Sustainable Transportation Systems
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Lecture 41
Modelling of Transport Emissions-II
Case Studies on Application of IVE and VAPI Models in India

Hello friends, you may recall last time we discussed various emission inventory models and today we will apply two of those models like IVE model and VAPI model. How to use them to get different scenarios so that policy related or technology related impacts can be analysed by application of these models.

So, the real life application of these models would be discussed in terms of case studies; 4 case studies we have included in this particular presentation.

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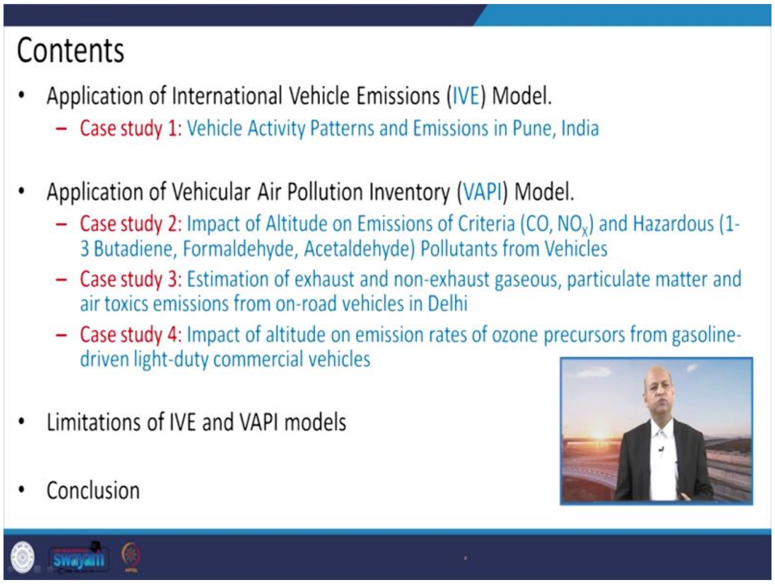

First case study is based on IVE model that is International Vehicle Emissions Model of USA and 3 case studies will be related to vehicular air pollution inventory model that is VAPI model which was developed by IIT, Roorkee.

So, these are the case studies basically one IVE model was applied in Pune to estimate emissions and their patterns and then like impact of altitudes on different kind of vehicle category on emissions of different criteria pollutants and estimation of exhaust and non-exhaust emissions of pollutants from vehicular emissions or transportation related emissions and the last 4th study is related to again impact of altitude on the rates of emission rates or precursors of ozone.

So, these will be discussed and then later on, we will discuss the limitations of IVE and VAPI model. You may recall last time also we discussed certain limitations of IVE model and then we will conclude this presentation.

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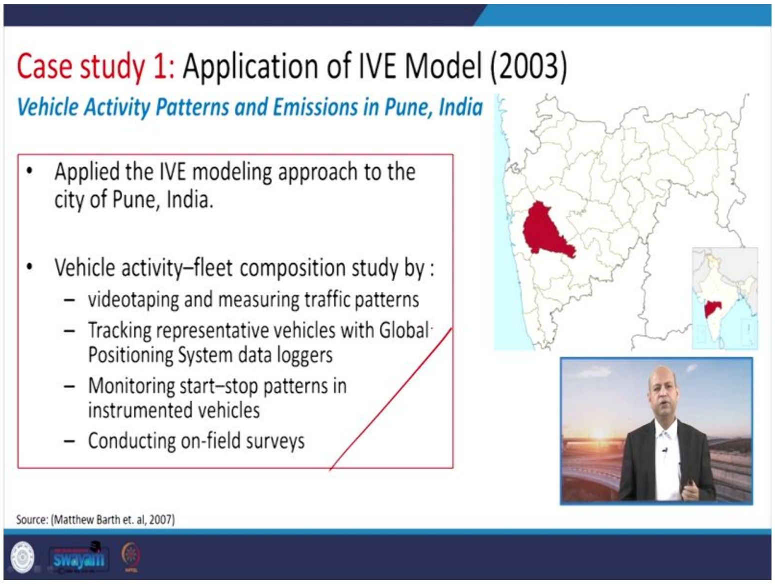

So, the case study first is related to application of IVE model in Pune, India. This was the study which was conducted in 2003 and later on the results were published in 2007. So, this was applied in this particular city of Pune of the Maharashtra State of India and different kind data were collected based on like videotaping or measurement of traffic counts and patterns of their movements and then tracking their representative vehicles with this GPS system.

And then monitoring like a start and start-up and breaking related patterns and conducting on field surveys. So, that the real life data could be included in the study that was very important not only the secondary data, but the first set of the data, primary data were also estimated or collected by virtue of survey.

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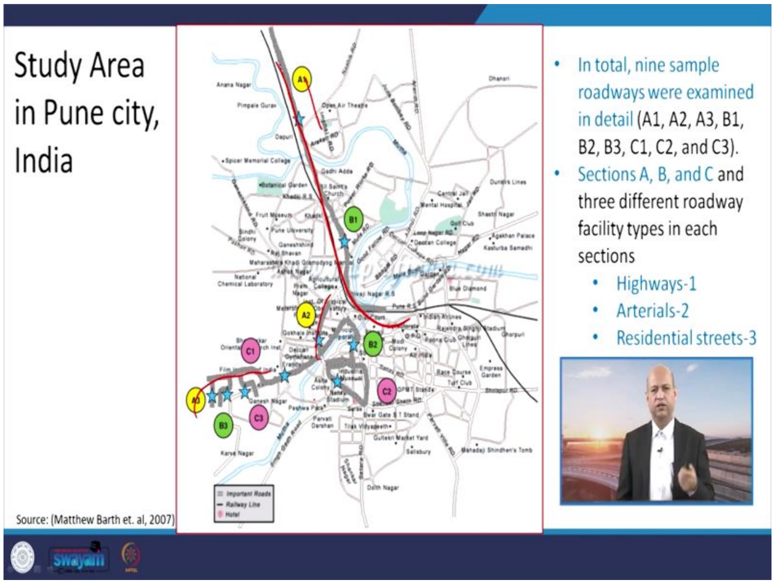

So, the study area of the Pune is shown and you can see they were 9 sample roadways where this survey and monitoring were conducted and vehicular movements were analysed those were like A1, A2, A3, B1, B2, B3, and C1, C2, C3 you can see this A1 road is like this one and then A2 road is there A3 is this one and then B3, B4.

So, they include basically the highway and then the arterial roads and then residential streets. So, all three kinds of means narrow, mid and the highway wide and like speedy traffic kind of moment were captured.

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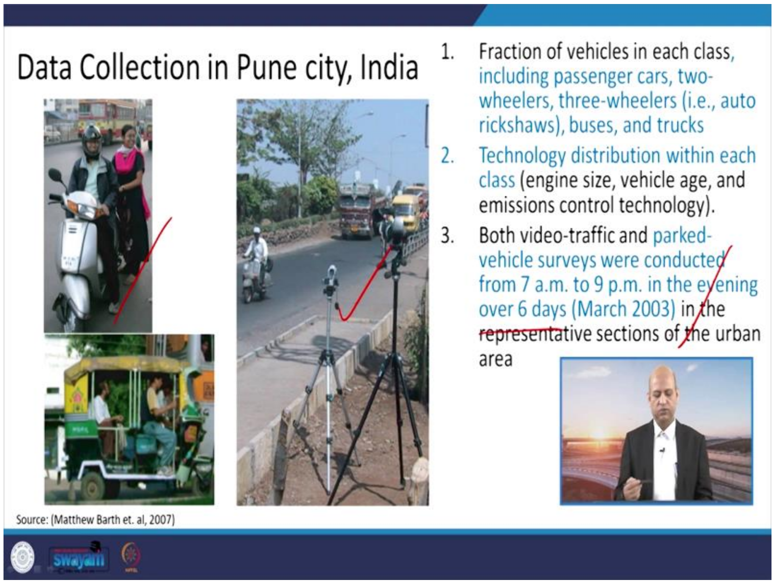

So, the data collection as I said, it was ground based survey and data were collected primary data were collected by using like camera related video capturing also surveying with the vehicles usage and stopping requesting people to give some information. So, the data were collected regarding like technology of day, like 2-wheeler, 3-wheeler, buses and then trucks, heavy vehicle light duty vehicles, automobiles, all those.

So, this was the 6 days survey basically from 7am to 9pm in March 2, 2003. So these were the data collection period.

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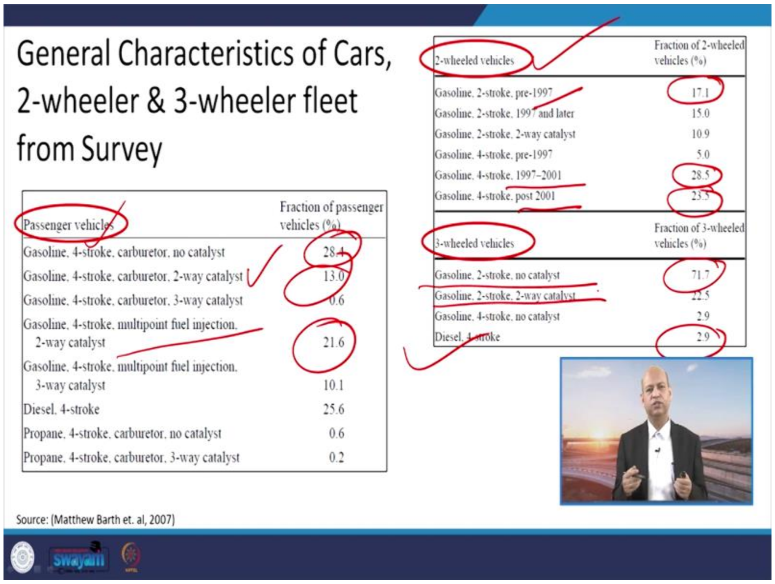

And you can see the general characteristics of the cars 2-wheelers, 3-wheelers fleet from the survey which was tabulated based on the data. So, like passenger vehicles or different kinds of categories, like gasoline 4 stroke with carburettor kind of technology and no catalyst, but then some vehicles will be like gasoline 4 stroke, but carburettor and 2 way catalyst.

So, if we talk about the percentage of fraction so the earlier one was 28 %, later on 13 % and then you can see this gasoline 4 stroke multi-point fuel injection related technology and 2 way catalyst these were around 22 %.

So, means population of the vehicle they were analysed the data were collected and their fractions were analysed and two wheeler technology or two wheeled vehicles. So, gasoline 2 stroke and 4 stroke and then their makes mean when it was made like 1997 to 2001 then post 2001 because the technology also changes, 4 stroke engines; 2 stroke engines, those population were count and the fraction were calculated like 17 % of pre 97, 2 stroke and gasoline.

Similarly like 4 stroke 1997 to 2001, 28 % or 28.5 and 23.5 % was gasoline 4 stroke two wheelers post 2001, three wheeled vehicles. So, gasoline based or diesel waste, all those populations were counted. So, diesel based were very less around 3 % or so, mostly gasoline 2 stroke without catalyst were there 72 % around 22.5 approximately this was 2 stroke but 2 way catalyst.

So, different technologies, different category of vehicles and different fuel category like gasoline, diesel all those kinds of things were calculated so that the estimations of the emissions of different pollutants may be realistic.

