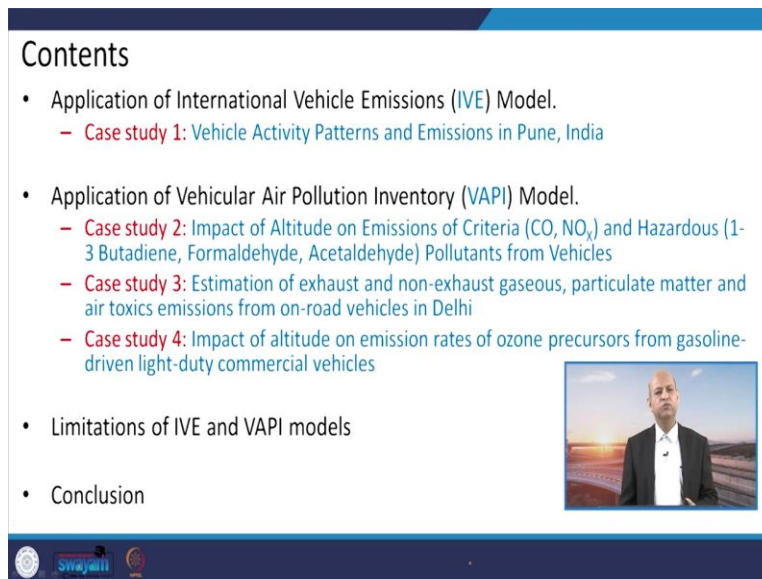


Sustainable Transportation Systems
Professor Bhola Ram Gurjar
Department of Civil Engineering
Indian Institute of Technology, Roorkee
Lecture 41
Modelling of Transport Emissions-II
Case Studies on Application of IVE and VAPI Models in India

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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Contents

- Application of International Vehicle Emissions (IVE) Model.
 - Case study 1: Vehicle Activity Patterns and Emissions in Pune, India
- Application of Vehicular Air Pollution Inventory (VAPI) Model.
 - Case study 2: Impact of Altitude on Emissions of Criteria (CO, NO_x) and Hazardous (1-3 Butadiene, Formaldehyde, Acetaldehyde) Pollutants from Vehicles
 - Case study 3: Estimation of exhaust and non-exhaust gaseous, particulate matter and air toxics emissions from on-road vehicles in Delhi
 - Case study 4: Impact of altitude on emission rates of ozone precursors from gasoline-driven light-duty commercial vehicles
- Limitations of IVE and VAPI models
- Conclusion





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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Case study 1: Application of IVE Model (2003)
Vehicle Activity Patterns and Emissions in Pune, India

- Applied the IVE modeling approach to the city of Pune, India.
- Vehicle activity–fleet composition study by :
 - videotaping and measuring traffic patterns
 - Tracking representative vehicles with Global Positioning System data loggers
 - Monitoring start–stop patterns in instrumented vehicles
 - Conducting on-field surveys

Source: [Matthew Barth et. al, 2007]

The slide features a map of India with Maharashtra highlighted in red, and a small inset photo of a man in a suit speaking.

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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Study Area
in Pune city,
India

Source: (Matthew Barth et. al, 2007)


- In total, nine sample roadways were examined in detail (A1, A2, A3, B1, B2, B3, C1, C2, and C3).
- Sections A, B, and C and three different roadway facility types in each sections
 - Highways-1
 - Arterials-2
 - Residential streets-3

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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Data Collection in Pune city, India



1. Fraction of vehicles in each class, including passenger cars, two-wheelers, three-wheelers (i.e., auto rickshaws), buses, and trucks
2. Technology distribution within each class (engine size, vehicle age, and emissions control technology).
3. Both video-traffic and parked-vehicle surveys were conducted from 7 a.m. to 9 p.m. in the evening over 6 days (March 2003) in the representative sections of the urban area

Source: (Matthew Barth et. al, 2007)

SVKM's

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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General Characteristics of Cars, 2-wheeler & 3-wheeler fleet from Survey

Passenger vehicles	Fraction of passenger vehicles (%)
Gasoline, 4-stroke, carburetor, no catalyst	28.4
Gasoline, 4-stroke, carburetor, 2-way catalyst	13.0
Gasoline, 4-stroke, carburetor, 3-way catalyst	0.6
Gasoline, 4-stroke, multipoint fuel injection, 2-way catalyst	21.6
Gasoline, 4-stroke, multipoint fuel injection, 3-way catalyst	10.1
Diesel, 4-stroke	25.6
Propane, 4-stroke, carburetor, no catalyst	0.6
Propane, 4-stroke, carburetor, 3-way catalyst	0.2

2-wheeled vehicles	Fraction of 2-wheeled vehicles (%)
Gasoline, 2-stroke, pre-1997	17.1
Gasoline, 2-stroke, 1997 and later	15.0
Gasoline, 2-stroke, 2-way catalyst	10.9
Gasoline, 4-stroke, pre-1997	5.0
Gasoline, 4-stroke, 1997-2001	28.5
Gasoline, 4-stroke, post 2001	23.5

3-wheeled vehicles	Fraction of 3-wheeled vehicles (%)
Gasoline, 2-stroke, no catalyst	71.7
Gasoline, 2-stroke, 2-way catalyst	22.5
Gasoline, 4-stroke, no catalyst	2.9
Diesel, 4-stroke	2.9

Source: (Matthew Barth et. al, 2007)



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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Characteristics of Buses in Pune city

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

Source: (Matthew Barth et. al, 2007)



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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Estimation of Driving Pattern in Pune city

VKT Estimation Technique Based on Vehicle Type	Number of Vehicles in Region (N)	Average Driving for Vehicle Type per Day (A) (km/day)	Fraction of Vehicle Type Observed in Fleet (f) (%)	Estimated Total Driving in Pune ($N * A * f$) (km/day)
Passenger car	72,000	24.2	14.60	11,946.575
2-wheeler	660,000	13.5	65.90	13,520.486
3-wheeler	17,000	120	15.90	12,830.189
Bus	890	200	1.50	11,866.667
Total vehicles	749,890		Overall average	12,540.979

NOTE: Number of vehicles in region has been estimated by the Pune municipal government.

