy consumed is high, up to around 83 seconds and then you are able to recover the energy, why are you able to recover the energy because right now after that, it is at the peak speed and slowing down. This is assuming all the deceleration energies converted back to the energy, electrical energy and put into the battery within (())(8:00), that is not always so.

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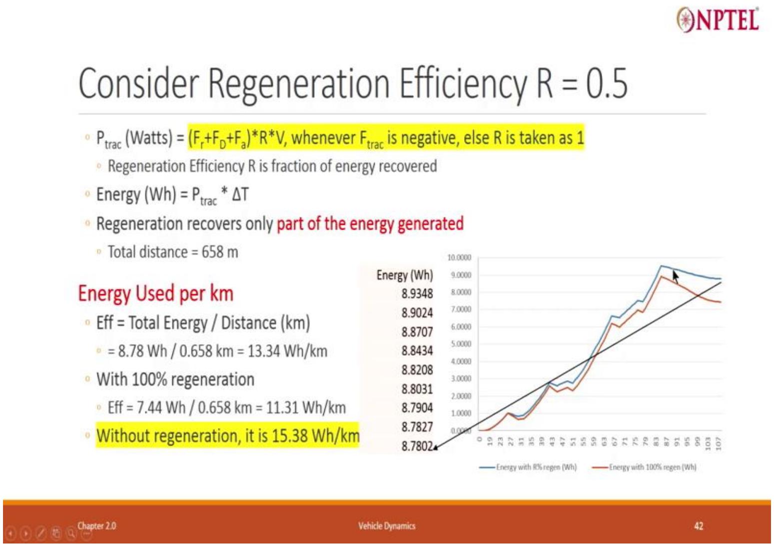

So, we introduced the concept of regeneration. And say, if I take only 50 percent regeneration then the energy consumer will be little more. And we actually introduced that in the spreadsheet, we can now change the regeneration to be 30 percent or 10 percent or even nothing.

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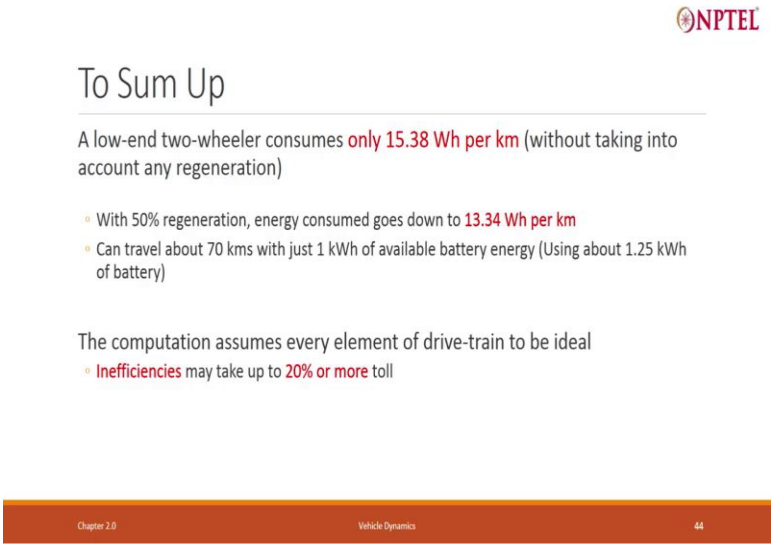

And we are able to compute what is energy per kilometer in every single case, this is something that we did for 2-wheeler, so we essentially have got the hang of it. Why did we do individual forces? Why did we look at the total traction force? Why did we look at the total torque, the total power and energy? Now, combined with a drive cycle variable to figure out what does it take, what is the energy that it takes. Now, remember that we have not taken into account the inefficiencies, inefficiency due to motor and motor controller that really one of the major inefficiency you lose a certain amount of energy , that is a result of that, that will show your watt hour per kilometer will change. We did not take into account the energy required for all kinds of other things like lights or air conditioning, you may have to include that in which case you will consume more energy per kilometer.