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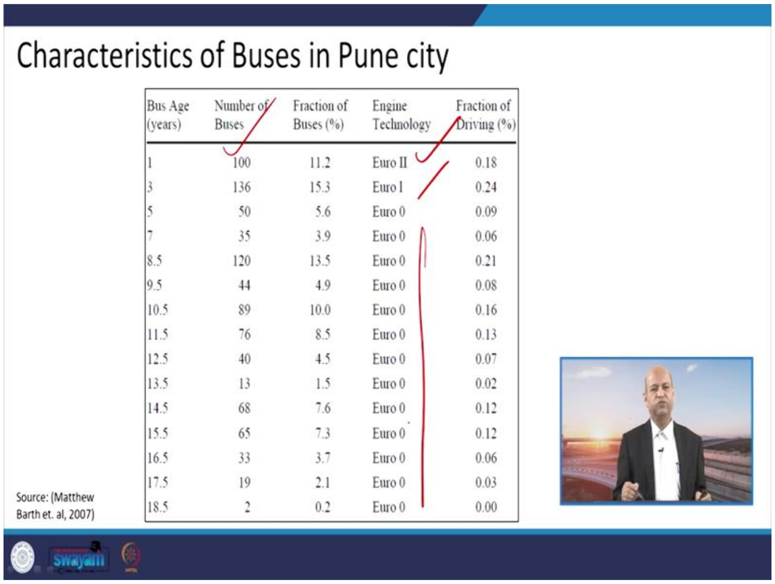

Bus Age (years)	Number of Buses	Fraction of Buses (%)	Engine Technology	Fraction of Driving (%)
1	100	11.2	Euro II	0.18
3	136	15.3	Euro I	0.24
5	50	5.6	Euro 0	0.09
7	35	3.9	Euro 0	0.06
8.5	120	13.5	Euro 0	0.21
9.5	44	4.9	Euro 0	0.08
10.5	89	10.0	Euro 0	0.16
11.5	76	8.5	Euro 0	0.13
12.5	40	4.5	Euro 0	0.07
13.5	13	1.5	Euro 0	0.02
14.5	68	7.6	Euro 0	0.12
15.5	65	7.3	Euro 0	0.12
16.5	33	3.7	Euro 0	0.06
17.5	19	2.1	Euro 0	0.03
18.5	2	0.2	Euro 0	0.00

As good data we can collect as much category or these like minor kind of categories, if we can include them, we can have good estimation, but at the same time, if you may recall, if we go for complex data related survey and then uncertainty also increases, so we have to strike a balance and resources are also needed for getting those kinds of data.

If you talk about characteristics of buses in Pune city, then not only the number of buses, but like Euro 2, Euro 1 or Euro 0 where no those norms were there. So, those kind of fractions and their population were also estimated and collected and then tabulated.

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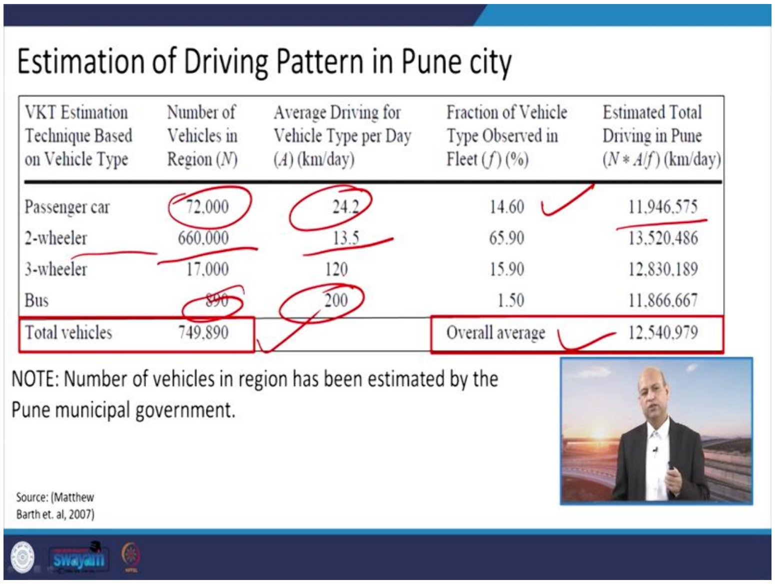

Then the driving pattern means; how do these different kinds of vehicles go with different kinds of speeds like average driving for vehicle type per day kilometre per day. So, passenger cars 72000 population were around 24 kilometre per day, two wheelers population 660000 around 30.5 kilometre per day.

So, those kinds of data have been calculated buses 890 and 200 kilometre per day. Similarly, fraction of vehicles and estimated total driving pattern you can see the fraction and their kilometre per day the total after multiplying so, the overall average is this much and the total vehicles are this much.

So, the number of vehicles in a region has been estimated by Pune municipal governments. So those data have been taken. So, if there is some uncertainty or gap that is that would be there. So, we have to take into account those kinds of uncertainties and data gaps also.

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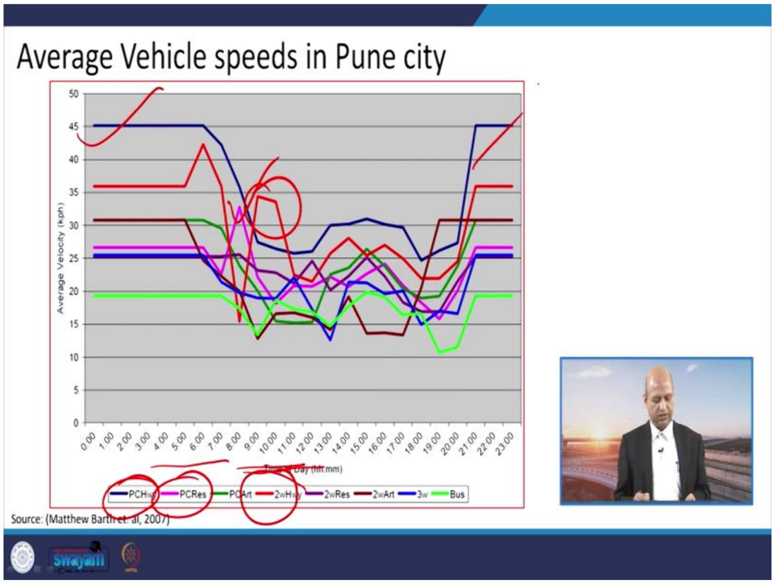

Well when we talk about average vehicle speed in Pune city, so like these you know passenger cars on highways they are having more speed, they these kind of times of the day in early hours of the day, but then this decreases when office hours are there. During office hours you can see these PC, these personal cars in resident areas.

So, their speed is increasing and then two wheelers are also there, which increased basically in office hours, you can see here these are the two wheelers So, their speed will increase in the office hours in the morning when people are going so, maybe because number of cars increase then the speed decreases on the road and meanwhile two wheeler people can increase their speed and they can take pass and they can go.

So, those kinds of things are there and again when road is vacant, after like 9 pm or so, so, then again speed of these passenger cars on the highways increases. So, those kind of speed parameters were also noted and considered.

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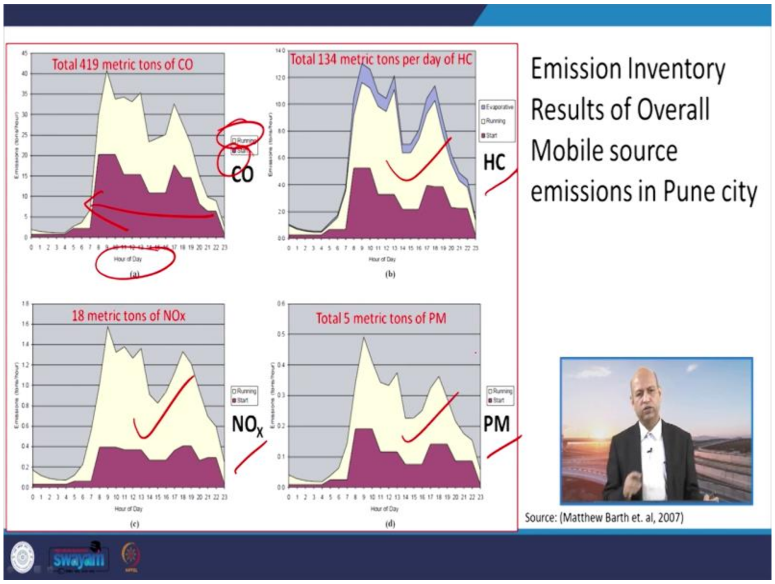

If you go for emission inventory using the IVE model, so, like CO emissions, if you see these related to start ups and the running kind of means; how much CO emissions are there when vehicle is starting, how much it is there when it is running? So at the start this is the you know start related estimations and hour of the day naturally from 7 am to like 9 or 10 pm kind of you can see that time spent when most of the activities are there.

So, you can see the fraction hydrocarbons basically operative hydrocarbons or VOCs are also there from leakage et cetera. So, that is considered in case of hydrocarbon otherwise, only two categories have been there like a start-up and when starting vehicle is starting and when it is running.

So, all these CO, NOx and particulate matters, they are only with this two category like when it is starting, when it is running. But in case of hydrocarbon the third parameter is also used which is like operative emissions you can see but, during running hydrocarbons are lot of emissions are of carbons. Similarly NOx emissions and particulate matter emissions due to running is more naturally they have more time span for the running that may be the reason.

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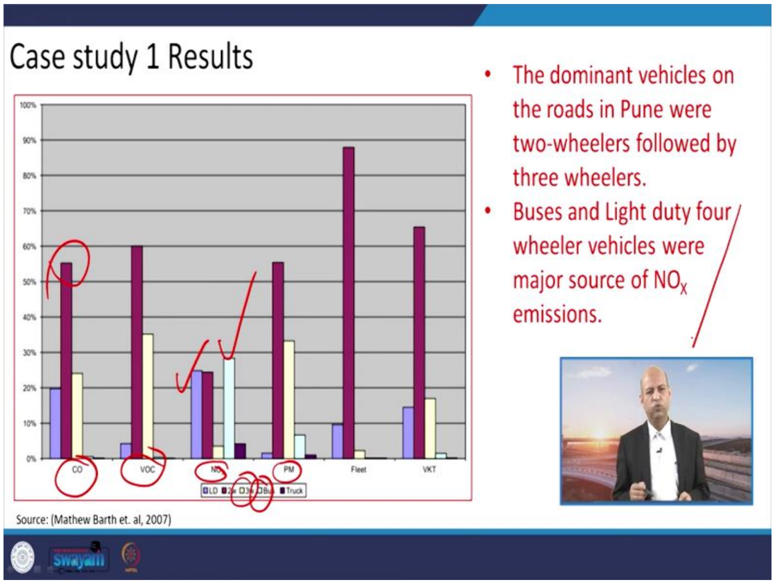

But in case of CO when cold start is there then unburned fuel is there and initially CO is produced more later on CO2 is produced more. When we talk about like different kinds of vehicle categories and their contribution into different pollutants like CO. So, you can see this is two wheelers is the maximum emission of the CO and there population is also more, okay. VOC are also more from two wheelers and the second is from three wheelers basically.

So, the CO, VOC and particulate matter and also like vehicle kilometre travel because their number is more So, naturally their vehicle kilometre travel is also more but pollutants perspective if you see the carbon monoxide, volatile organic compounds and particulate matter they are more from basically two wheelers and three wheelers.

When we see about NOx then situation is different. Here the buses are the real source or dominating source in Pune city and then this light duty vehicles are the second and the two wheelers are also equally responsible, but the majority of the emissions of the NOx are coming from this particular these buses, okay, you can see. So, buses and light duty four wheelers were responsible for NOx emissions otherwise other pollutants are coming from two wheelers and three wheelers.