Source: [Matthew Barth et. al, 2007]

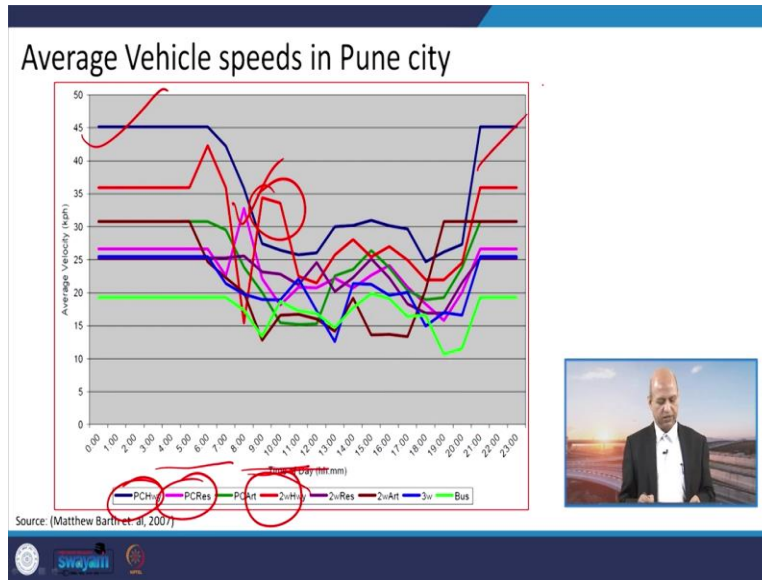


Then the driving pattern means; how do these different kinds of vehicles go with different kinds of speeds like average driving for vehicle type per day kilometre per day. So, passenger cars 72000 population were around 24 kilometre per day, two wheelers population 660000 around 30.5 kilometre per day.

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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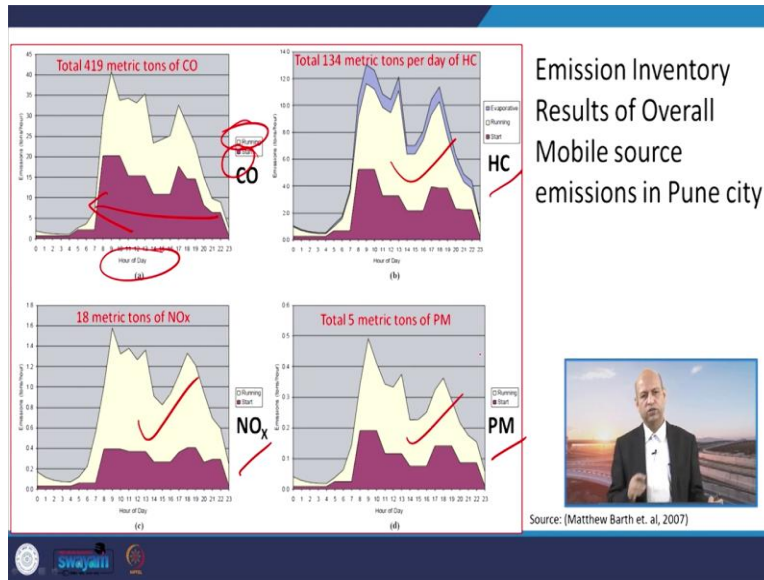


Well when we talk about average vehicle speed in Pune city, so like these you know passenger cars on highways they are having more speed, they these kind of times of the day in early hours of the day, but then this decreases when office hours are there. During office hours you can see these PC, these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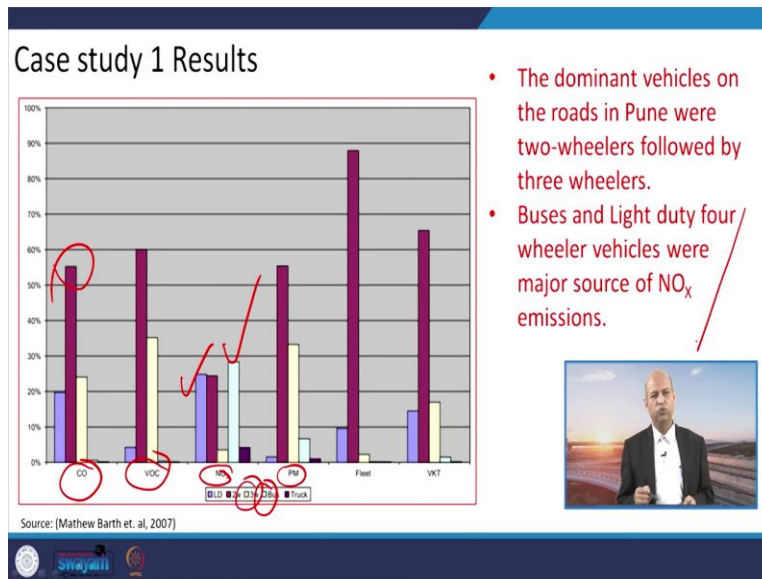


If you go for emission inventory using the IVE model, so, like CO emissions, if you see these related to start ups and the running kind of means; how much CO emissions are there when vehicle is starting, how much it is there when it is running? So at the start this is the you know start related estimations 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, NO_x 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 NO_x 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 NO_x 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 NO_x are coming from this particular these buses, okay, you can see. So, buses and light duty four wheelers were responsible for NO_x emissions otherwise other pollutants are coming from two wheelers and three wheelers.

