Fundamentals of Electric vehicles: Technology & Economics
Professor Ashok Jhunjhunwala
Lecture 16
Drive Cycles and Energy used per Km

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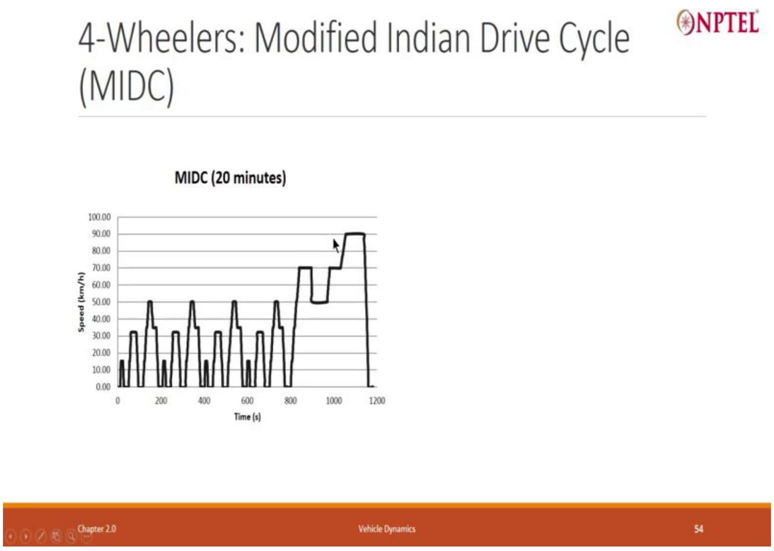

Now let me come to a sedan and this is a very common dry cycle that is used in India called Modified Indian Drive Cycle, this has been defined by various regulatory agency it is a 20 minutes for cars for cars. And it is a modified India drive cycle, to was a India drive cycle and then they modified it by looking at actually how the vehicles travel.

And if you find this one thing again you see that it actually is driving, so lot of stop and wait it, it drives then stops, drives then stops that is a very common of the city driving, but so this is a city driving this is not highway driving but you also see that occasionally it goes to 70 kilometer and even 90 kilometer per hour.

So, this is a big difference between a four wheeler or four wheeler does when we for example drive on IT highway 80-85 kilometer per hour is quite common you also in the evenings and all that you can go to 90 kilometer per hour and of course highway driving would largely be between 40 and 80, 90 kilometer that will be a different kind of drive cycle but this drive cycle is also standardized, it was actually standardized for a petrol vehicle but we are using the same thing for electric vehicle.

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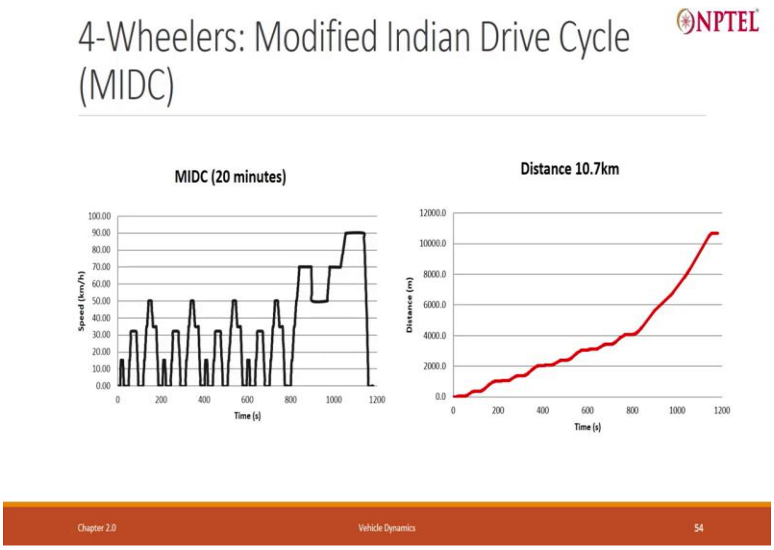

So, once again we can calculate the incremental distance travelled and you find that if you go through at and this is only giving you velocity versus time velocity versus time, that is all the drive cycle gives you and from there you have to compute the acceleration. You find that integration of the, find the distance it travels incremental distance integrated it comes to 10.7 kilometer. So, it is a standard 11 kilometer drive 10.7 kilometer you compare one vehicle versus another, how much energy does it consume?

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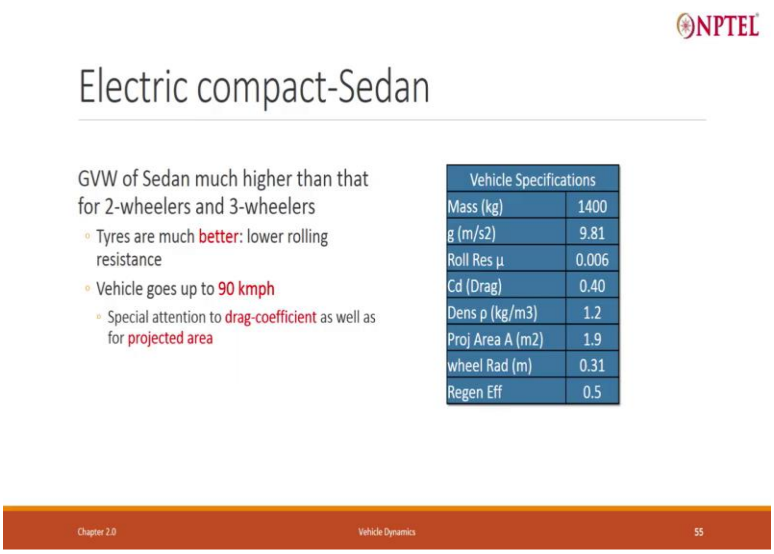

Given this, you again take a sedan, we have taken a rough sedan 1400 kg rolling resistance is good you put better tyres in the four wheelers, drag coefficient is 0.4 projected area is close to

2 square meter, wheel radius is bigger 0.3 meters, again we have assumed regeneration efficiency of 0.5 well we will keep changing that and we then as you pointed a vehicle goes up to 90 kilometer, so drag coefficient matters a lot projected area matter a lot remember these two parameters play a role.