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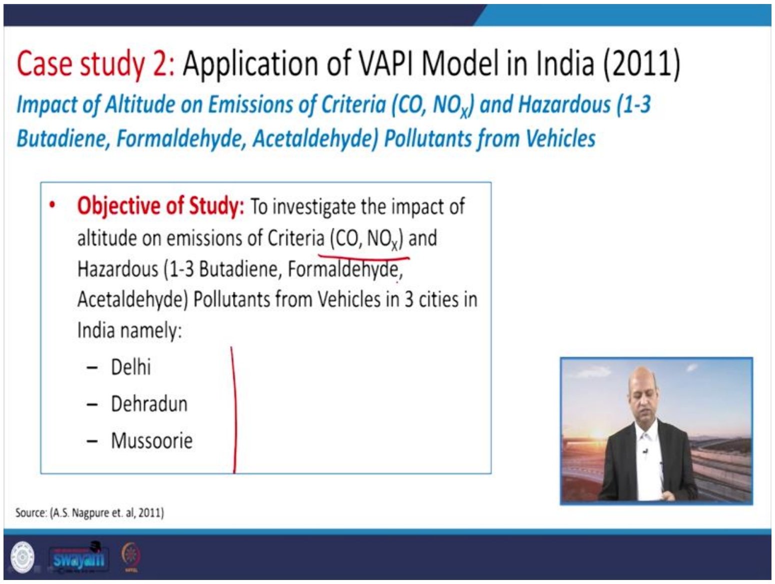

Now, we come to the second case study which is the application of VAPI model; Vehicular Air Pollution Inventory Model and that is applied for estimating like impact of altitude. So, we have considered three cities Delhi and then Dehradun in Uttarakhand this is on higher elevation, altitude and then Mussoorie which is a hilly station, you can see.

So, 3 those altitudes are quite different. So, we wanted to see what is the impact of those altitude on emissions. So, we have seen like criteria pollutants CO, NOx and hazardous pollutants like butadiene, formaldehyde so on in these three cities. So, let us see using VAPI model how these estimations are there.

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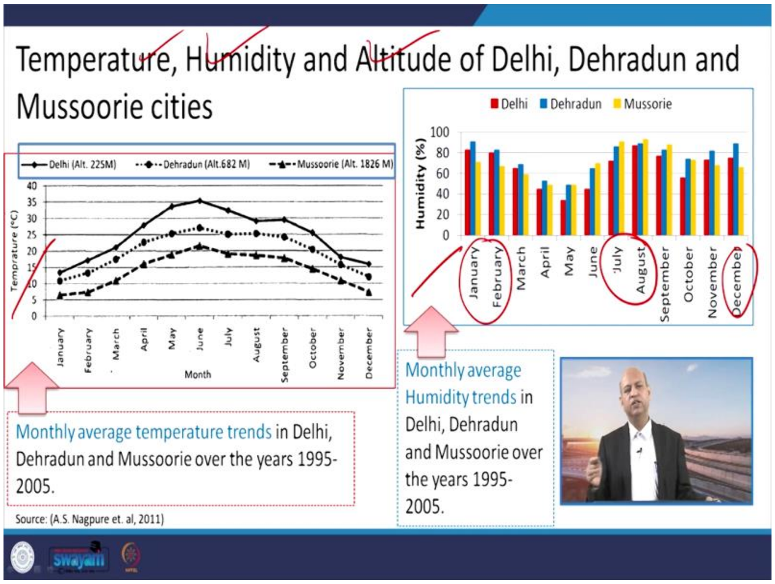

Well there are no correction factors which we have taken which depends on the topography and the geographical location. So, that is temperature humidity and altitude of Delhi, Dehradun and cities you can see the variation of temperature here humidity is here. So, as per the month humidity varies basically.

In Mussoorie like July August, so, it is more followed by Dehradun and then Delhi. But winter time Dehradun has more in January and February or December also and then second is Delhi but in Mussoorie it is rather less in comparison to these 2 cities. So, basically if you see the whole year, different months have different kind of humidity content in the atmosphere of these cities.

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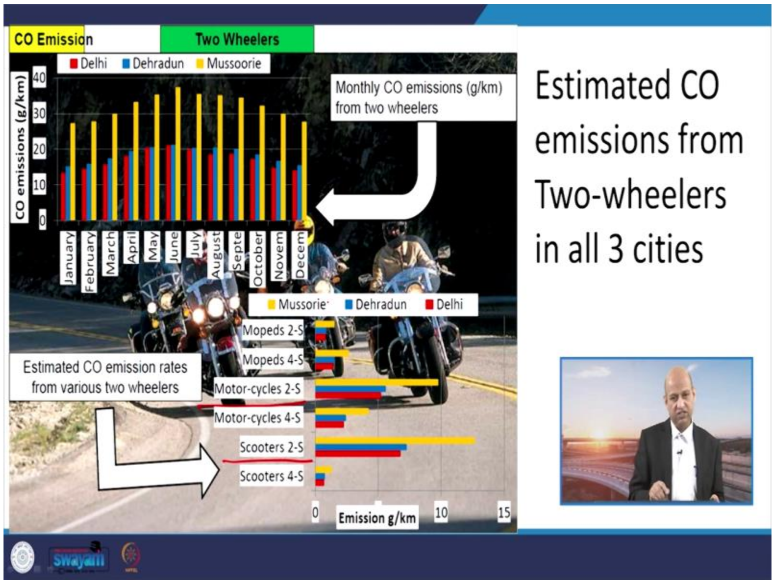

If you see the CO emissions, so using VAPI model we estimated so in Mussoorie, CO emissions in different months you see dominating emissions are in Mussoorie in comparison to other these two cities. So, monthly CO emissions have been estimated and are shown gram per kilometre. If you see the this vehicle category wise, so, these motorcycles 2 stroke and scooters 2 stroke they are emitting a lot of CO emissions and more in basically Mussoorie and followed by Dehradun and Delhi.

So, these kinds of variations you can see across the cities in different months as well as across the different vehicular category like moped, RS mopeds are emitting very less CO in all cities, but still in Mussoorie it is more in comparison to Dehradun and Delhi. So, that means CO increases when we go up on the altitude.

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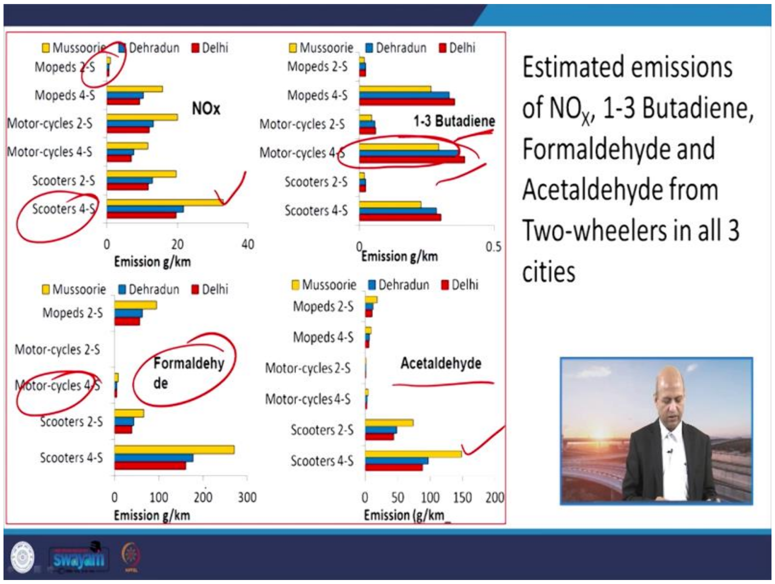

If you see the NOx emissions, again scooter 4 stroke engines they are emitting more and it is more in case of Mussoorie and then moped again they emit very less of NOx emissions. Well when we consider about like butadiene and formaldehyde situation changes like motorcycle 4 stroke very less formaldehyde, but it is quite high butadiene, okay motorcycle 4 stroke.

So, if you consider different kinds of pollutants, different situation occurs at different places and like in places also for example, NOx emissions were more in case of Mussoorie but it is less this butadiene is less in case of Mussoorie, it is more in case of Delhi and in between this Dehradun is there. So, when we come down then butadiene emissions increase, but acetaldehyde again they increase like formaldehyde emissions as you go up. So, those kind of variations you can see.

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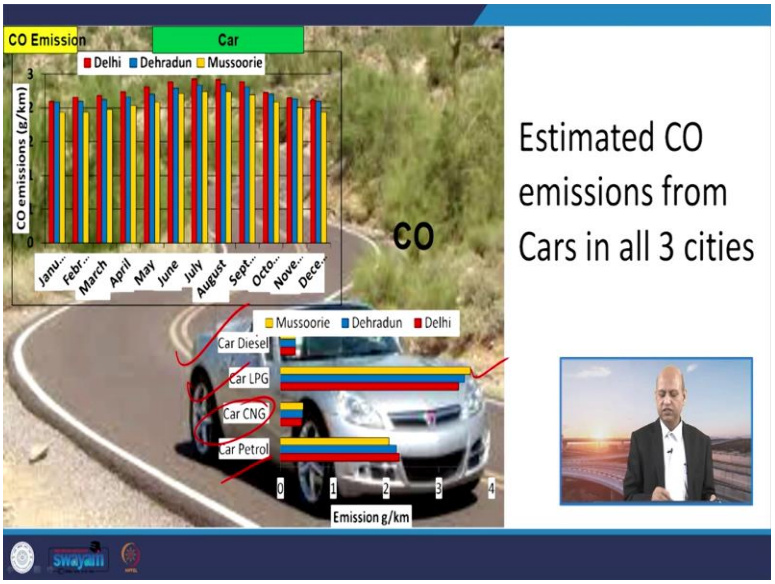

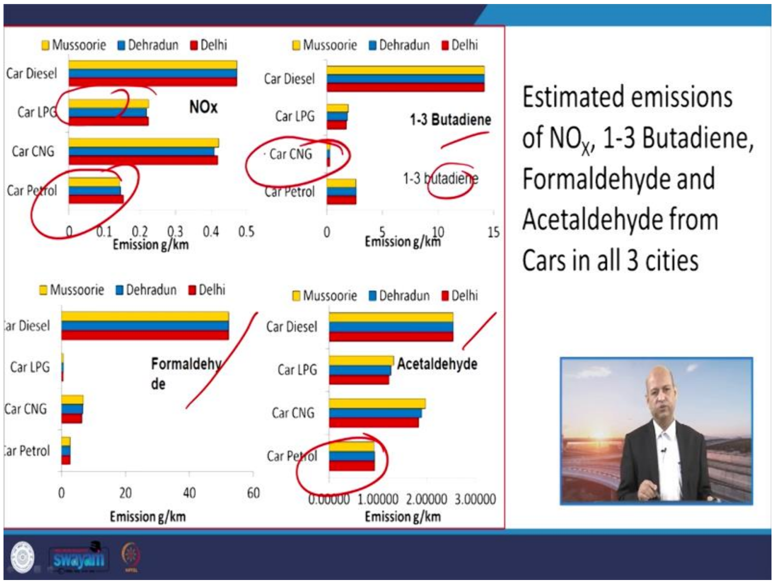

Similarly, estimated CO emissions if you compare different months of cars so, those were those were 2 wheelers basically, now, if you compare the cars then in car also you can see like, in Delhi it is more but in Mussori it is less CO emissions. When we go for different fuel category, so, diesel cars are emitting less CO emissions in comparison to LPG, LPG is the highest one and in Mussori, it is more. So, again you can see the difference and CNG is again less so, that means CNG emissions for CO emissions from CNG car will be less in comparison to these petrol and diesel will be further less.