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Case study 2: Application of VAPI Model in India (2011)
Impact of Altitude on Emissions of Criteria (CO, NO_x) and Hazardous (1-3 Butadiene, Formaldehyde, Acetaldehyde) Pollutants from Vehicles

- **Objective of Study:** To investigate the impact of altitude on emissions of Criteria (CO, NO_x) and Hazardous (1-3 Butadiene, Formaldehyde, Acetaldehyde) Pollutants from Vehicles in 3 cities in India namely:
 - Delhi
 - Dehradun
 - Mussoorie

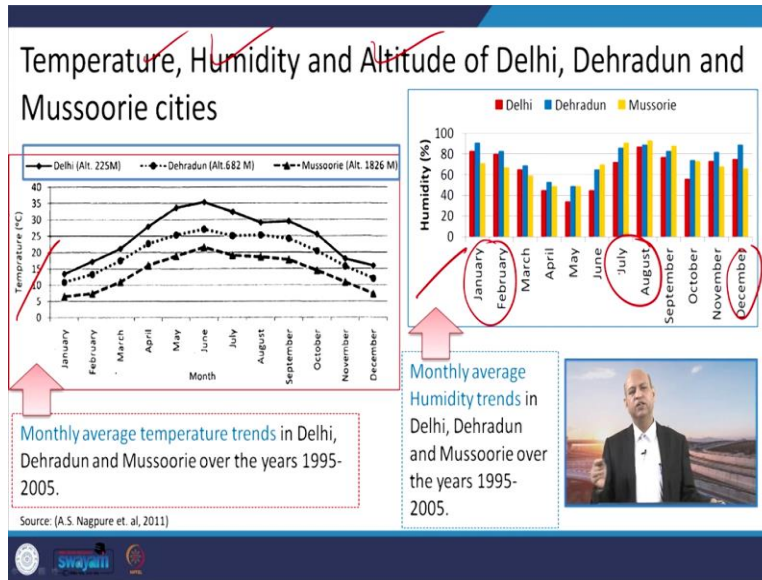
Source: (A.S. Nagpure et. al, 2011)



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, NO_x and hazardous pollutants like butadiene, formaldehyde so on in these three cities. So, let us see using VAPI model how these estimations are there.

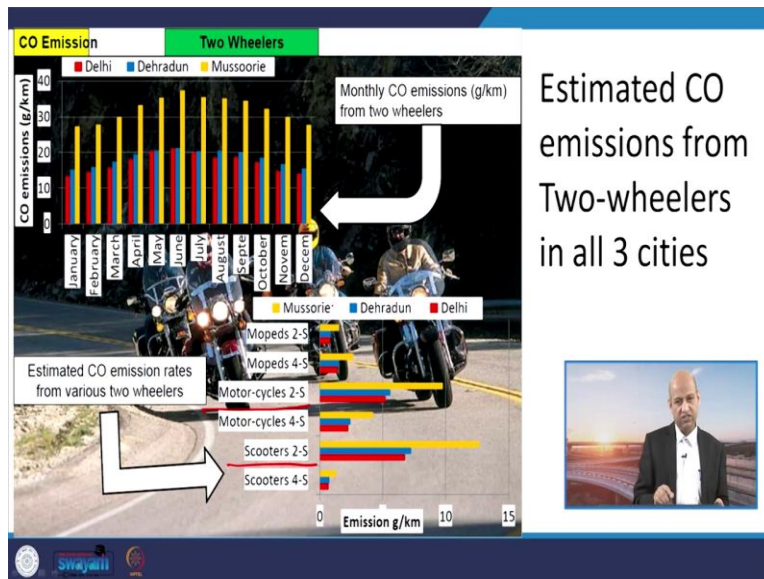
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Well there are no correction factors which we have taken which depends on the topography and the geographical location. So, that is temperature humidity and altitude of Delhi, Dehradun and cities you can see the variation of temperature here humidity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