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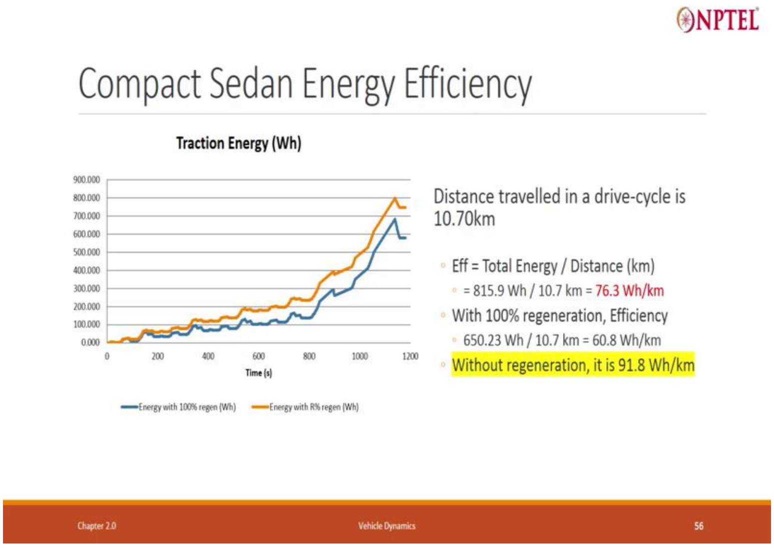

And again i calculate what is the energy efficiency, first I will just put that in the spreadsheet the numbers, the velocity numbers versus every second find the distance traveled convert into meters per second, find the acceleration then find all the three forces acceleration force, the rolling resistance force and aerodynamic force I find the total force required from there I compute torque on the one hand I compute power on the other hand integrate it to get the energy and integrate the distance incremental distance to get the total distance.

And if I find here if I look at this the efficiency is coming to 815, 815, 815 again I see here the curves showing slightly different I will check out all these things maybe this is with 100 percent regeneration this is with 50 percent regeneration I think I have taken 50 percent and the peak goes to little bit above 815 actually should have gone to 750 but if I take 816 watt hour and I divide it by 10.7 kilometre I only need 77 watt hour per kilometer and if I do not take the with the 100 regeneration it only consumes 60 650 again not correct here but I will double check these figures 650 or watt hour and that comes to 60.8 watt hour, without regeneration consumes 91.

So you can see 90, 76, 60 if I can get regeneration I need much smaller battery between regeneration and without regeneration watt hour per kilometre is 50 percent higher I mean from the 100 percent regeneration is 50 percent higher with no regeneration, why? Because you are going up and down increasing the speed and going down, thats what you are doing not travelling at constant speed lot of acceleration and deceleration. Well, that gives us what do we need, it will give us of course this is not taking into account efficiencies, so you have to add all of that.

Reality my vehicle consumes closer to 125 watt per kilometer it clearly tells me that there is something not right because I am more or less given the data for my vehicle I do not know whether the tyre is that good probably probably not as good but the main difference is in the motor it actually uses a induction motor this is a version one of electric verito it uses a induction motor which at high speed gives me alright efficiency but at lower speed gives me very poor efficiency.

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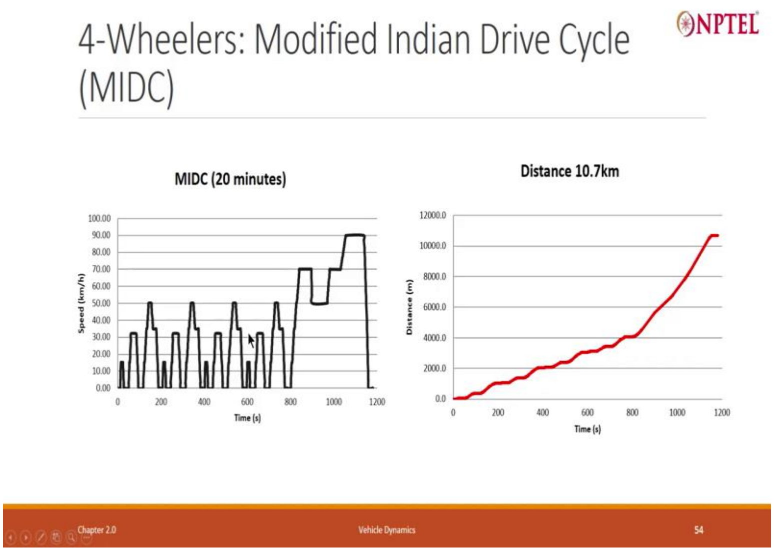