So, that means, the fuel wise variation is also there. Similarly, if we see this emissions from the car of NOx, butadiene etc., different kinds of scenario is there. So, diesel cars are emitting a lot of formaldehyde and similarly, a lot of acetaldehyde and butadiene and NOx. So, diesel car from that perspective toxic pollutants perspective is not good and the NOx emissions are less in case of LPG and petrol car rather and it is also less this acetaldehyde but butadiene basically CNG car is very good in that sense.

So, what kind of pollutants are emitting and which is dominating those kinds of things we can play with the model and as per the total emissions if we want to reduce certain pollutants then we have to see which kind of category of vehicle is emitting more we have to attack that from policy and technology perspective. Similarly, if we want to decide a particular vehicle, which is better in higher altitude, then we have to see that which kind of fuel is giving less emission.

So, that we should promote those kinds of vehicles, so that way these models really help us deciding better technology better vehicle which emit less of emissions.

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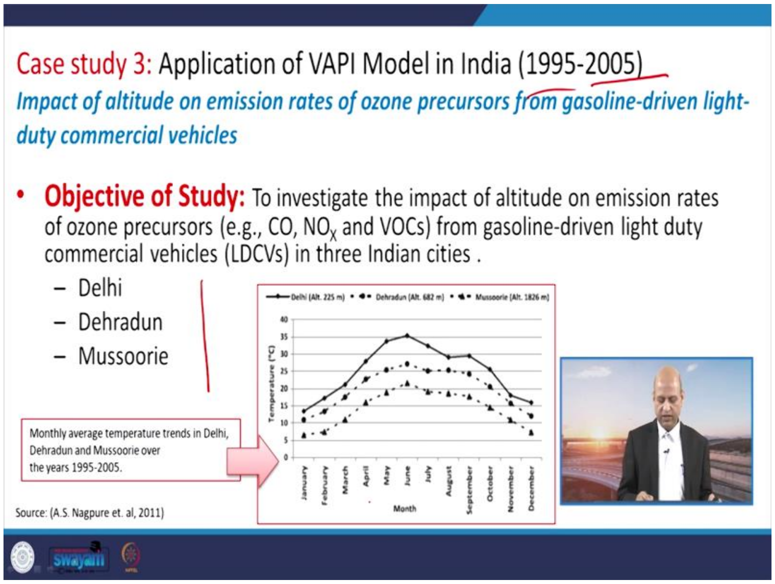

Third case study again from VAPI model 1995 to 2005 this period was considered for calculations and the objective was again to compare these 3 cities to see the ozone precursors, ozone precursors are basically like carbon monoxide or oxides of nitrogen, NOx emissions or VOC is volatile organic compounds. So, we have to see that temperature monthly average you have already seen for Delhi and those, so, this is the same graph.

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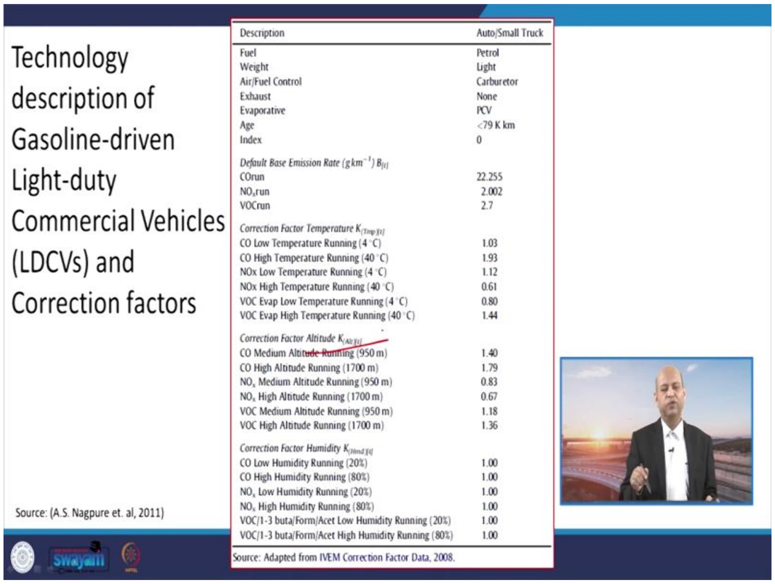

Then technology description you can see like fuel related and then correction factors related to temperature related to altitude all these things have been as input parameters basically.

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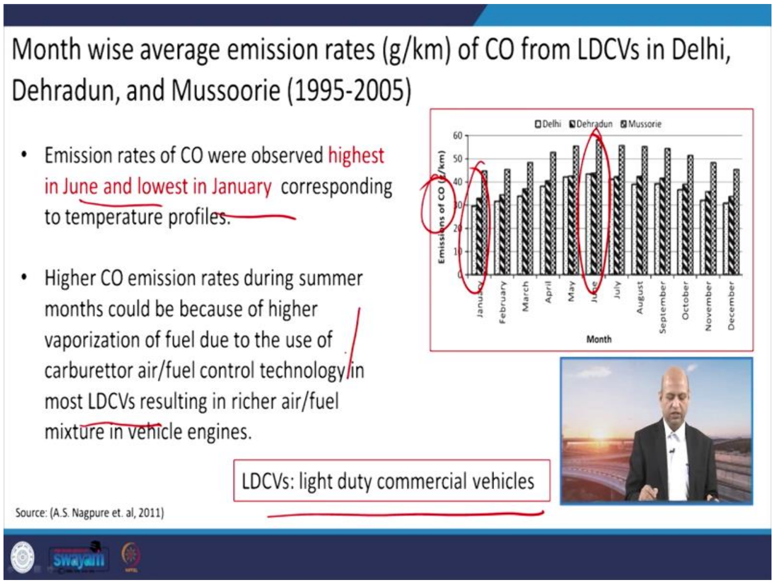

So, we see this monthly variation of you can see for Delhi, Dehradun and Mussoorie again CO emissions and CO emissions you can see highest in June and lowest in January highest in June and lowest in January in all cities. But basically it is more in case of Mussoorie and less in case of Dehradun and further less in case of Delhi. So, basically these rates depend upon the season as well as on the altitude and this is related to this light duty commercial vehicles basically, light duty commercial vehicles. So, these are the variations.

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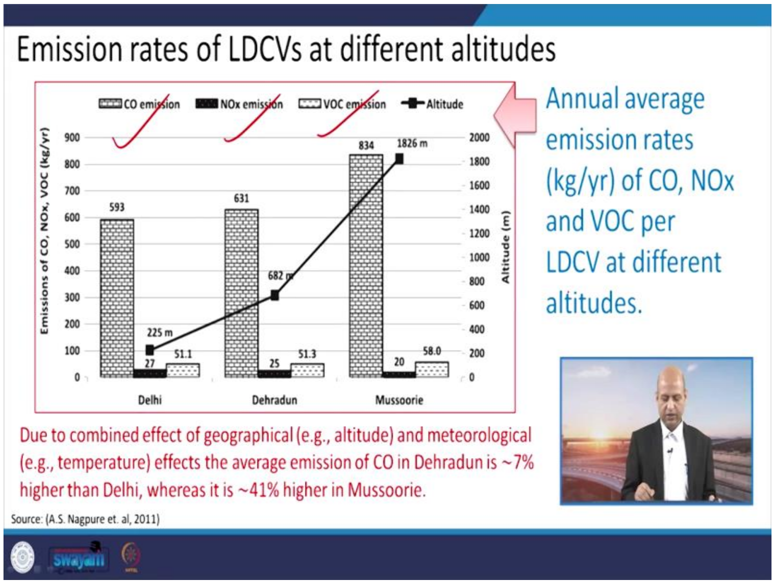
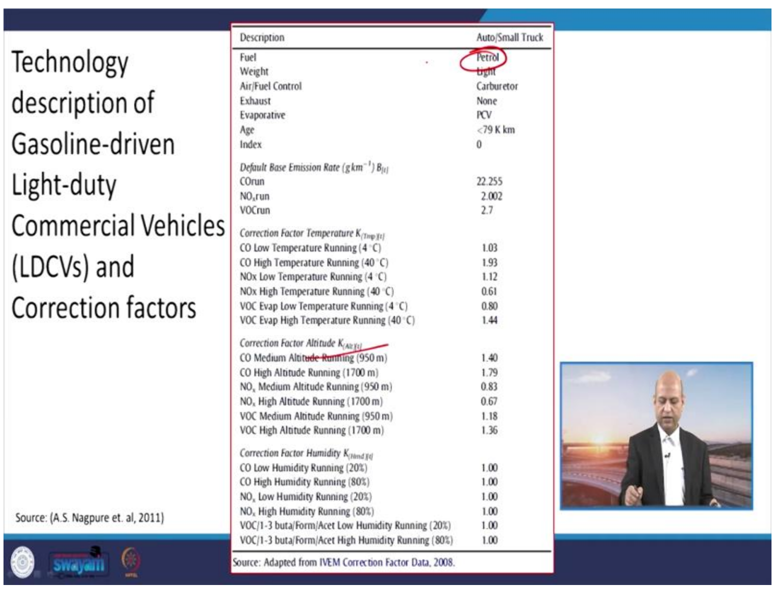
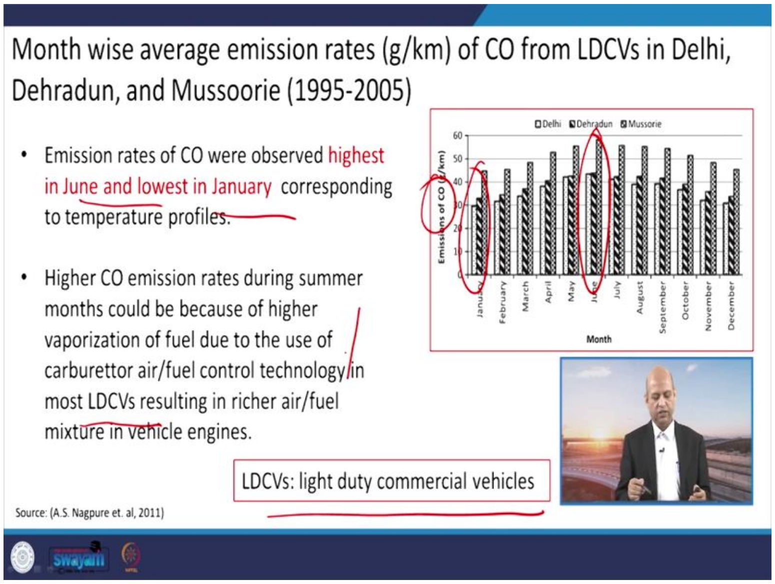




Description	Auto/Small Truck
Fuel	Petrol
Weight	Light
Air/Fuel Control	Carburetor
Exhaust	None
Evaporative	PCV
Age	<79 K km
Index	0
Default Base Emission Rate $(g\,km^{-1})\ B_{[t]}$	
COrun	22.255
NO_xrun	2.002
VOCrun	2.7
Correction Factor Temperature $K_{(Tmp)[t]}$	
CO Low Temperature Running (4 °C)	1.03
CO High Temperature Running (40 °C)	1.93
NOx Low Temperature Running (4 °C)	1.12
NOx High Temperature Running (40 °C)	0.61
VOC Evap Low Temperature Running (4 °C)	0.80
VOC Evap High Temperature Running (40 °C)	1.44
Correction Factor Altitude $K_{(Alt)[t]}$	
CO Medium Altitude Running (950 m)	1.40
CO High Altitude Running (1700 m)	1.79
NO_x Medium Altitude Running (950 m)	0.83
NO_x High Altitude Running (1700 m)	0.67
VOC Medium Altitude Running (950 m)	1.18
VOC High Altitude Running (1700 m)	1.36
Correction Factor Humidity $K_{(Hmd)[t]}$	
CO Low Humidity Running (20%)	1.00
CO High Humidity Running (80%)	1.00
NO_x Low Humidity Running (20%)	1.00
NO_x High Humidity Running (80%)	1.00
VOC/1-3 buta/Form/Acet Low Humidity Running (20%)	1.00
VOC/1-3 buta/Form/Acet High Humidity Running (80%)	1.00

Source: Adapted from IVEM Correction Factor Data, 2008.