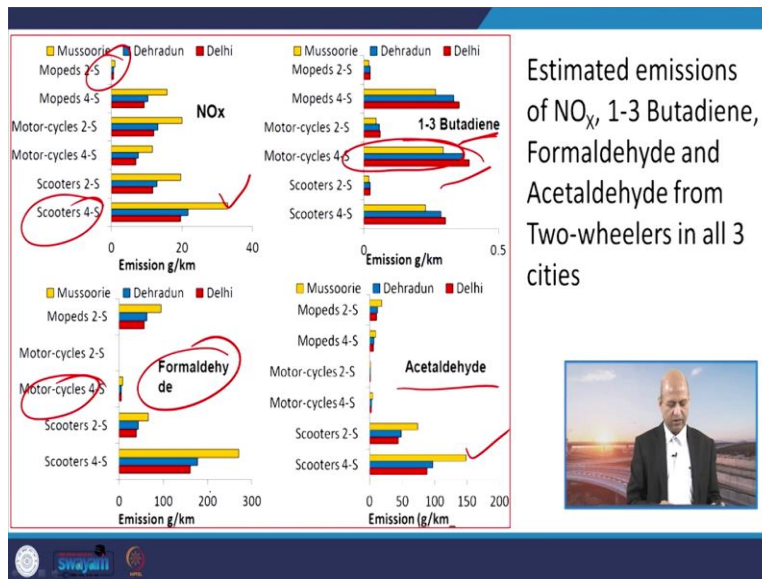
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If you see the CO emissions, so using VAPI model we estimated so in Mussoorie, CO emissions in different months you see dominating emissions are in Mussoorie in comparison to other these two cities. So, monthly CO emissions have been estimated and 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 NO_x 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 NO_x 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.

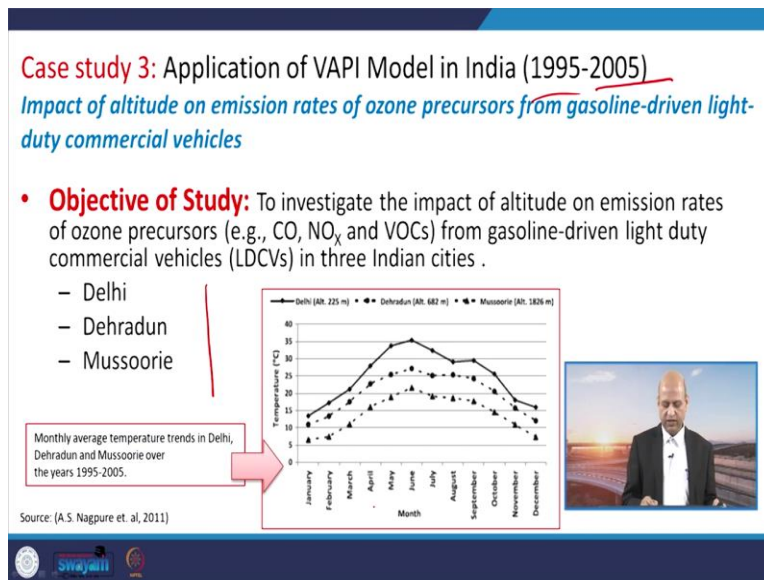
So, if you consider different kinds of pollutants, different situation occurs at different places and like in places also for example, NO_x emissions were more in case of Mussoorie but it is less this butadiene is less in case of Mussoorie, it is more in case of Delhi and in between this Dehradun is 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.

So, that means, the fuel wise variation is also there. Similarly, if we see this emissions from the car of NO_x, 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 NO_x. So, diesel car from that perspective toxic pollutants perspective is not good and the NO_x 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, NO_x 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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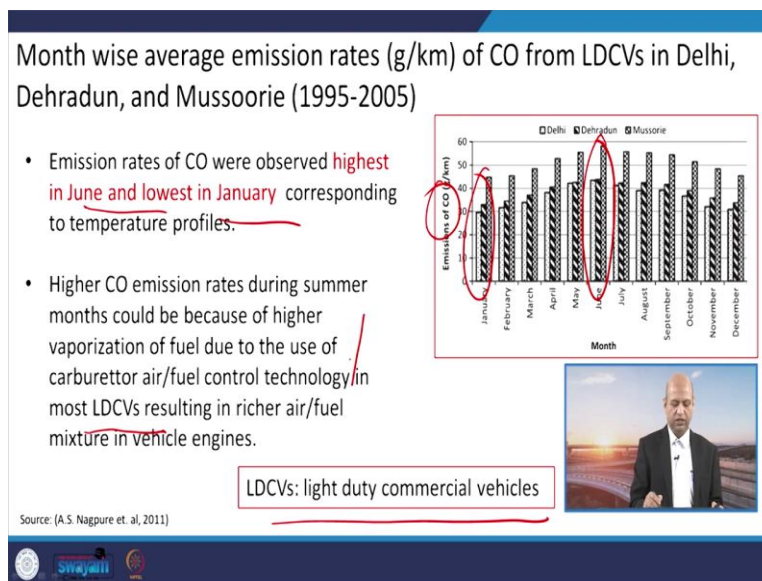
Description	Auto/Small Truck
Fuel	Petrol
Weight	Light
Air/Fuel Control	Carburetor
Exhaust	None
Evaporative	PCV
Age	<79 K km
Index	0
Default Base Emission Rate ($g\ km^{-1}\ B_{ij}$)	
CO _{run}	22.255
NO _{x,run}	2.002
VOC _{run}	2.7
Correction Factor Temperature $K_{Temp}(T)$	
CO Low Temperature Running (4 °C)	1.03
CO High Temperature Running (40 °C)	1.93
NO _x Low Temperature Running (4 °C)	1.12
NO _x 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 $K_{Alt}(H)$	
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 $K_{Humid}(RH)$	
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: [A.S. Nagpure et. al, 2011]

Source: Adapted from IVEM Correction Factor Data, 2008.

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.