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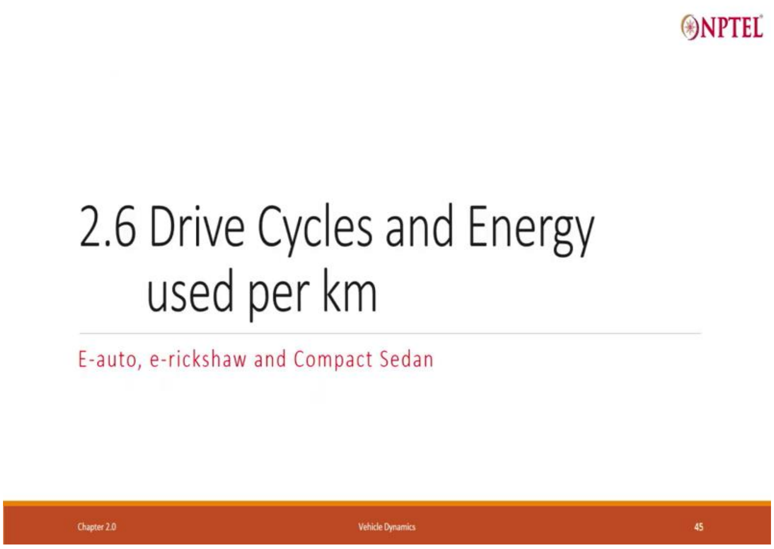

So, all these things we will be looking at it, but what we will now do is pretty much repeat the exercise that are almost I repeat, so we will go fairly rapidly. Drive cycles and energy use per kilometer for 1st an auto, then an e-rickshaw and then a Compact Sedan. Remember that for a 2-wheeler that was a little low-end 2-wheeler, we did not go above 45 kilometer also that drive cycle does not go above 45 kilometer.

It will, it could consume between 13 to 17 watt hour per kilometer, not taking inefficiencies into account. So, total energy consumed depending on the regeneration. And if you take the inefficiencies, it still be under 20 watt hour per kilometer. So a 2-wheeler essentially is like a 20 watt bulb. Remember, it is actually consumes very little electricity. Once we are able to build that we can do things quite well.

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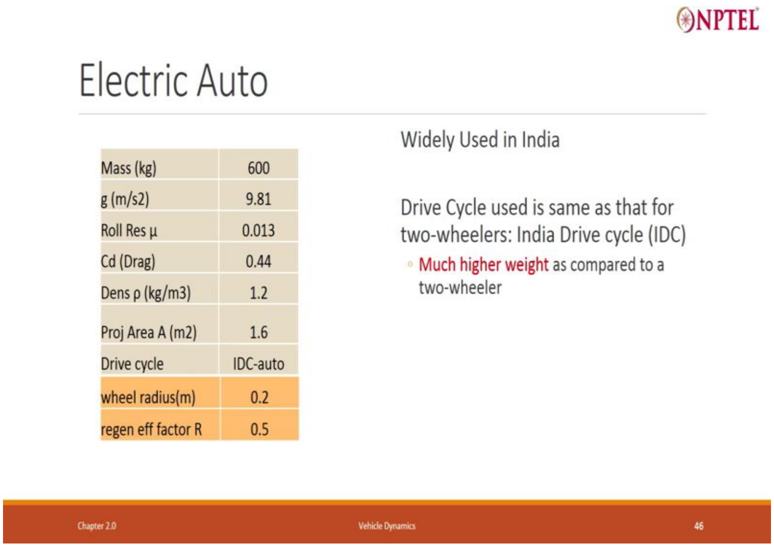

Let us now, look at an auto. If I look an auto, one of the major thing is the mass changes the cross vehicle weight, because number of passengers will be about 3 passengers plus the driver that itself will consume quite a bit then the vehicle, the gravity is going to be same rolling resistance, drag all these parameters we have air density is same 1.2 kilogram per meter cube projected area is 1.6 meters square, we will use the drive cycle IDC auto. An IDC auto is same as a drive cycle for IDC 2-wheeler, so we will use that, wheel radius is 0.2 meters smaller radius. And we take regeneration efficiency 0.5, we will actually vary that. And as I pointed out, we will use the same drive cycle.