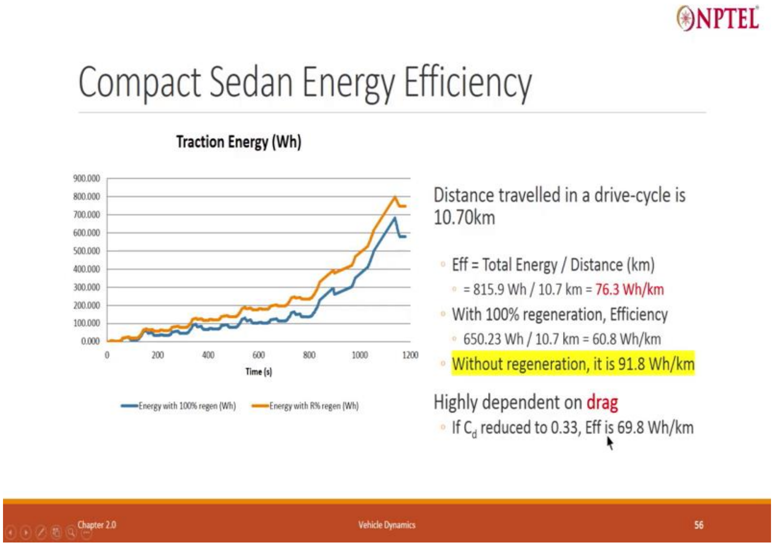

And since most of the time I am actually travelling at lower speed look at this, that is what the city drive does, on campus I always travel at lower speed I do not even ever go to 50 kilometer per hour it gives a very poor efficiency and that is the reason on the other hand if you design a good pmsm motor you can get very good efficiency. This is something that we learn from this, the other thing that we will see in a little while is that it is highly dependent on drag, drag why? Because we are going up to 90 kilometer per hour drag plays a very important role if cd is reduced efficiency goes down from 76.3 or probably I do not remember now whether it was done with 100 0 regeneration or 50 percent rejection I will double check that but you can significantly reduce that I will show you this number later on again.

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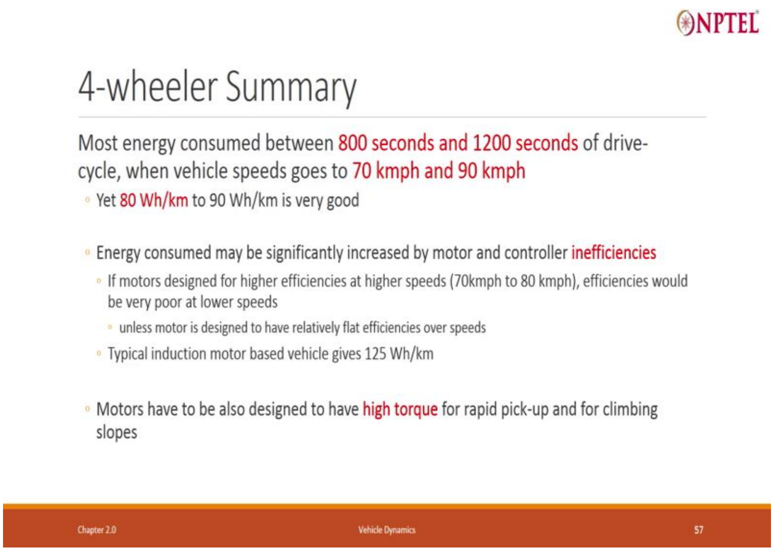

So, if I summarize my four wheeler most energy consumed between 800 second and 1200 hundred second, in fact that is what you see most of the energy actually energy consumed till 800 seconds not very large most of the energy is consumed here this, now between 800 seconds and 1200 seconds what is happening? It is vehicle is going to look at between 800 seconds and 1200 second this is a time the vehicle is going up to very high speed 70 and 90 kilometer per hour.

Now, 70 to 90 kilometer per hour thats a time drag takes over and that is the reason most energy is consumed there. So if I do not drive that speed I should get very good energy efficiency, yet 80 watt hour per kilometer to 90 watt hour per kilometre even with inefficiency if I can get 100 watt hour per kilometer is actually good as I point out motor inefficiency will take into account.

As I pointed out if motors are designed at for higher efficiency sorry higher efficiency at higher speeds at lower efficiency it may not be at lower speed it may not have a good efficiency and will hurt you a lot, that is what actually is happening and typical induction motor based vehicle is giving you 125 watt hour per kilometre because of that. So how important it is for you to design good vehicle, the other thing that will become very important which you have not done while you have calculated torque we have not yet talked about how much torque is required and is the motor giving me sufficient torque.

We have calculated what the torque is required, we have not done climbing well but even I have shown you how to calculate that and in one of the home assignment I have told you given you that when you climb and go down what is the torque and energy required. So the torque needs to be also taken into account in designing the motor.

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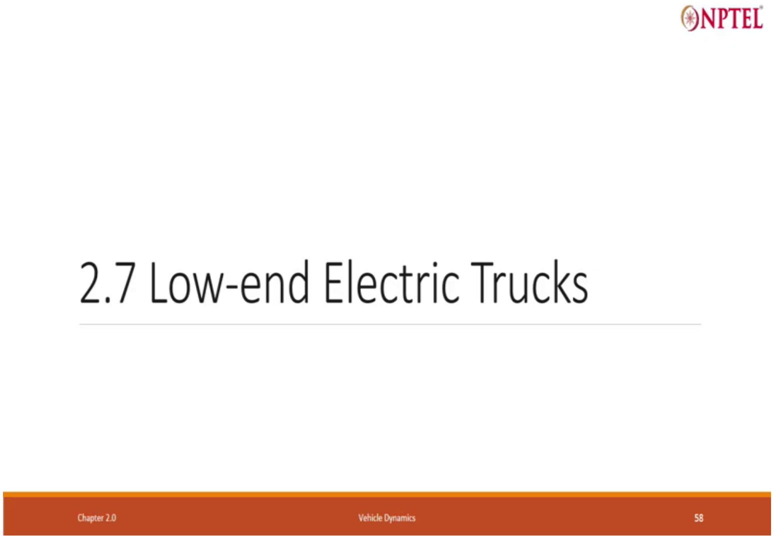