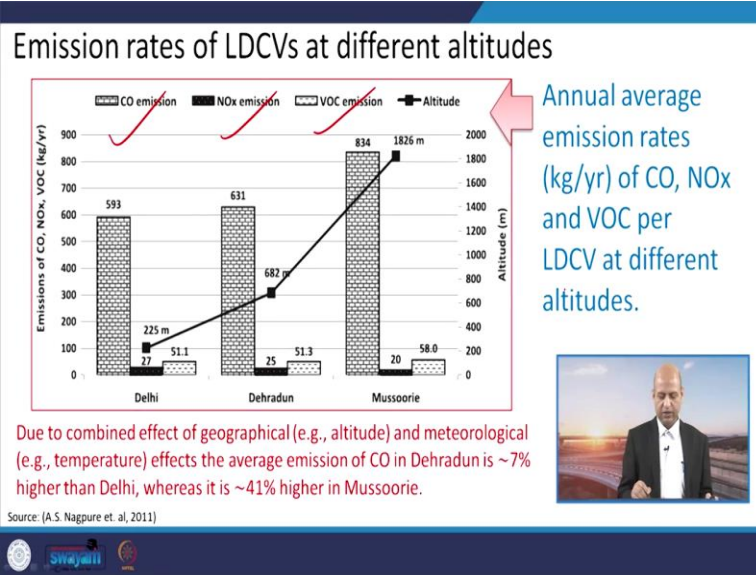
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So, we see this monthly variation of you can see for Delhi, Dehradun and Mussoorie again CO emissions and CO emissions you can see highest in June and lowest in January highest in June and lowest in January in all cities. But basically it is more in 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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Technology description of Gasoline-driven Light-duty Commercial Vehicles (LDCVs) and Correction factors

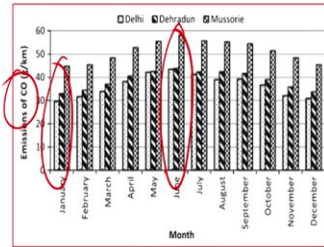
Description	Auto/Small Truck
Fuel	PETROL
Weight	Light
Air/Fuel Control	Carburetor
Exhaust	None
Evaporative	PCV
Age	<79 k km
Index	0
Default Base Emission Rate ($g\ km^{-1}\ B_{ij}$)	
CO _{run}	22.255
NO _{x,run}	2.002
VOC _{run}	2.7
Correction Factor Temperature $K_{Temp,Bj}$	
CO Low Temperature Running (4 °C)	1.03
CO High Temperature Running (40 °C)	1.93
NO _x Low Temperature Running (4 °C)	1.12
NO _x 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 $K_{Alt,Bj}$	
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 $K_{Hum,Bj}$	
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: (A.S. Nagpure et. al, 2011)

Source: Adapted from IVEM Correction Factor Data, 2008.

Month wise average emission rates (g/km) of CO from LDCVs in Delhi, Dehradun, and Mussoorie (1995-2005)

- Emission rates of CO were observed **highest in June and lowest in January** corresponding to temperature profiles.
- Higher CO emission rates during summer months could be because of higher vaporization of fuel due to the use of carburettor air/fuel control technology in most LDCVs resulting in richer air/fuel mixture in vehicle engines.



LDCVs: light duty commercial vehicles

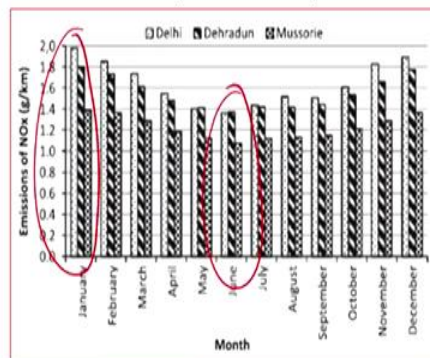
Source: [A.S. Nagpure et al, 2011]



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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Month wise average emission rates (g/km) of NO_x from LDCVs in Delhi, Dehradun, and Mussoorie (1995-2005).

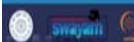


- The LDCVs emit minimum NO_x in June (hottest month of the year-about 1.64 g/km in Delhi, 1.55 g/km in Dehradun and about 1.22 g/km in Mussoorie).
- After June, monthly emission rates of NO_x starts increasing while the temperature declines in all three cities



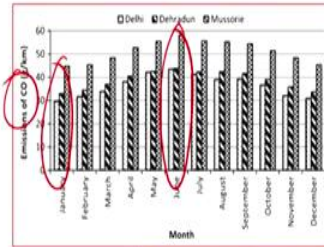
LDCVs: light duty commercial vehicles

Source: [A.S. Nagpure et al, 2011]



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- Higher CO emission rates during summer months could be because of higher vaporization of fuel due to the use of carburettor air/fuel control technology in most LDCVs resulting in richer air/fuel mixture in vehicle engines.

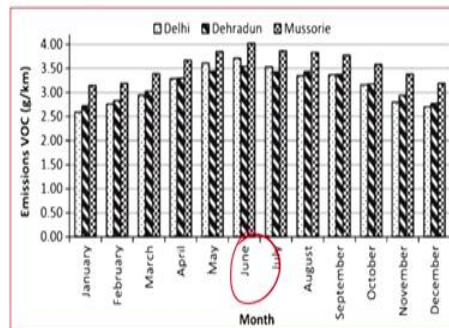


LDCVs: light duty commercial vehicles

Source: [A.S. Nagpure et al, 2011]



Month wise average emission rates (g/km) of VOC per LDCVs in Delhi, Dehradun, and Mussoorie (1995-2005).