So, you can see here you know this is basically emissions related to light duty commercial vehicle which are driven by gasoline as you can see in the last slide. This is like petrol this is the basically gasoline. And here also the reason is given higher CO emissions rates during summer months could be due to this high fuel, air fuel kind of ratio those kinds of things are there.

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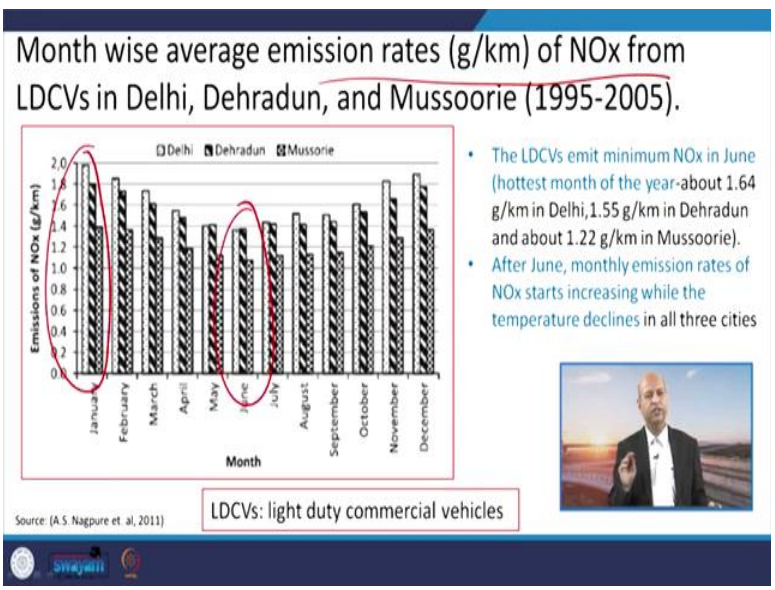

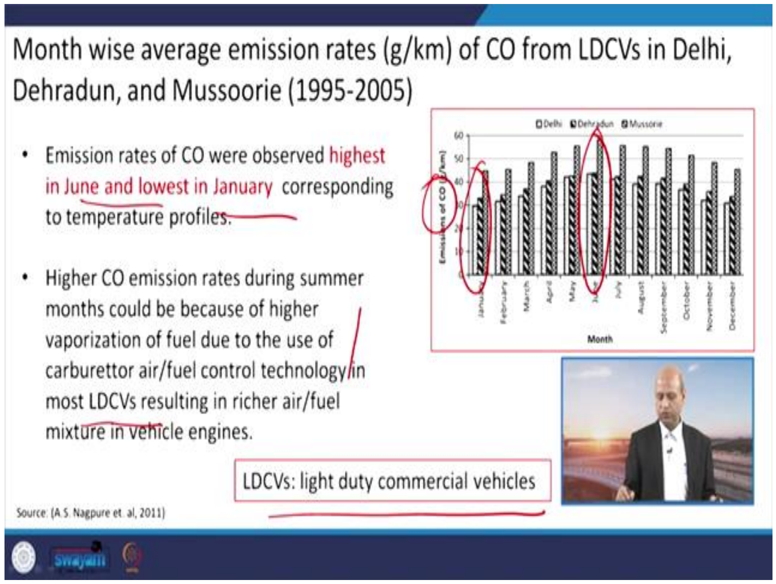

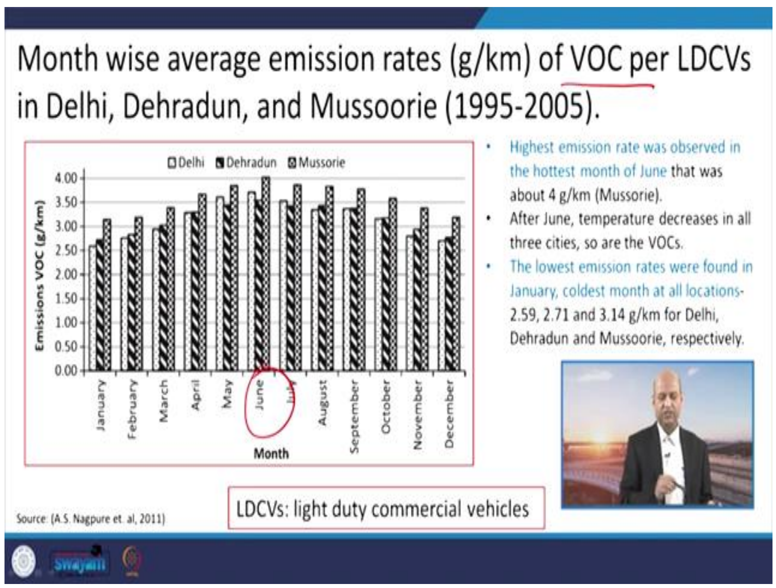

When we go for basically monthly emission rates of NOx emissions so, again this is different means CO was more in case of like in case of summer it was more and in winter it was less, but in case of this NOx in summer it is less and in winter it is more so, those kinds of variations you can get from pollutant to pollutant.

So this light duty commercial because they emit minimum NOx in June and maximum in these January and basically, so January and December you can see. So, monthly variations can be there again you can see this VOC. So, again VOC is like CO it is more in case of summer and less in case of winter months.

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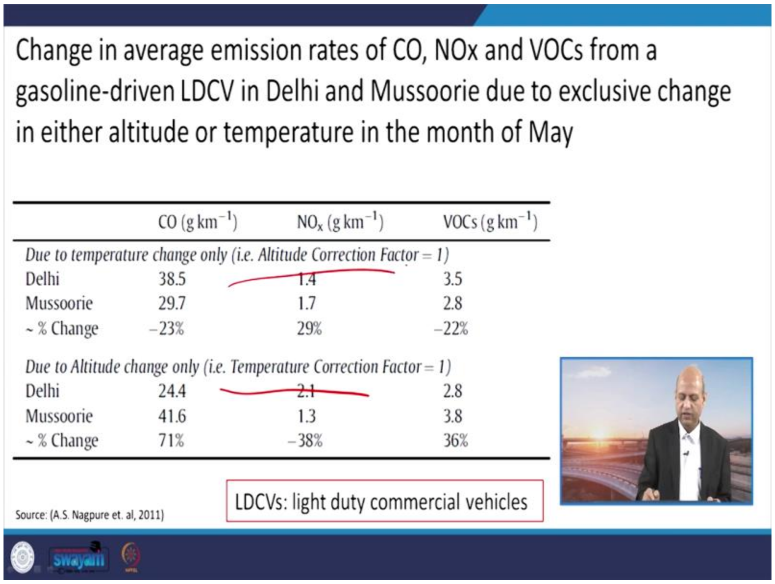
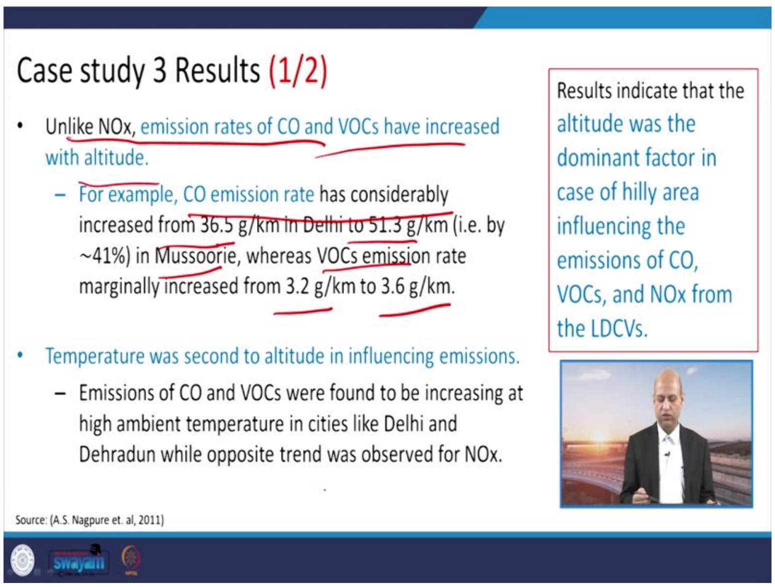
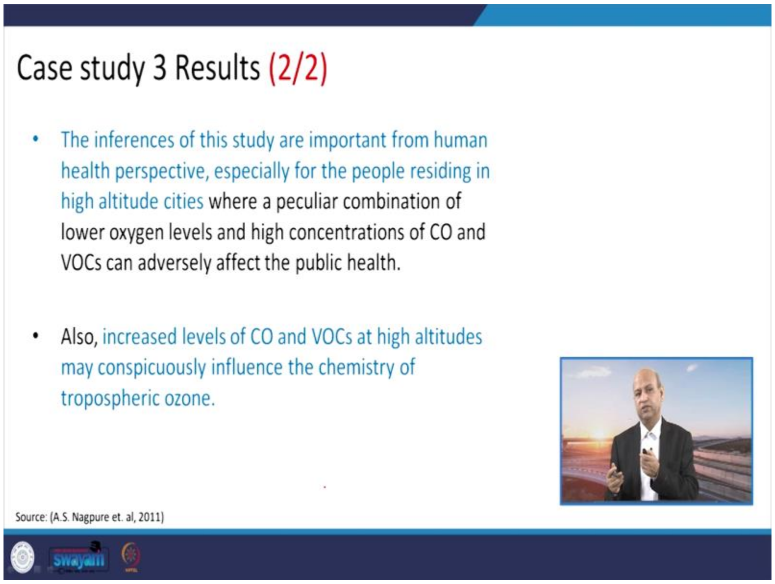


	CO (g km^{-1})	NO_x (g km^{-1})	VOCs (g km^{-1})
Due to temperature change only (i.e. Altitude Correction Factor = 1)			
Delhi	38.5	1.4	3.5
Mussoorie	29.7	1.7	2.8
~ % Change	−23%	29%	−22%
Due to Altitude change only (i.e. Temperature Correction Factor = 1)			
Delhi	24.4	2.1	2.8
Mussoorie	41.6	1.3	3.8
~ % Change	71%	−38%	36%





So, basically there are correction factors are also to be applied related to altitude correction temperature correction and then total emissions are estimated and we see that the impact is basically more CO and more VOC in summer light duty commercial vehicle based on petrol we are talking and then less of the NOx opposite of the NOx then if we see these results so, it is also known NOx is less but emissions of CO and VOC have increased with the altitude that was my basically implication when I was talking.