Now, one can change the drive cycle and redo the competition, all that it means that in the spreadsheet, the velocity at different seconds will become different. So, if you do that you do the same thing, no different.

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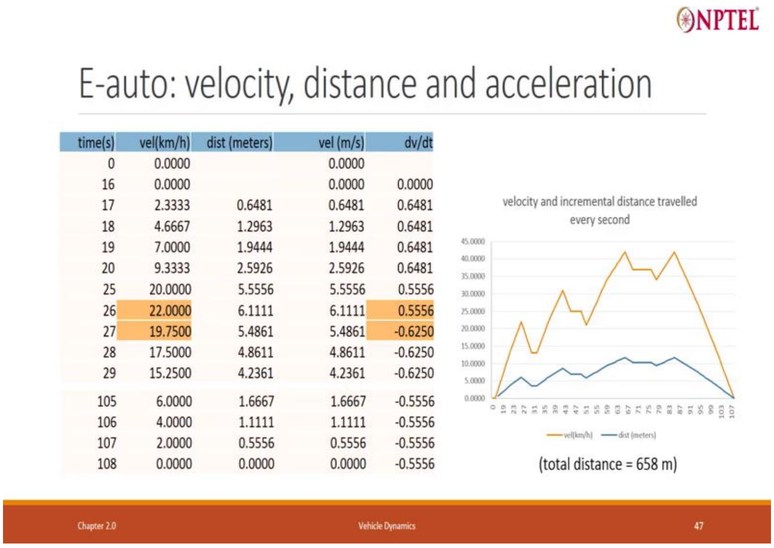

You start with at different time 0 1 2 3 4 5 6 7 8. Now why am I not shown here after 0 straightaway 16 seconds, because 0 to 15 seconds is supposed to be idling. So everything will be 0 0 0, I have just shown it out here. From 16 second onwards, you will see the velocity is going on increasing, I put the kilometer per hour, we convert it into meters per second, we actually compute the distance that it travel and the acceleration, we actually compute all of this. And if you plot this, the same plot that you saw, because the same drive cycle, this is the actual velocity at every second, it starts goes to top velocity 42 kilometer per hour and goes to 0.

And this gives you the incremental distance. And if you integrate the total distance, you find that you traveled 658 meters. Now, these 658 meters is a single drive cycle in about 108 seconds, two minutes. Now you keep repeating it 6 or 8 times I had done that. That is how you actually do the performance measurement. This is for an auto.

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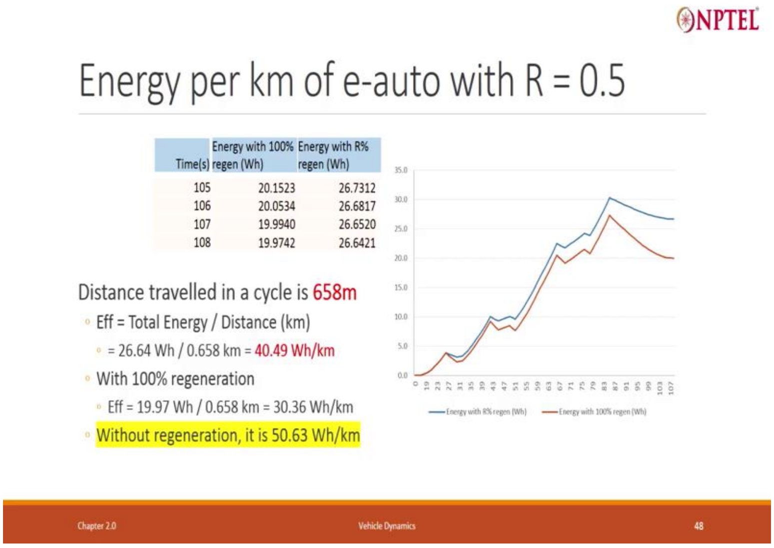

Now, let us look at what is the energy consumed. And this time, I am not getting into the details the same the spreadsheet will give you it will give you from the velocity and acceleration you will be able to then figure out what is the force due to rolling resistance force due to aerodynamic resistance, no slope I have not taken. So that is the ignored force due to acceleration because acceleration value that I have, I calculate the traction force. And after traction force, I will actually compute the torque on one side and power on one side. And then I will integrate the power that will give me a energy consumed and remember that when I am decelerating or climbing down in this case there is no climbing down then I get negative energy consumed.