- Highest emission rate was observed in the hottest month of June that was about 4 g/km (Mussoorie).
- After June, temperature decreases in all three cities, so are the VOCs.
- The lowest emission rates were found in January, coldest month at all locations- 2.59, 2.71 and 3.14 g/km for Delhi, Dehradun and Mussoorie, respectively.



LDCVs: light duty commercial vehicles

Source: [A.S. Nagpure et al, 2011]



When we go for basically monthly emission rates of NO_x 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 NO_x 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 NO_x 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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Change in average emission rates of CO, NO_x and VOCs from a gasoline-driven LDCV in Delhi and Mussoorie due to exclusive change in either altitude or temperature in the month of May

	CO (g km ⁻¹)	NO _x (g km ⁻¹)	VOCs (g km ⁻¹)
<i>Due to temperature change only (i.e. Altitude Correction Factor = 1)</i>			
Delhi	38.5	1.4	3.5
Mussoorie	29.7	1.7	2.8
~ % Change	-23%	29%	-22%
<i>Due to Altitude change only (i.e. Temperature Correction Factor = 1)</i>			
Delhi	24.4	2.1	2.8
Mussoorie	41.6	1.3	3.8
~ % Change	71%	-38%	36%

Source: (A.S. Nagpure et. al, 2011)

LDCVs: light duty commercial vehicles



Case study 3 Results (1/2)

- Unlike NO_x, emission rates of CO and VOCs have increased with altitude.
 - For example, CO emission rate has considerably increased from 36.5 g/km in Delhi to 51.3 g/km (i.e. by ~41%) in Mussoorie, whereas VOCs emission rate marginally increased from 3.2 g/km to 3.6 g/km.
- Temperature was second to altitude in influencing emissions.
 - Emissions of CO and VOCs were found to be increasing at high ambient temperature in cities like Delhi and Dehradun while opposite trend was observed for NO_x.

Results indicate that the altitude was the dominant factor in case of hilly area influencing the emissions of CO, VOCs, and NO_x from the LDCVs.



Source: (A.S. Nagpure et. al, 2011)



Case study 3 Results (2/2)

- The inferences of this study are important from human health perspective, especially for the people residing in high altitude cities where a peculiar combination of lower oxygen levels and high concentrations of CO and VOCs can adversely affect the public health.
- Also, increased levels of CO and VOCs at high altitudes may conspicuously influence the chemistry of tropospheric ozone.



Source: (A.S. Nagpure et. al, 2011)



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 NO_x opposite of the NO_x then if we see these results so, it is also known NO_x 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 NO_x 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 NO_x emissions are less so, the VOC and CO emission they can participate in producing the ozone rather than NO_x 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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Case study 4: Application of VAPI Model in India (2011)
Estimation of exhaust and non-exhaust gaseous, particulate matter and air toxics emissions from on-road vehicles in Delhi

- **Objective of the study:** Analysis of emissions from on-road vehicles in megacity, Delhi, by:
 - Estimation of CO₂, HC, PM₁₀, CO, NO_x and mobile source air toxics (MSATs such as 1,3-butadiene, acetaldehyde, benzene, formaldehyde, total aldehyde, and total PAHs) emissions from vehicle exhaust by considering vehicle characteristics (e.g. age, technology).
 - Assessment of non-exhaust (e.g. road-dust, tyre wear, brake wear and evaporative) emissions from on-road vehicles in Delhi.
 - Future projection (2011-2020) of exhaust and non-exhaust emissions using GDP and per capita based econometric model.

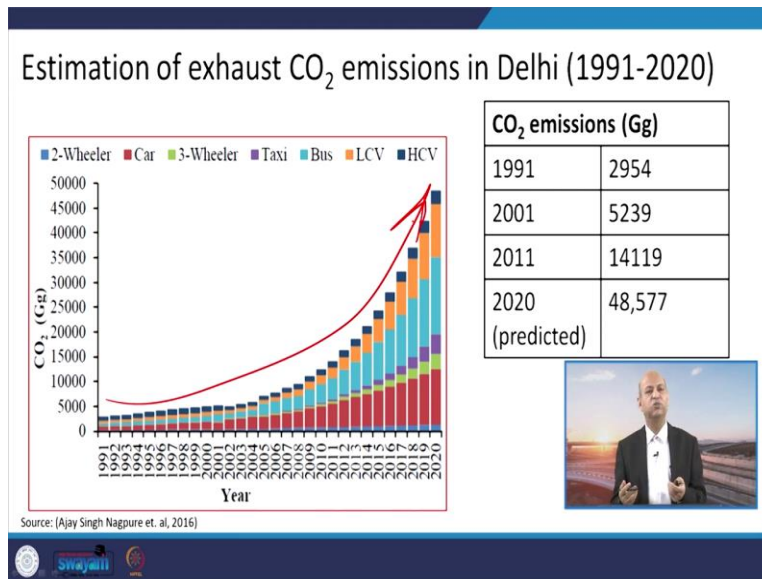
Source: (Ajay Singh Nagpure et. al, 2016)



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, NO_x hydrocarbons, greenhouse gas CO₂ and then butadiene, acetaldehyde, benzene, formaldehyde aldehydes all those total PAHs.