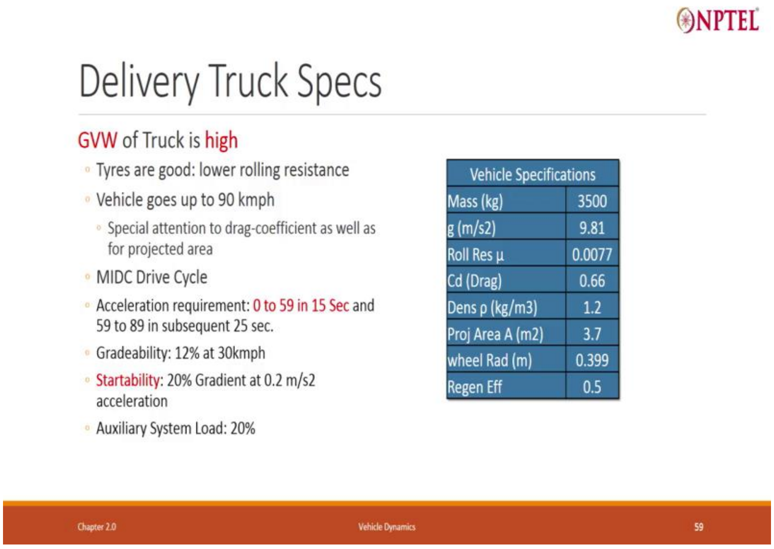

I will once again now take up one more thing a low end electric trucks very similar to what we have done except the requirements now will change. Fortunately, the GVW the gross vehicle weight is very high you are talking about 3500 kg remember that for a four wheeler we took 1400 kg that is and this is a low end truck this is not a high end truck with the material, rolling resistance is very good I deliberately make my tyre very would I spend money on tyre, why should I waste energy drag coefficient, well cannot do much about it, it is a large vehicle, so there will be lot of drag lot of projected area.

Wheel radius is made higher 0.4 meters I have taken different regeneration efficiency the vehicle is designed to go up to 90 kilometer per hour which is also travels limited extent on the highway but I have we have taken this midc cycle the same side cycle that we did for four wheelers so it will mostly run at lower speed once in a while go to the higher speed.

So. something that you have seen between 59 to 89 second it travels. There is a acceleration requirement, this is something that we had not taken but the accelerate requirement is in first 15 seconds it should be able to go to 60 kilometer per hour, you will see that this does not impact the power or energy as much it will impact the torque and then from 60 to 90 seconds it should be able to go in 25 seconds 60 to 90 kilometer per hour kilometer per hour and this is kilometre per hour I should have added then I will make the change this is a kilometer per hour in 25 seconds.

There is another very important parameter about the truck, what is the gradability? So, I have taken 12 percent it should be able to do at 30 kilometer per hour. Now, that is again will show will impact the torque quite a bit but not just that suppose it is on a slope sometime you are traveling on a slope say 12 percent but then you need to park so you actually move around there is a small thing much higher and you go and park there.

Now, at 20 percent gradient it should be able to start, we are not talking about 30 kilometer per hour, we are talking about 0 or 1 kilometer per hour it not only has to start but also has to do a little bit of acceleration if it does not accelerate it will never reach never increases velocity. So small acceleration will take time for it to start moving that is additional requirement that we have put and we have put auxiliary system load of 20 percent. So some of these things will impact the torque we have not done too much but the first level come back to this vehicle again and again this specs this vehicle.

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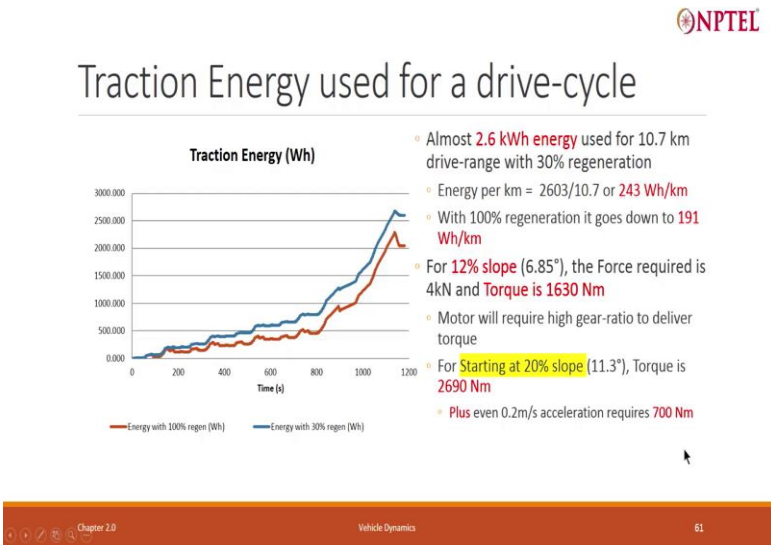

But what I have done is I have taken the same midc cycle same distance of 10.7 kilometer no slope I have not taken slope into account and I have actually calculated the energy requirement and you find that with 30 percentage I have done it for 30 percent regeneration and I have done it with 100 regeneration.

At 30 percent regeneration this number is right 2603 watt hour it consumes 10.7 kilometer it consumes close to 243 watt hour per kilometre, this is a much bigger truck and if I take 100 regeneration, of course it consumes much less it will only be slightly above 2000 watt hour it will consume in 10.7 kilometer I can calculate it is 191 watt per kilometre.

I have also calculated the torque and that comes from the numbers that we saw for 12 percent slope at 30 kilometer per hour at 30 kilometer I should have written at 30 kilometer per hour the force required is 4000 Newtons that number is there in our calculation 4000 Newtons and torque requirement goes to 1630 Newton meter very difficult to design such kind of motors with gears will bring the gear later on, we will require a high gear ratio 1630 Newton otherwise motor will not electric motor will not be (())(15:00)

But I had also added that starting torque 20 percent slope that is 11.3 degree slope remember I had told you how to convert the percentage slope into degree the torque required is 2700 Newton meter and torque is independent of velocity, so even at 0 velocity you require the same torque plus even for 0.2 meter per second acceleration to just get it moving, we are not bothered about the speed at that time get it moving by 0.2 meter per second that is a acceleration you require another 700 Newton meter so you require almost 3500 Newton meter torque, that is going to be not easy and that is something you have to worry about when you design a motor.