Now here, I have to put in the factor. What is the regeneration efficiency? As, I do that, I actually get this and this, this is the energy required. If you take 0.5, if you take 100 percent energy efficiency, you get this and this is the energy required if you take into account the regeneration efficiency of 0.5.

So, you actually find out that the total energy required if I take regeneration of approximately 50 percent which is by the way high. I told you that 25 to 30 percent is what we will actually get. It is about 26.64 watt hour. That is a total energy consumed. You have traveled 658 meters we had just seen. So, you actually consume in a auto approximately 41 watt hour per kilometer assuming 50 percent regeneration if you took 100 percent regeneration then you will only consume 30 watt hour per kilometer.

What does it mean? I challenge the people who design motor, get me a motor which comes closer to 100 percent regeneration it is a big gain if you can get. Remember from 40 to 30. What does it mean? We actually consume only 3, 4th of the energy. My battery size can therefore goes down by three 3, 4th but this is the theoretical efficiency this required simply to move, we have just taken the rolling resistance and the aerodynamic resistance inefficiency will be on top of it. So, we will actually consume about 15 percent to 20 percent more there also depends on the motor and controller depends on the battery, we look at some of those things.

The good autos today do consume 45 watt hour per kilometer. So, they have a decent regeneration efficiency and then their motor (())(16:19) are decent. So motor controller and any other loss of course, this does not take into account if you put the lights on that time you will consume more energy, that is fine. This is what you can get, this pure from theory.

Now, how do you reduce this further from, if somebody says well, I want it to reduce from 40 watt hour per kilometer. Well, of course, if I make the regeneration better, I will improve that. I can also do by reducing weight, remember that, that is the 1st thing that helps m comes in everywhere m comes in rolling resistance, in acceleration; it comes when you travel up the slope. If I reduce the rolling resistance and put better tire that will improve, we will see that in the end. If, I put better aerodynamics, it will reduce the energy required to overcome the drag that will also improve, and as I pointed out regeneration.

So, this is something that we have to actually do. So, without regeneration, you consume as much as 50. So, regeneration is very important. Now remember, regeneration is a combination of battery and motors in (())(17:45) first of all motor it will as it turns reverse, it has to act as a generator and give you the electricity, particular to convert that electricity back into the voltage which can go into the battery if you are not able to put sheet into the battery, that is wasted.

So, it requires some careful design of battery and motor combined. So, what is regeneration, deceleration kinetic energy is getting converted to electricity. What about climbing up and down? When you climb down, you have a gravitational energy, potential energy, you are converting it back to electricity. So, that is what you do. I think getting 40 is quite easy. And that is what people are getting.

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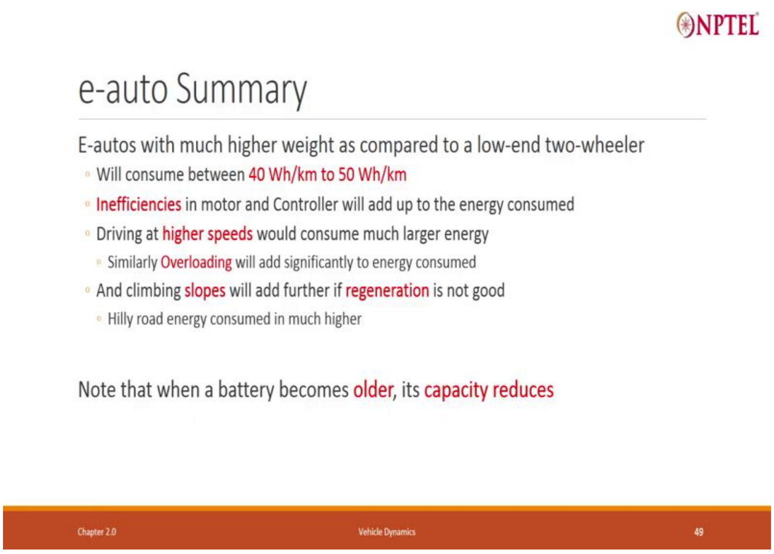