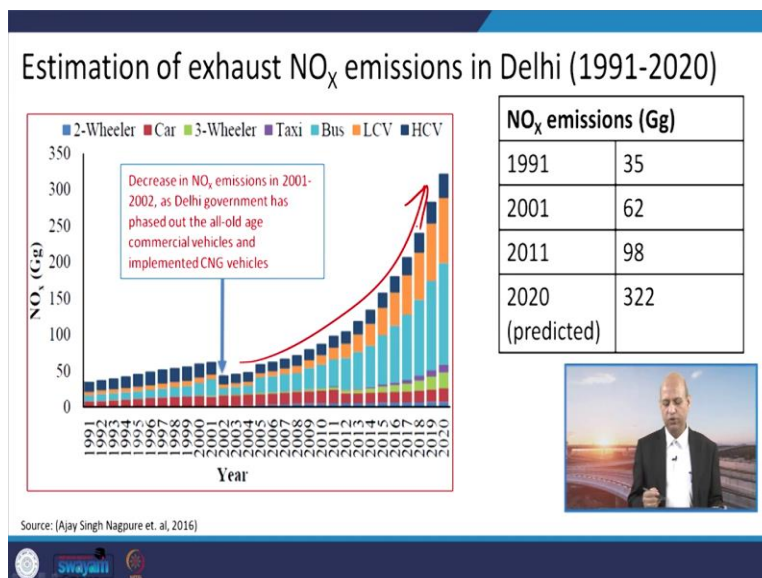
So, all those pollutants have been considered and non exhaust emissions like the re-suspension of road dust and wear and tyre of the tires and the brake wear an operative emissions. So, non exhaust emissions have also been estimated.

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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 1991 to 2020 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.

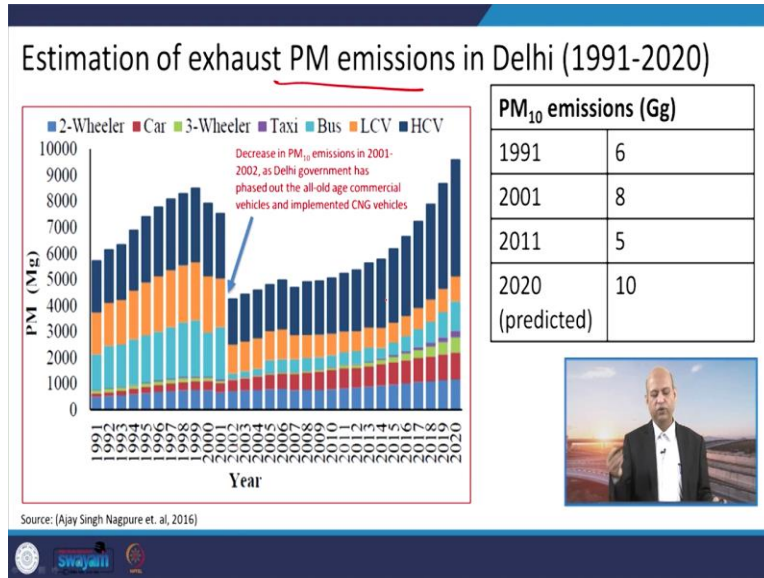
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When we talk about NO_x emissions, then there is decrease in case of like 2002 when this CNG implementation was there, the whole bus fleet was converted to the CNG. So, this dip was there,

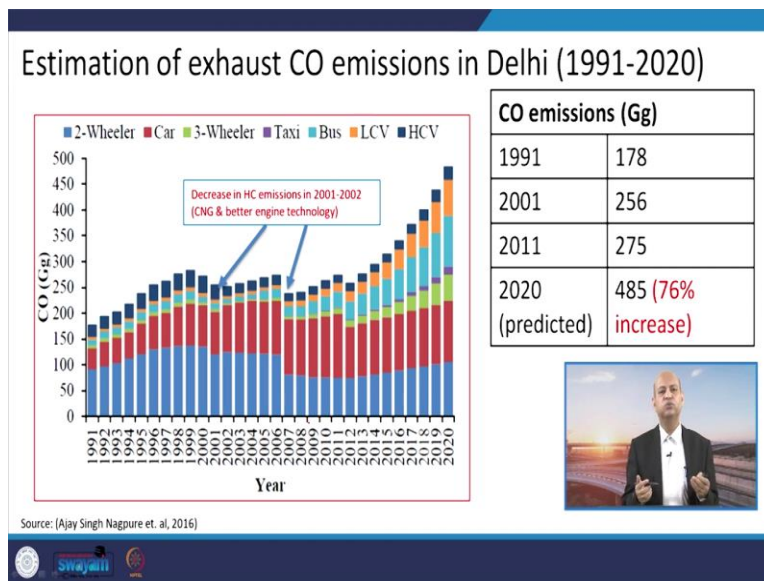
but because you know this number of vehicles were increasing and buses also increased. So the emission again increased because of the population of the vehicles.

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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.