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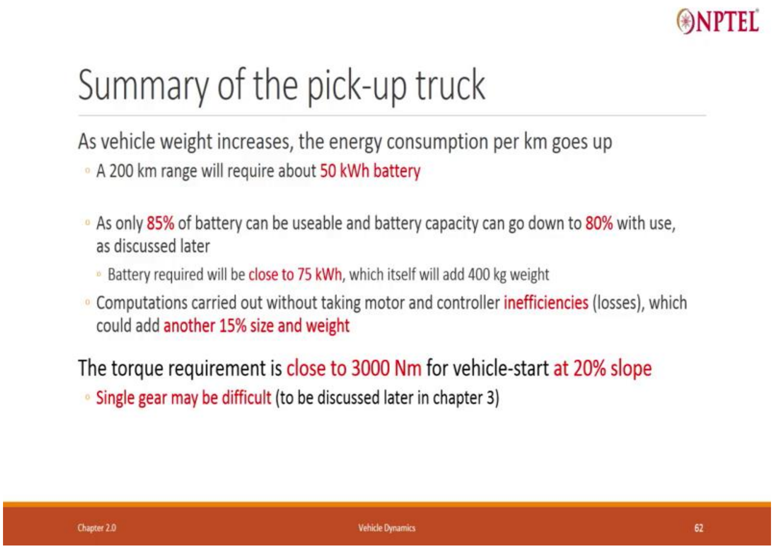

So, summary of the pickup truck, it is a low end pickup truck we actually find that since it consumes, how much energy? It consumes about 250 watt hour per kilometre so I if I have a 200 kilometer I require a 50 kilowatt hour battery I may require slightly excess because I am not taking into account the inefficiencies so 55 maybe 60 kilowatt hour as 85 percent is used and finally it goes to 80 percent because the battery deteriorates and still should give me 200 kilometer my requirement goes to 75 kilowatt hour, I will look at this 85 percent 80 percent number in greater detail later on.

Now, remember that 75 kilowatt hour itself will add 400 kg of weight, so my total gross weight has to include this if I have a smaller battery 50 kilowatt hour it will be less so we have to compromise we to have to figure out. Computations carried out without taking motor and control in efficiencies which could add another 15 percent weight and size.

So, the motors and controllers will be better designed so you get good efficiencies but 15 percent size. Torque requirement is about 3000 little more than that 3500 at 20 percent of slope single gear may be very difficult and yet one might try to do it with single gear, otherwise one has to do gear change in which case you have to have a clutch which disengages the gear and then go to another gear. Remember that high slope when you are trying to climb up maybe just for that you may have one gear for acceleration you probably will manage, this is what will be required.

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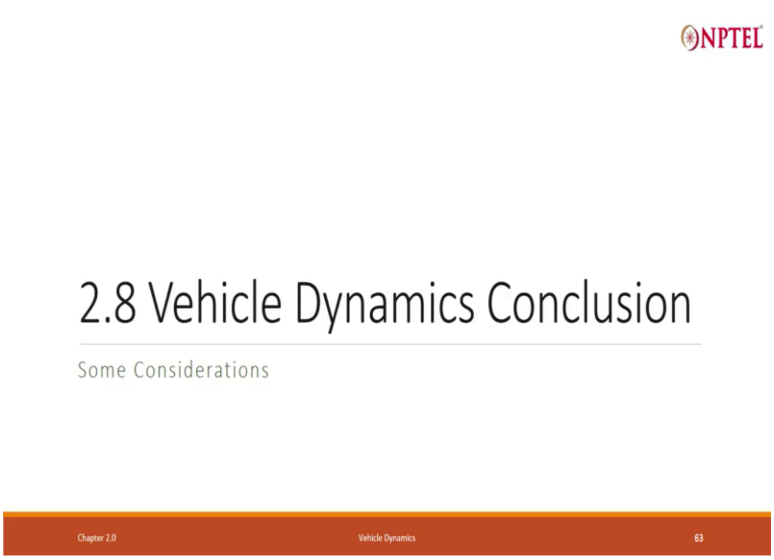

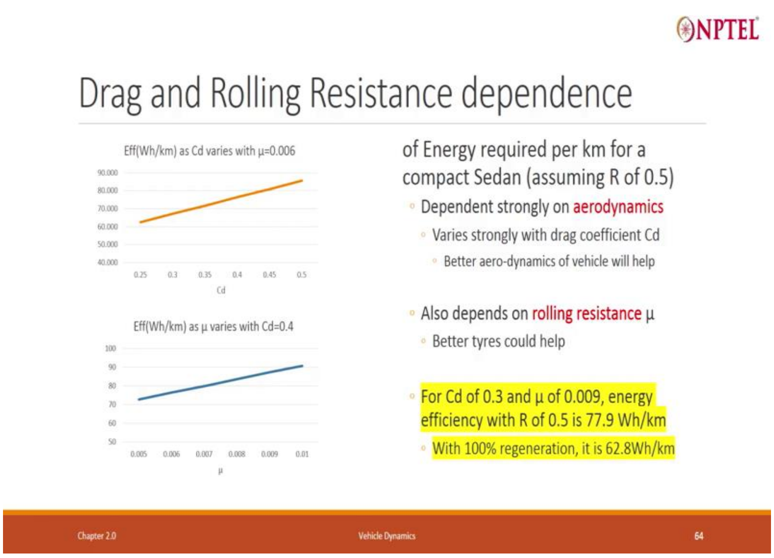

So, let me come to the conclusion of vehicle dynamics I have done that over last four four and a half five hours. One more thing that I actually did after we computed this energy efficiency I took this sedan and say what if I vary the drag coefficient, what will happen I have taken here mu to be 0.006 and I vary the drag coefficient as I vary the drag coefficient I see the watt hour per kilometer significantly varies if my drag coefficient can go down to 0.25, then my energy requirement is only about 60 to 63 watt hour per kilometer this is assuming r equal to 0.5 regeneration.