So, e-auto summary will consume it in 40 watt hour to 50 watt hour per kilometer as I told you, most of them today actually consume 45; remember that 45 consumption is without lights on. If there is any such thing as light, etc. on, it is always extra it is not counted as a standard thing. As I told you inefficiency in motor controller will add up the energy required.

Driving at higher speed. You do not drive as per the drive cycle. If you drive at higher speed, you will consume more energy. If you overload a vehicle, you will consume more energy and that is quite common in India. If you climb slopes, you will use more energy, well range will go down. The key thing is that you are not climbing slopes all the time. Of course, if the regeneration is good, it will only marginally impact.

The other thing that is very important which we will go through as we look at the battery in more detail, the battery starts with certain capacity. And as you start using its capacity keeps coming down, coming down, coming down, finally, it reaches a certain level, where the energy in a battery becomes too small, even when it is fully charged, that time you replace the battery. So, you must remember that range that you calculate using this will come down as the battery becomes older. All this has to be taken into account in a vehicle design.

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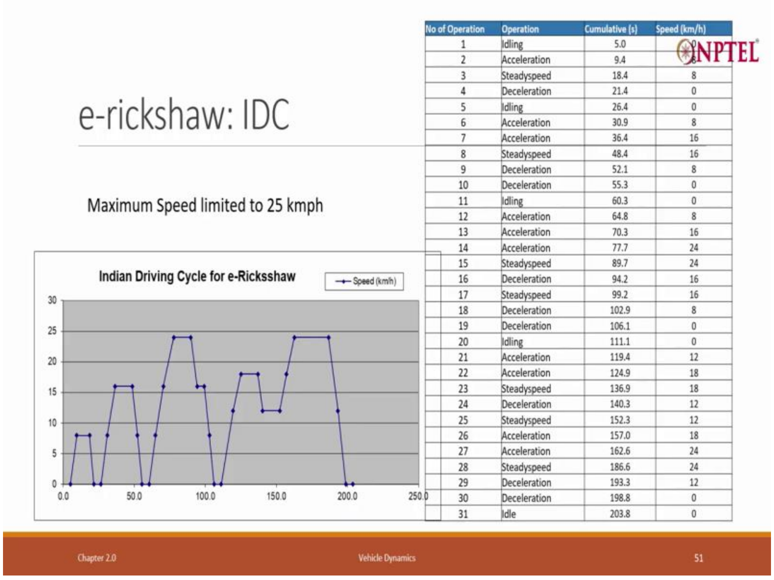

No of Operation	Operation	Cumulative (s)	Speed (km/h)
1	Idling	5.0	0
2	Acceleration	9.4	8
3	Steadyspeed	18.4	8
4	Deceleration	21.4	0
5	Idling	26.4	0
6	Acceleration	30.9	8
7	Acceleration	36.4	16
8	Steadyspeed	48.4	16
9	Deceleration	52.1	8
10	Deceleration	55.3	0
11	Idling	60.3	0
12	Acceleration	64.8	8
13	Acceleration	70.3	16
14	Acceleration	77.7	24
15	Steadyspeed	89.7	24
16	Deceleration	94.2	16
17	Steadyspeed	99.2	16
18	Deceleration	102.9	8
19	Deceleration	106.1	0
20	Idling	111.1	0
21	Acceleration	119.4	12
22	Acceleration	124.9	18
23	Steadyspeed	136.9	18
24	Deceleration	140.3	12
25	Steadyspeed	152.3	12
26	Acceleration	157.0	18
27	Acceleration	162.6	24
28	Steadyspeed	186.6	24
29	Deceleration	193.3	12
30	Deceleration	198.8	0
31	Idle	203.8	0

Let me read, do the same exercise for e-rickshaw. Now, e-rickshaw is a new thing in India, though we know that the upper limit is 25 kilometer per hour, this is a requirement, you do not get a license if it is above 25 kilometer per hour. In fact, you do not need a driving license to drive e-rickshaw. And that is a good regulation saying that well, it has to be under 25 kilometer per hour. So, slow moving, but a very important part of life in India, it has actually replaced all rickshaws and therefore, all slow moving baker, traffic, it is a slow moving traffic.