So, you can see this CO emission rate has considerably increased from 36.5 grams per kilometre to 51.3 grams per kilometre in Mussorie means altitude higher altitude in comparison to Delhi and then VOC increased from 3.2 to 3.6 but NOx emissions are less. So, they were found increasing with the temperature also like in June it was more so, with altitude it is increasing with temperature it is increasing that is more important thing we have to remember.

Similarly, you know inferences from this VOC and CO related emission because these are the precursors basically and NOx emissions are less so, the VOC and CO emission they can participate in producing the ozone rather than NOx in those particular high altitude cities. So, we have to cater those particular precursors to reduce by some technological intervention otherwise with the in the presence of sunlight in summer ozone production maybe there that is very negative impact which can be estimated.

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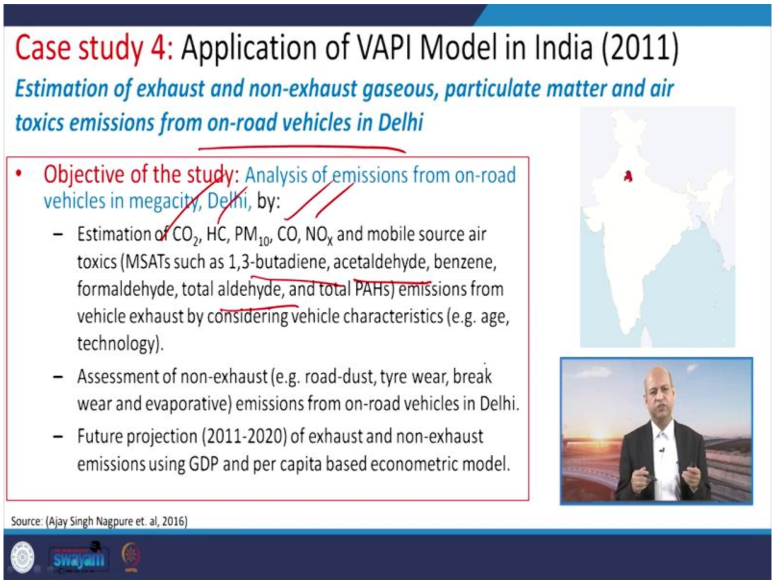

When we talk about the 4th case study using VAPI model then this is related to estimation of exhaust and non-exhaust gases plus PM particulate matter and toxic material or toxic air pollutants from on road vehicles in case of Delhi. So, this is only focused in Delhi and the pollutants maybe like particulate matter PM10, CO, NOx hydrocarbons, greenhouse gas CO2 and then butadiene, acetaldehyde, benzene, formaldehyde aldehydes all those total PAHs.

So, all those pollutants have been considered and non exhaust emissions like the re-suspension of road dust and wear and tyre of the tires and the brake wear an operative emissions. So, non exhaust emissions have also been estimated.

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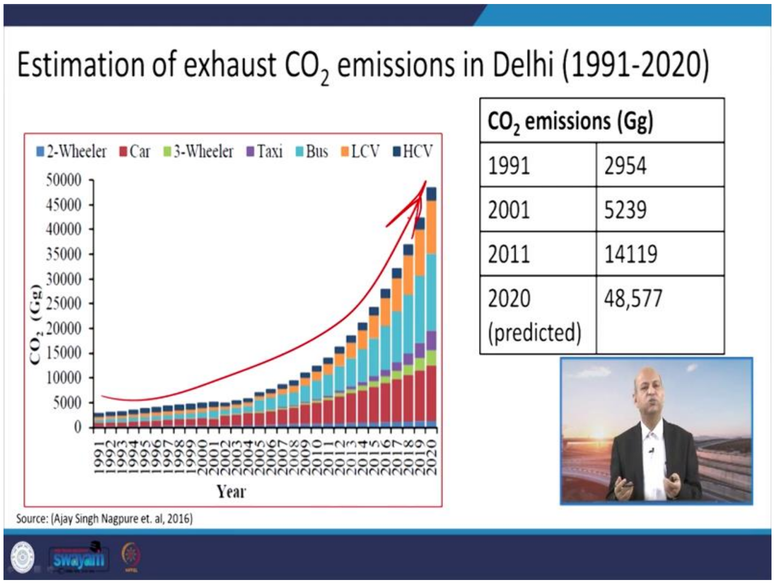

If you see the exhaust emissions of CO2 this is increasing all the over the years 91 to 2020 means 20 years study have been considered this period have been considered running the model for different years and we found that CO2 emissions is going on means even if rather when you go for efficient technology then naturally CO2 emission will increase.

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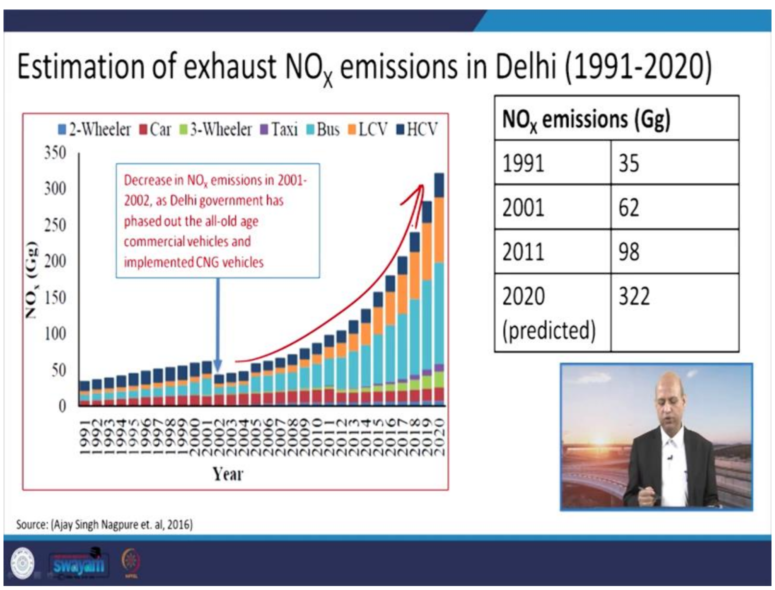

When we talk about NOx emissions, then there is decrease in case of like 2002 when this CNG implementation was there, the whole bus fleet was converted to the CNG. So, this dip was there, but because you know this number of vehicles were increasing and buses also increased. So the emission again increased because of the population of the vehicles.

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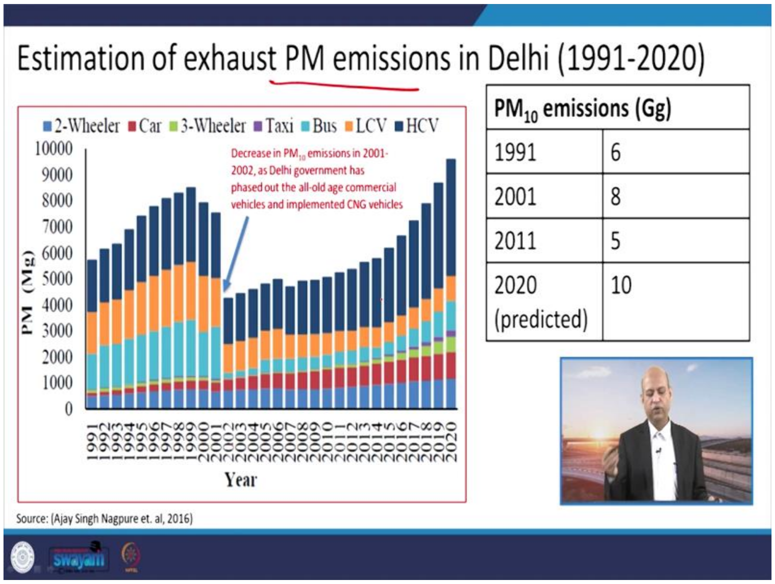

PM_{10} emissions (Gg)	
1991	6
2001	8
2011	5
2020 (predicted)	10

Similarly, if we see like in case of particulate matter emissions, so there was a significant dip in 2002 in comparison to this kind of trend and then again, it increased over the years because the population of vehicles were increasing.

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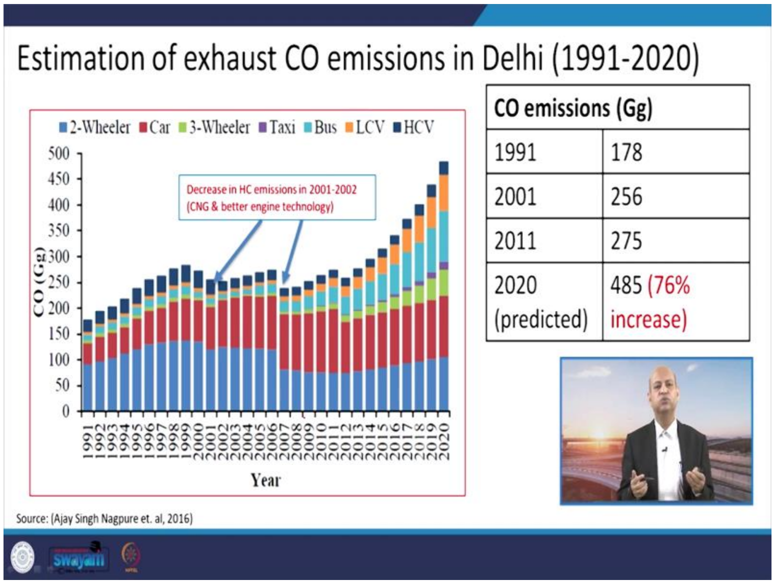

CO emissions (Gg)	
1991	178
2001	256
2011	275
2020 (predicted)	485 (76% increase)

In case of like this CO emissions basically you can see that two dips one is in 2001, 2002 another is 2007 or so, so, the earlier one was related to CNG but the second dip was related to technology

So, better technology emissions are there then naturally CO emissions will go down because CO2 emissions will increase due to fuel efficiency in that technology.