On the other hand if drag coefficient goes up to 0.5, then it goes significantly high to almost 85, 90. So one has to be very careful each of the parameters sensitivity this is called sensitivity analysis I will be very careful that my cd does not go up, cd is as low as possible.

Similarly, I look at fix the cd and start varying the mu the rolling resistance this time now remember that you cannot do too much about the area it was cd into area so area you cannot do too much cd is one thing that you can change and the other thing is this is not as bad but even here it goes to 70 to 90. Well, here it goes from 60 to almost 88, 90 here it goes 72 to 90 and again I have taken mu to be 0.6 if I increase it it can get very bad if I reduce it can go down.

Now this means value of a tyre, remember somebody will say, well it will add 2000 rupees extra for or all the tyre there are so many tyres in a sedan there are only four tires it will add 5000 rupees but if 5000 rupees will give me 10 watt hour per kilometre reduction you just compute in no time in a year you can recover that cost.

This kind of optimization which is extremely important for electric vehicles your battery size can go down, your that means capital cost cut down and of course energy will also go down. So, this is something that I talked about this is with r equal to 0.5 and with 100 percent regeneration it is much better. Now, so far I have not talked about torque, though I did compute torque the importance of torque we have not talked about, torque is required one is an acceleration again in the slope.

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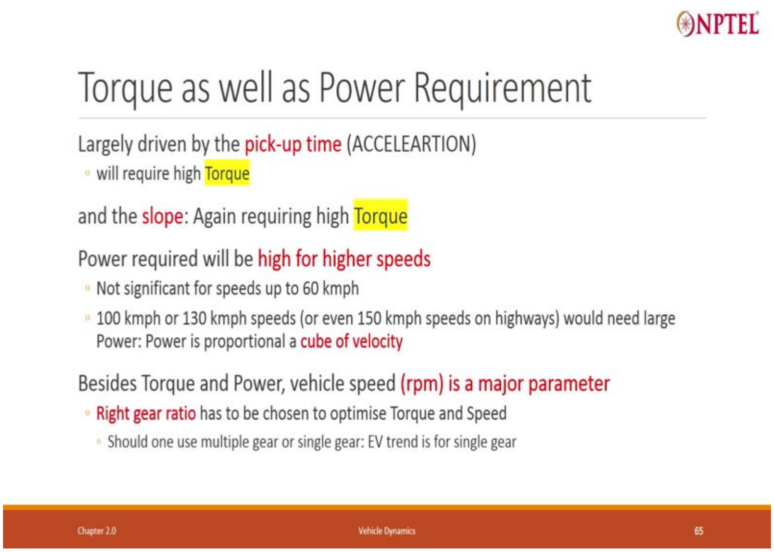

And you will repeat it why we have computed it so you will find it that this is a major issue as speed becomes high power requirement goes high torque remains more or less constant does not depend on speed. So, on the one hand I have to worry about torque otherwise I have to worry about power at high speeds and low speed power requirement is not large if you saw the number below 50 kilometer 60 kilometer very little once you went to 80, 90 it went up.

So, power requirement above 60 kilometer per hour you have to worry about if you go to 100 kilometer per hour or 130 or 150 kilometer per hour your power becomes very high but do not forget power is a cube of the velocity. So, correspondingly your energy requirement will also go up the battery size will go up, so besides torque and power the other critical thing that has to be one has to worry about is RPM because RPM will give you what is the speed at which you can go you can design for power and torque to go to 150 kilometer if your RPM does not allow you to go to 150 kilometer per hour what you use.

Of course, both power torque and speed you can multiply torque divide speed by a certain factor by the gear ratio, of course if you change if you have different gears that is multi gear which will require a clutch and all that you can use a different gear ratio a smaller gear ratio when at high speed and we need high torque you can have a higher gear ratio but if you use a single gear you have to balance between the two, we will learn all these things going forward.

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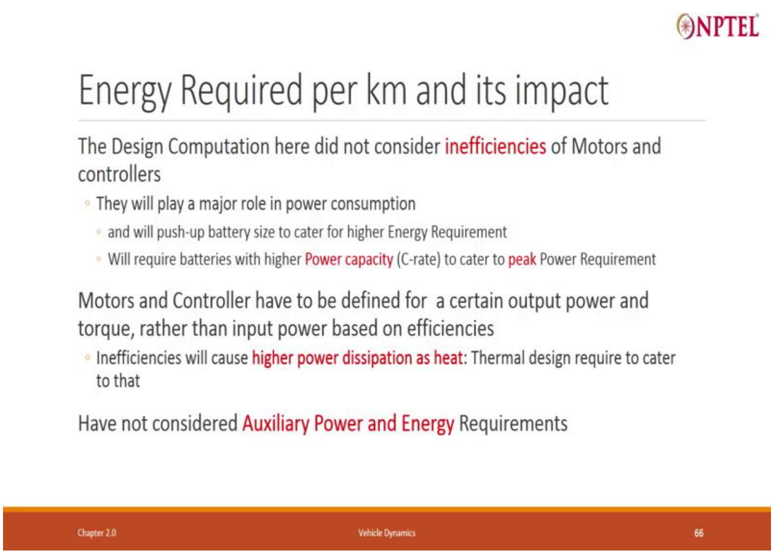

Energy required per kilometer and its impact I am repeatedly pointing out while we are learn to calculate it we have not taken into account inefficiencies if we take into inefficiencies actual requirement we is very close to what we computed. We just multiply by that inefficiency and you will see that. We also require in the battery when we talk about battery we will see there are two parameters, one is the total energy required another is a peak power requirement a peak power means you are trying to draw higher current from a battery and as we learn as we talk about battery you will see higher current drawing large currents also is a problematic it impacts the life of the battery.