So, in fact, e-rickshaw are not allowed on the highways, e-rickshaw are not allowed on the bridges, it does not have the sufficient torque for it to climb. But, with this restriction it works very well. Remember that old hand pulled rickshaw and cycle rickshaw that used to be used old person trying to cycle with some 2, 3 heavy people have sat down, all this to some extent has gone whereas, now, with the motor driving it becomes easier (())(21:53) e-rickshaw is a big boon. Of course, a slow moving so, it can block the traffic so, that those are concerns, but there is a drive cycle defined this is not a strictly a standard it is some of us had got together all, with all the e-rickshaw manufacturers and figured out what kind of drive do they actually do.

How do you find that either they drive, they 1st they will go to a certain speed and keep on going down then they will go to another speed and keep on going down on average we found that with when measuring that this what they are doing and we actually defined this and there is a frequent stopping and increasing the speed and therefore there is a increase in speed and going down.

Now, remember if there is regeneration of 100 percent this will not consume much energy but otherwise it will consume energy and we have defined that again every second what happens every second or 5 seconds or 9 seconds, 5 to 9 second speed will be this we defined that and then from 9 to 18 seconds speed will be this. So, you can compute the acceleration, you can compute the acceleration put the input to the spreadsheet every second what the velocity will be every half a second what the velocity will be compute the acceleration. And you take the specification of e-rickshaw that is very important. This is the input to the spreadsheet.

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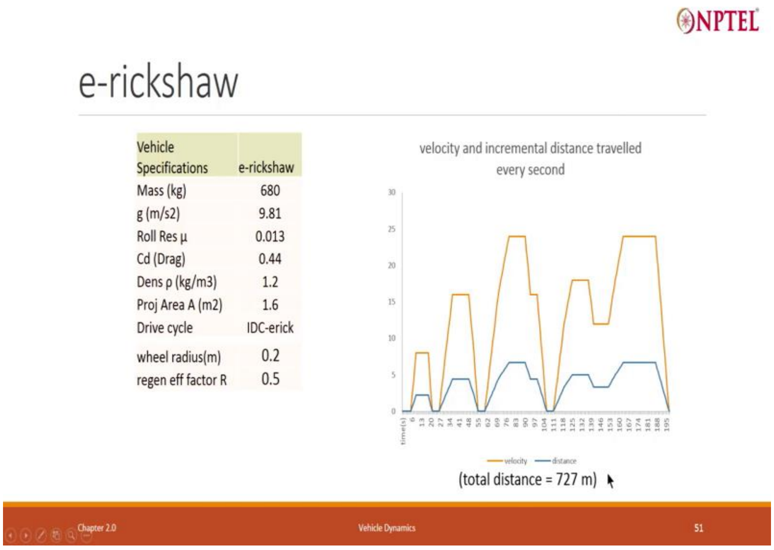

The mass 680 kg, g, the rolling resistance, drag density of air, projected area, the drive cycle, wheel radius and regeneration efficiency. So, you take all of that and you find that this is what the drive cycle gives you, it is a 727 meter this plots the incremental distance that will travel this plots the velocity and 727 meter drive cycle.