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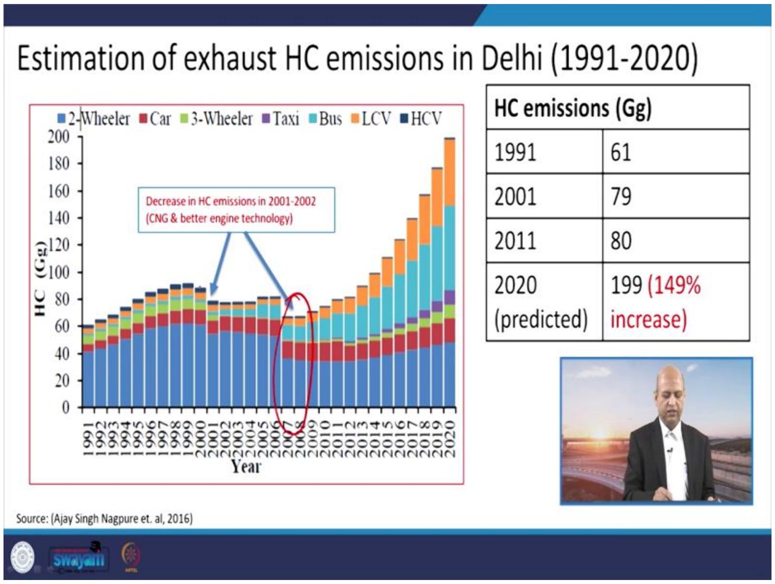

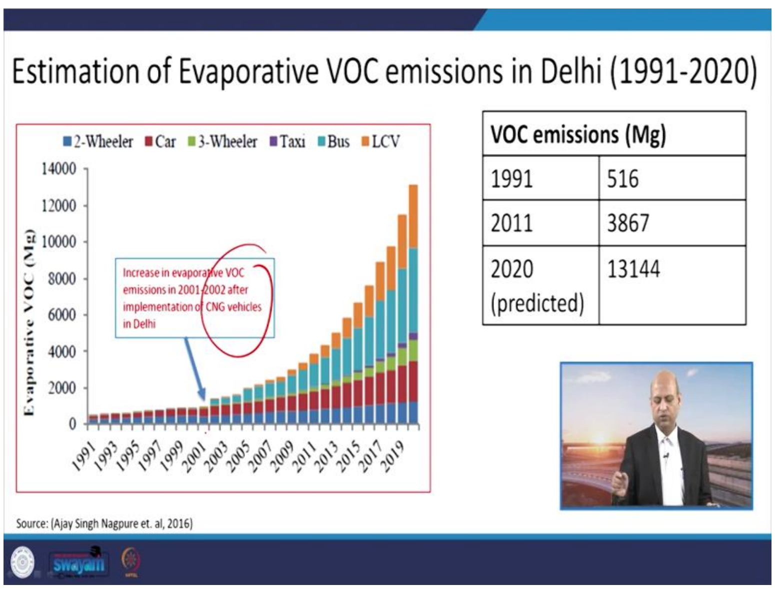

Similarly, like hydrocarbons the same thing has happened because their emissions have to be reduced because better burning is there then combustion is better than CO2 increases, but other like CO and hydrocarbons decrease in this particular year and that is related to the CNG. So, you can see like, the implementation of a technology can also be captured in the emission inventory based on good models increasing the operative VOC you can see the implementation of CNG vehicles was there and then it also increased.

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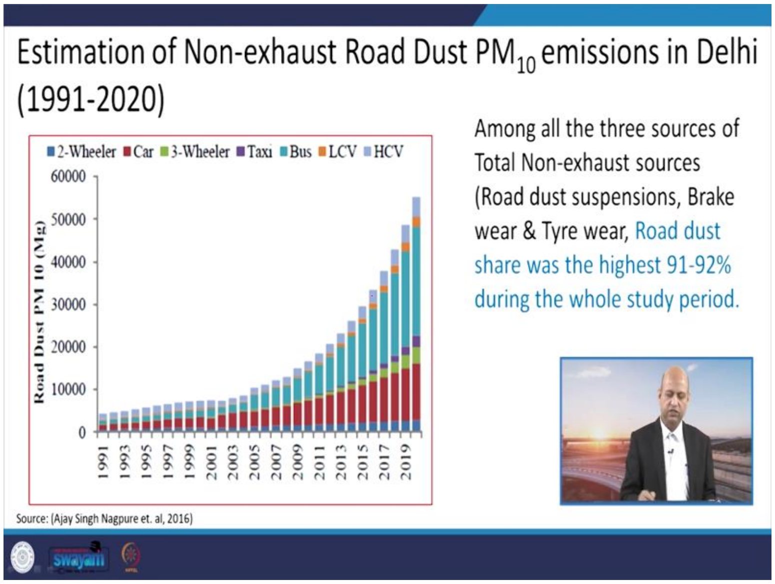

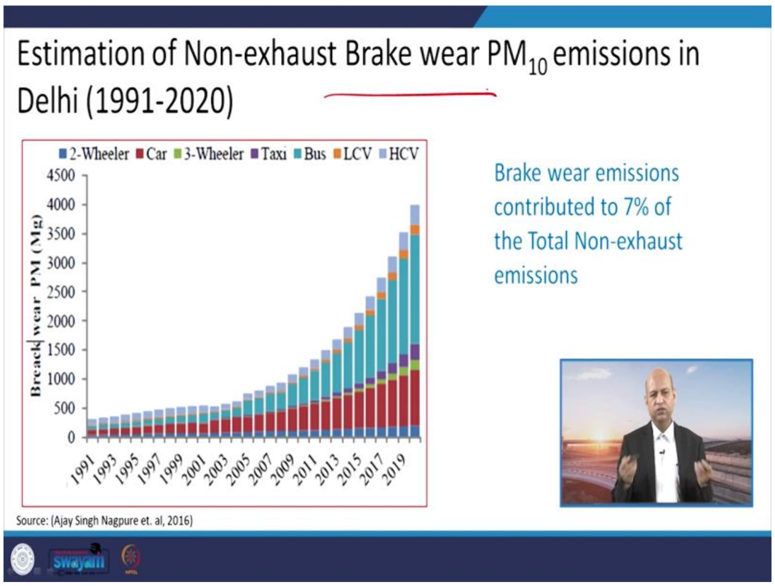

Then we can see the estimations of non exhaust road dust and PM10 emissions from the road dust. So, that was estimated as increasing over the years similarly, PM10 from break wears, it also increased because number of vehicles are increasing. So, naturally it is increasing.

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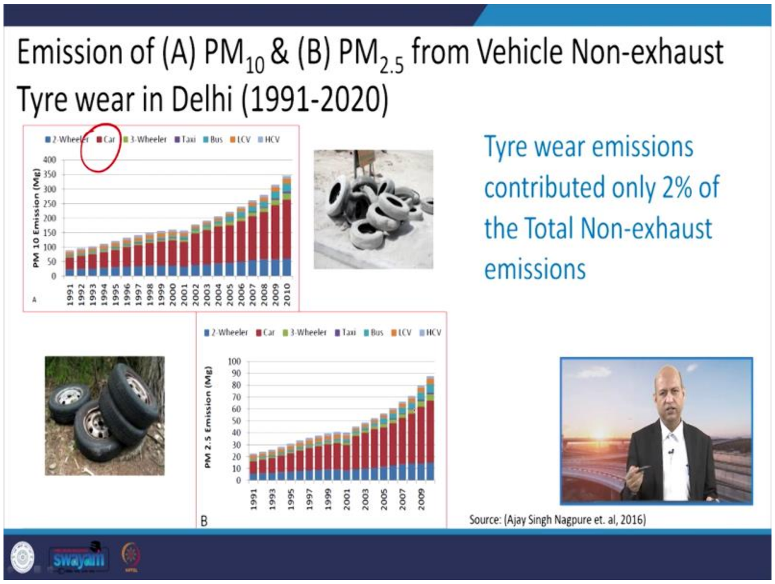

If we see this tire wear and from different vehicle category, then cars are more responsible for the PM10 this particular you can see the number and also these PM 2.5 this predominant source is car tires basically when we consider these vehicle related non exhaust emissions. So, tires are responsible for PM10 and PM2.5.

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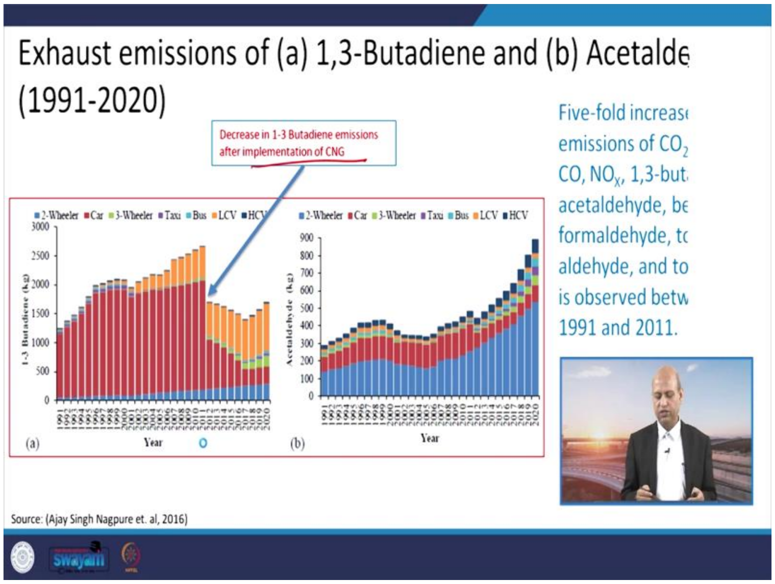

If we consider butadiene acetaldehyde then you know this decrease was there due to implementation of CNG in 2001 Otherwise, the later on then because of number of year population of the vehicles it increased.

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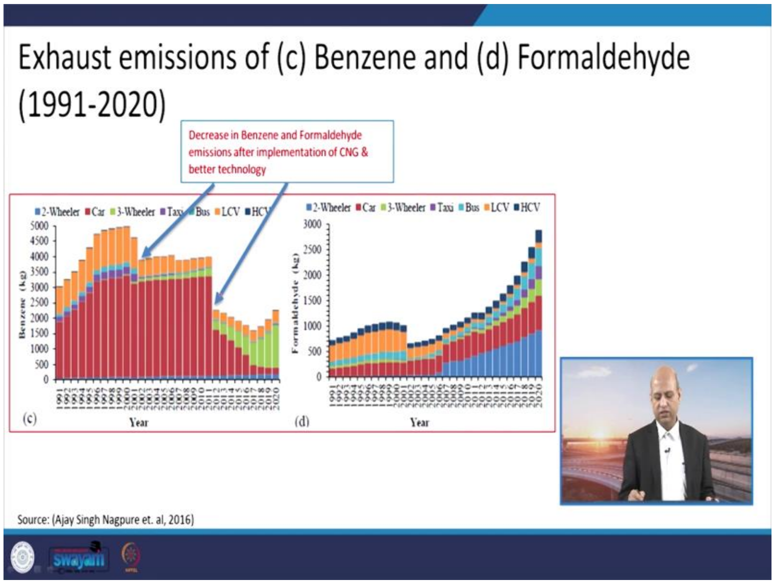

If you see the benzene and formaldehyde and these exhaust emissions then again there is this dip 2 times because of CNG and technology. Otherwise, the increment is there after the number of population of the vehicle increase.

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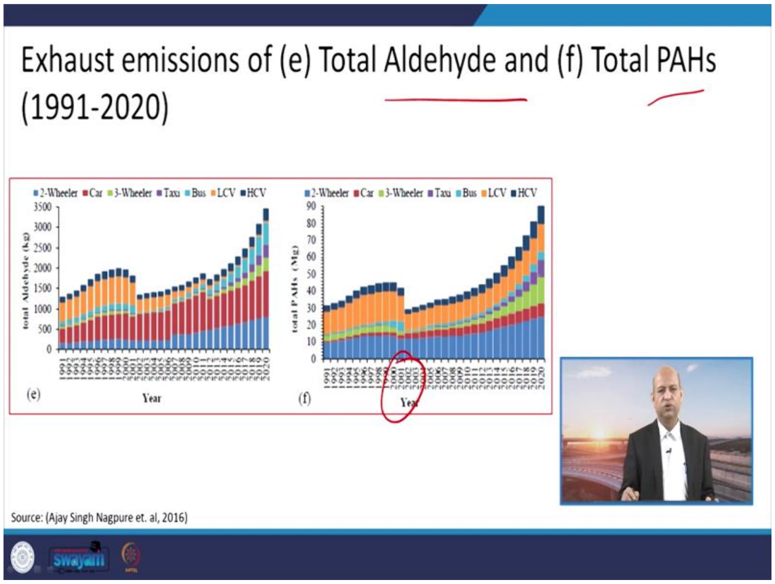

Same thing you can see in aldehyde and total PAH's in you can see the increase after the 2001 but technology did not much impact the PAH emissions.