So, we will look at what is called c rate the power requirement also in greater detail. Motor controllers have to be defined for a certain output power and torque and rather the input power. So, the input power could be whatever and we have the inefficiency that means the output power that I want what we have all computed is output power.

One other issue that comes up if you have larger inefficiency in motor controller your output power is much less than the input power, what happens to the rest of the energy rest of the power? It actually dissipates as heat, so thermal will become very important what will you do with the you cannot allow it to keep on getting heated up you have to remove that heat so in motor and controller that also will become very important. All the time so far we have not considered the auxiliary power and energy requirement in real vehicle you will have to add this.

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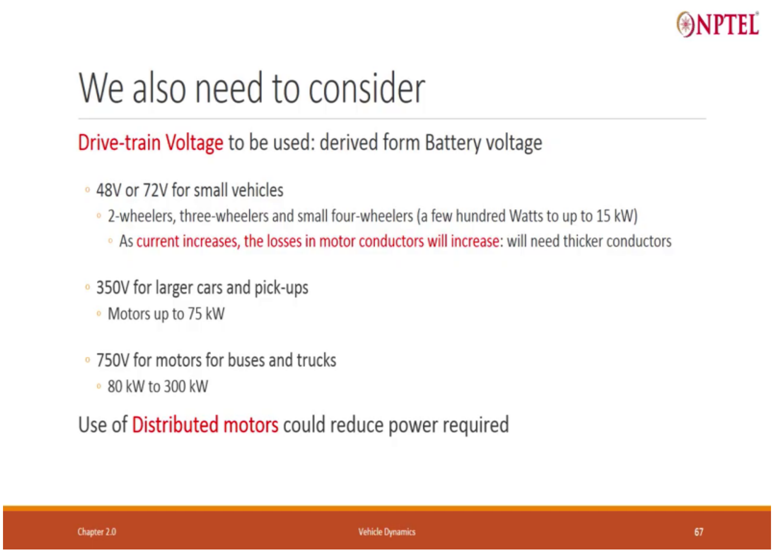

I think the last thing that I want to actually look at, what should be the drivetrain voltage that I should use? Well, the one which is commonly used actually is 48 volt for small size vehicles very common 48 (())(26:28) these have more or less become standard throughout the world for two wheelers, three wheelers, four wheelers in the marginal 48 volt is not good enough for in India some four wheelers are defined at 72 volt, 72 volt is not a standard in the world it is more used in India 48 volt is very common.

As you go higher vehicle cars you tend to go to higher voltage, why? Because for the same power if voltage goes high current goes down if voltage is small 48 volt your current will be 200, 300 amperes anytime you have to use 200 to 300 ampere first all your battery should be capable of giving that not easy, you will see that. Number two, lot of heat dissipation I square r loss will always there even a conductor he has a resistance I square law r loss will be there large current I square.

So, if you limit yourself to 100 ampere you will get loss is 100 square into r if you go to 200 amperes your actually losses become 4 times and if you go to 300 ampere losses become 9 times. So, you if you go for higher voltage your current can be smaller and that is the reason for motors up to 75 kilowatt this is used for motors up to 12 to 15-kilowatt 15 kilowatt you know 15 kilowatt itself at 48 volt is 300 amperes.

At 350 volt if I go to 75 I am still talking about slightly higher than 200 amperes and for even higher power you go for 750 volt 80 kilowatt to 300 kilowatt. Now, of course that 300 kilowatts you still have a very very high current requirement of 400 amperes but I have not seen vehicles going above 750 volt. So, these three are emerging to be standard 48 volt, 350 volt, 750 volt and everything will have to design motor and controllers to design battery has to be design, your converters has to be designed accordingly.

There is one more concept which will not deal with in this course, can I use distributed motors? Can I use four motors on four different tyres? My cost goes up but can I reduce my increase my energy efficiency use less energy per kilometre, can I have more maneuverability all this is possible. So, you will see more and more distributed motors instead of one motor driving the whole vehicle maybe two more or maybe four motors and you will see that.

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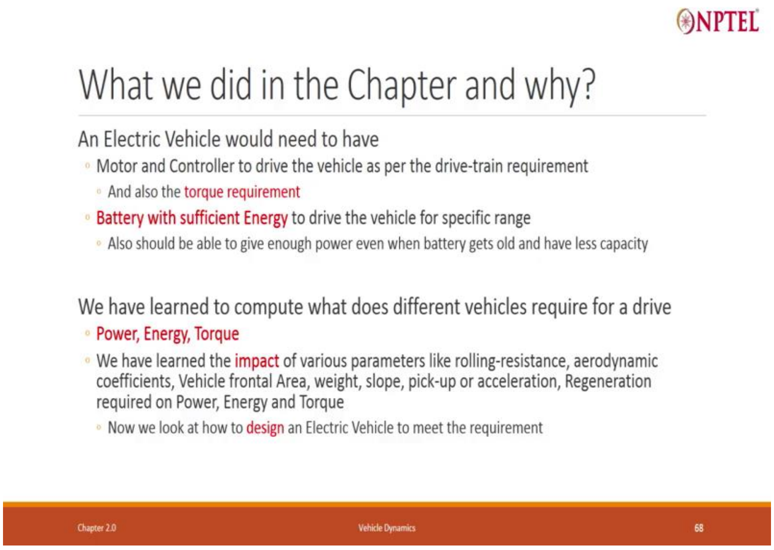

Finally, what did we do in this chapter and why? An electric vehicle would have to have a motor and controller, we have for that computed what is a torque requirement we have computed what is the energy required power requirement for the motor battery will have to have sufficient energy, so we have actually talked about what is the energy required to move a vehicle go to a certain drive cycle and at every instant it should be able to give me a give sufficient power to motor and controller that is what well we have tried to figure out.