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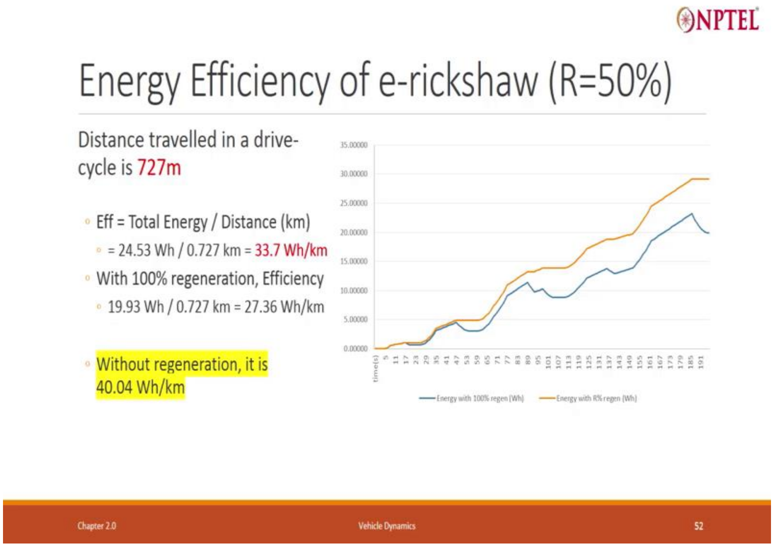

Now, you compute the force, traction force, power, torque remember so far we have not been using torque because we went into energy and energy efficiency torque will play a very important role later on when we design the motor as well as the battery, it will play a very important role. And but we know what the torque will be and we find again that if I take the thing with 100 with approximately it takes 24.53 watt hour, this actually shows middle higher at 727 meter, this shows me more like 28 29 watt hour this actually shows me 20. So this is probably a different regeneration efficiency with 100 percent regeneration efficiency. It should be 27 watt hour per kilometer.

And, again the number here shows different I will check this out why it is so, but I am able to I know they travel 727 meters, so I am able to find out the energy efficiency, energy efficiency is 27 with 100 percent regeneration efficiency, 33 with 50 percent regeneration efficiency and without regeneration is 40. This is what a e-rickshaw consumes. Remember, it is a slow moving vehicle. So in some sense, it is different, it is a slow moving vehicle. And that is what happens. Any questions? So, I have done it for 2-wheelers, I have done it for e-rickshaw, I have done it for auto. Let us do it for the vehicle that I drive, a small Sedan.

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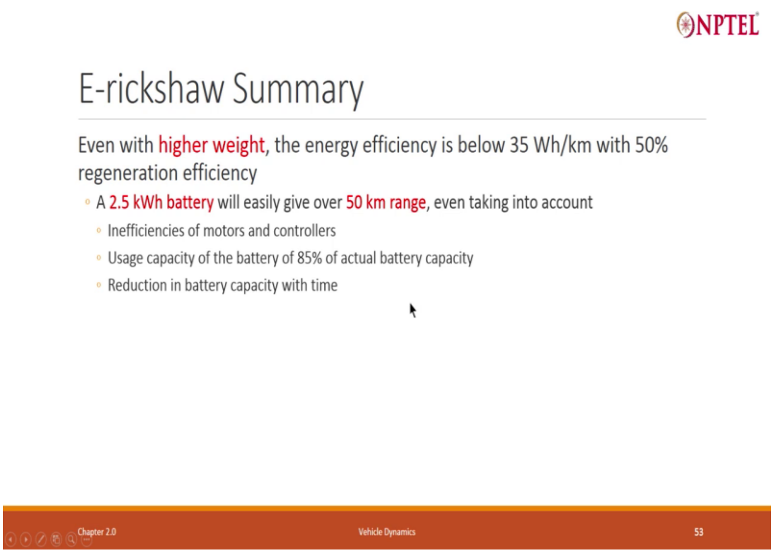

So, e-rickshaw summary even with higher rate, the energy efficiency is below 35 watt hour per kilometer with 50 percent regeneration efficiency. Now what does it mean if I take a 2.5 kilo watt hour battery, and I am consuming only 35 watt hour per kilometer, it can easily give me 50 percent, 50 kilometer range, even taking into account that only 85 percent the battery is usable at any time. Of course you will remember that these reduction in battery capacity over time, so your 50 kilometer range will start slowly coming down. Overloading and over-speeding will hurt always.