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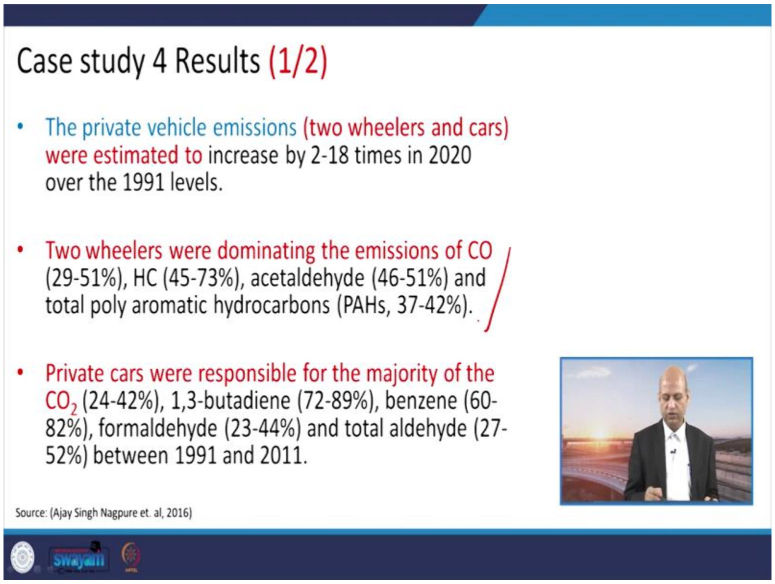

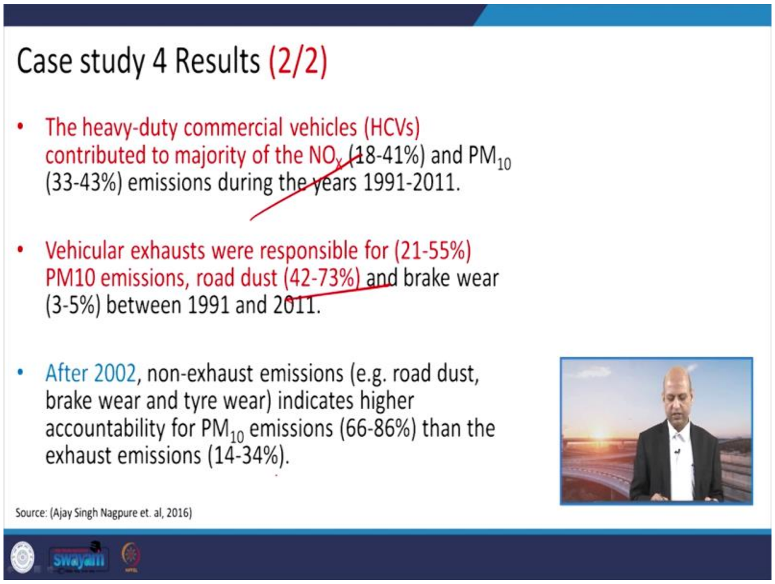

So, this 4th case study related results are basically like private vehicles admissions like 2 wheelers and cars they were estimated to increase from like 2 to 18 times in 2020 over the 1991 level because of their number increased although when you if you discard the population of the people who are shifted towards metro then it will further increase but, this is basically only the scenario which was responsible for this increased two wheelers were dominating emissions of CO you can see and then private cars are responsible for CO2.

So, those kind of category wise domination in different kinds of pollutants, we can see heavy duty commercial vehicles were responsible for more of the NOx emissions and PM10 were coming basically from exhaust emissions and then road dust also like 40 to 73 %. So, a lot of emission sources are there in non-exhaust emissions also similarly, like tire wear etc., they were also emitting these particulate matters.

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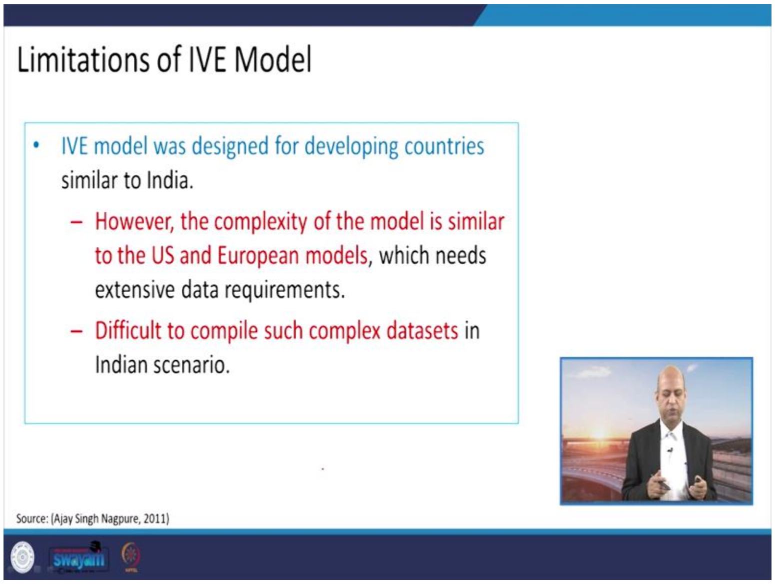

If we see like IVE model the limitations that is why we went to VAPI the model because we have seen that in developed countries these models have data intensive kind of characteristic and rather IVE model was designed for developing countries is still we found that the data complexity and the extensiveness is much more in IVE which in our cities basically is not available that kind of data. So, that is VAPI was constructed with our group by our group.

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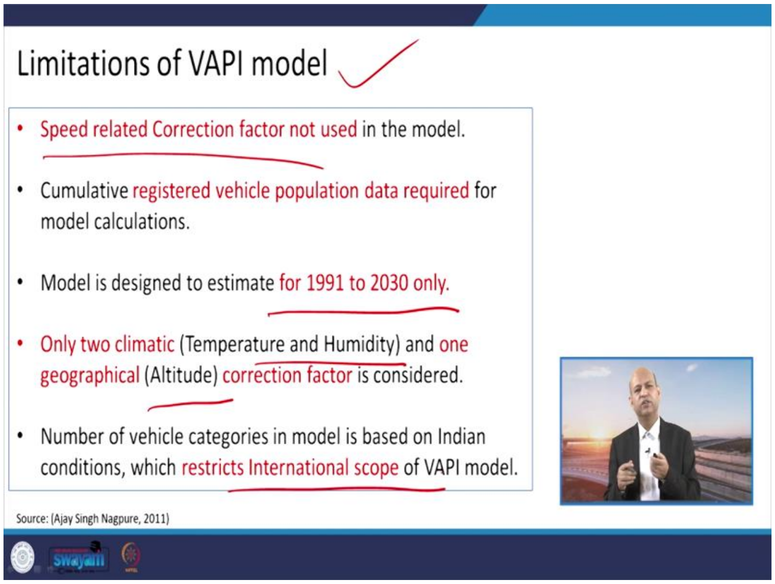

But it also has limitations it is not the perfect model, because there are like speed related correction factors which are not included in this because we have taken only the vehicle kilometre travel. We have not seen the variation of the speed, we have taken the only the average speed of a vehicle category. So means estimations may not be so realistic. If we have the driving cycle and different kinds of speeds then better estimations may be there. So this is one limitation of the VAPI model.

Then we have also seen like it is designed for like 1991 to 2030. So, beyond that there is no scenario creation we have to alternate otherwise, only 2 climatic factors like temperature and humidity and one geographical factor that is the altitude these three correction factors have been implemented some other models those complex or sophisticated models, they have more correction factors depending upon technology and other things.

Number of vehicle categories in the model it is restricted in international scope because it is only in Indian context. So, we have taken only those categories which are in India. So, that means, if some country like nearby like Bangladesh or so, we can use it but if you want to use for other developed or middle kind of economies, then it may not be so realistic. So, that is the limitation of the VAPI model.

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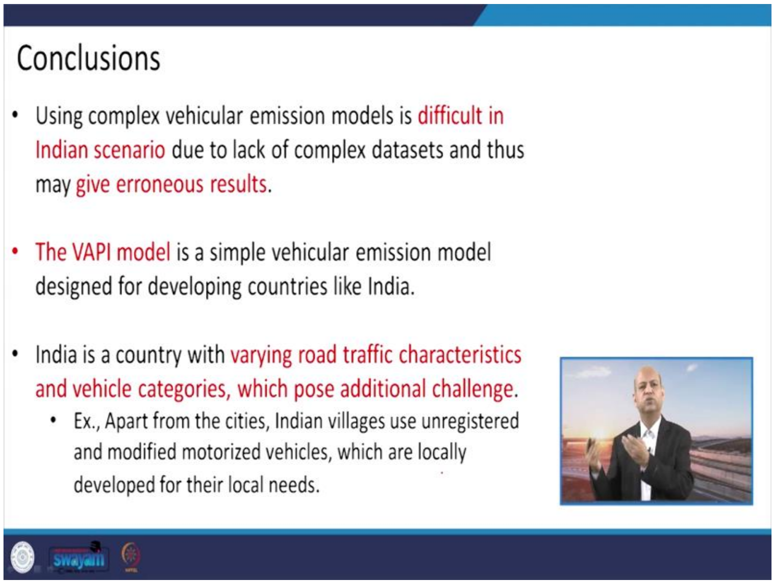

And in conclusion, we can say that the application of these models can really help us to generate different kinds of scenarios, we can play with them, using the emission factors of different fuel or different technology and then we can apply correction factors of the altitude. So, we can also see the variations in terms of impact of altitude on emissions of different pollutants.

So, that way the implications or impacts of the policies or technologies can easily be traced by these models, whether they are effective or not you have seen and which kind of vehicle will be better if we are going for like on hilly areas. So, those kinds of suggestions can also be made based on these admission inventory development using these models. So, this is all for today.

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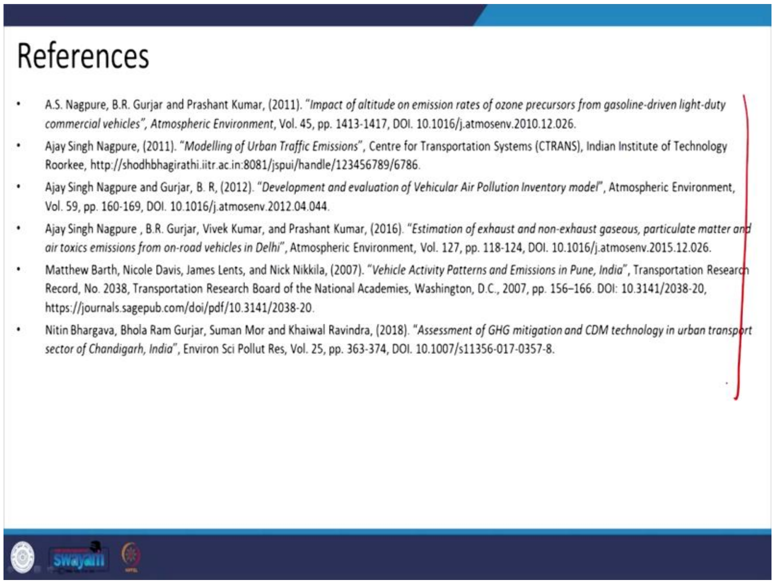

And these are the references which are the basis of this presentation. So, thank you for your kind attention. See you in the next lecture. Thanks again.