We have learned to compute power energy and torque for different vehicles at different speeds of course at different speeds and this is something that we will be doing more and more, we also learned the impact of various vehicle parameters like rolling resistance aerodynamic resistance vehicle frontal area, weight, slope, pickup acceleration, regenerative requirement, on power energy and torque.

And all at different RPM and we have touched upon we have not really covered this the impact of gear ratio which I will actually do in the next next chapter. What we will do having done that I am going to go to the overview now, chapter 3 will look at the subsystems of electric vehicle, where we will also look at what motors are controlled what battery? What is the gear ratio that you require? What are the parameters for a vehicle? And what are the sub systems?

After that in chapter 4, we will do fundamentals of batteries, then chapter 5 and 6 will run concurrently one on motor and controller another is details of battery design getting into the details of battery design. And then in chapter 7 we will talk about charges and charging infrastructure and finally we will end by talking about the overall what kind of in management that you do when you try to run electric vehicles. I have completed this second chapter which is a very important chapter which actually helps you understand what is the force, torque, energy, power at different RPM for all kinds of vehicles.

This as I pointed out right in the beginning would be done for even a internal combustion engine vehicle, petrol vehicle, diesel vehicle more or less the analysis is same we may use few terms like regeneration is unlikely to be there in a petrol vehicle though today's petrol vehicle have a electrical battery and does a regeneration because the transition is going on.

So, that much is common so automotive engineer would probably already know that but here I trained we also got it for electrical, electronics, computer science, civil, aeronautical engineer to figure this out. One thing that I have not done I have done all kinds of vehicles two-wheeler, three-wheeler, four-wheeler, trucks.

Now pretty much any other vehicle can be figured out what I did not do is a boat or a aircraft both are vehicles the mechanism is not exactly the same but a very similar approach let me see at least if I can do something towards the end on a aircraft the because a lot of UAY lot of youngsters are not designing UAY, what is the motor required? What is the battery required? At least you will figure it out.

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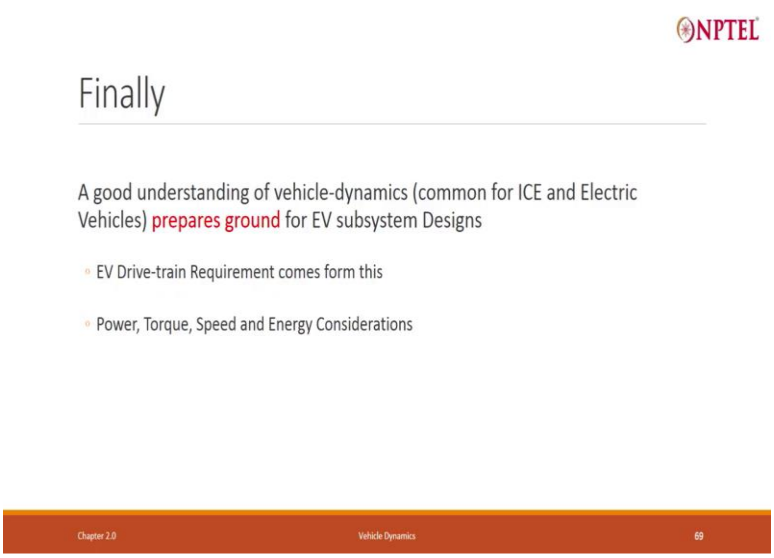

And want to point out that a good understanding of vehicle dynamics prepares ground for EV sub systems design EV drive trade requirements come from this power, torque, speed and energy consideration at different RPM different speeds because very important.

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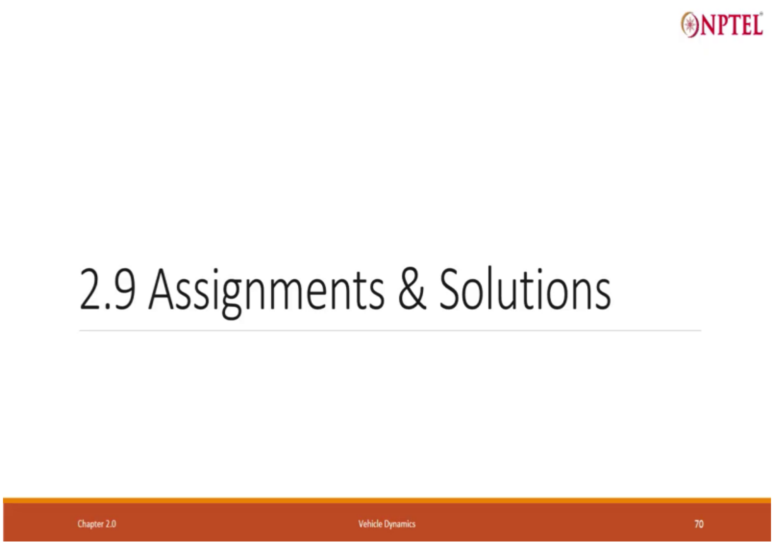

I have we have given a number of assignments throughout the chapter, please do that a lot of learning will come from those assignments, thank you very much.