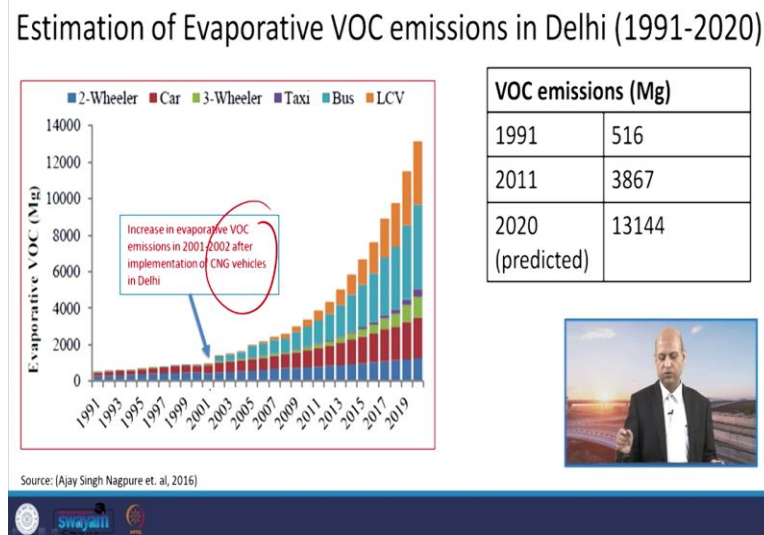
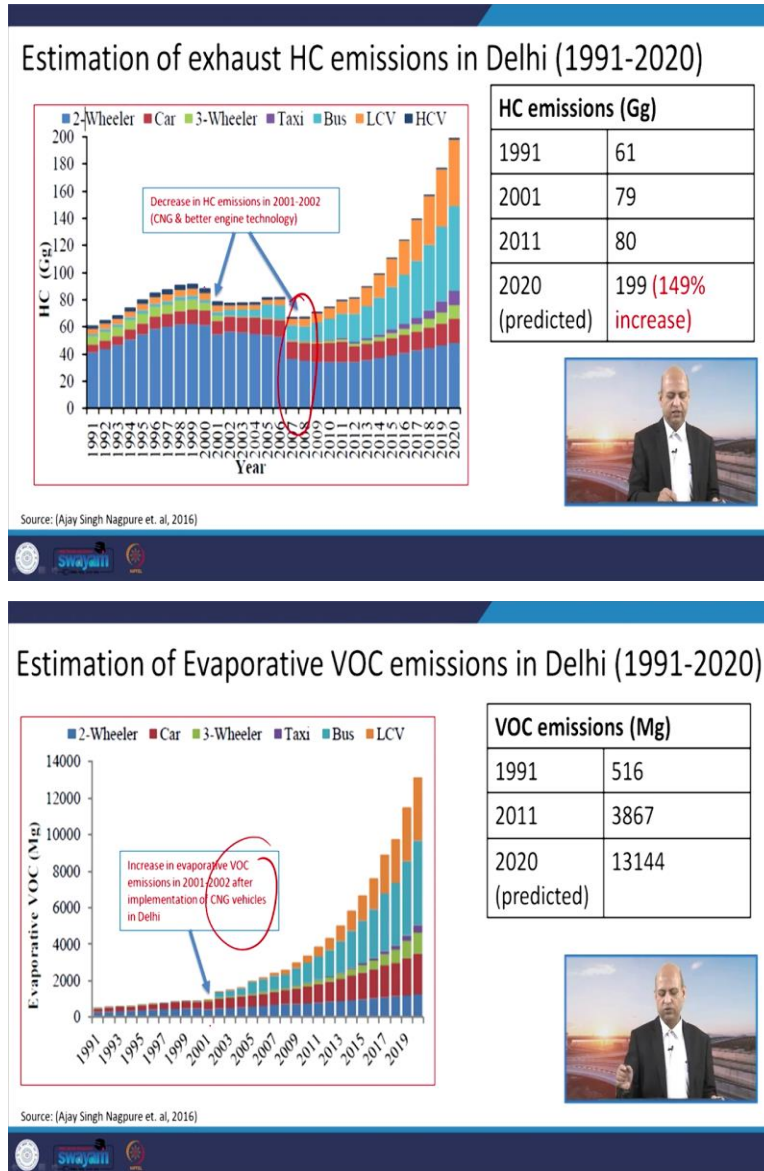
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In case of like this CO emissions basically you can see that two dips one is in 2001, 2002 another is 2007 or so, so, the earlier one was related to CNG but the second dip was related to technology

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.

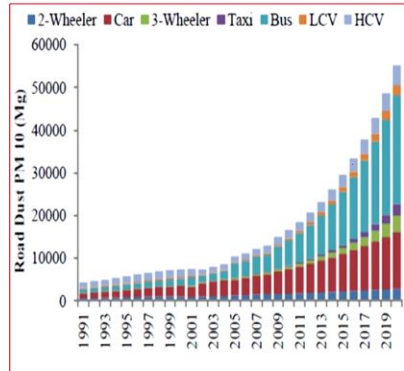
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Similarly, like hydrocarbons the same thing has happened because their emissions have to be reduced because better burning is there then combustion is better than CO2 increases, but other like CO and hydrocarbons decrease in this particular year and 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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Estimation of Non-exhaust Road Dust PM₁₀ emissions in Delhi (1991-2020)



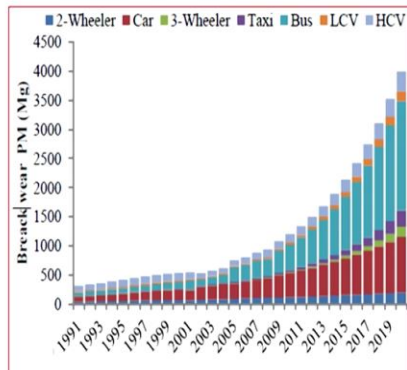
Among all the three sources of Total Non-exhaust sources (Road dust suspensions, Brake wear & Tyre wear, Road dust share was the highest 91-92% during the whole study period.



Source: (Ajay Singh Nagpure et. al, 2016)



Estimation of Non-exhaust Brake wear PM₁₀ emissions in Delhi (1991-2020)



Brake wear emissions contributed to 7% of the Total Non-exhaust emissions

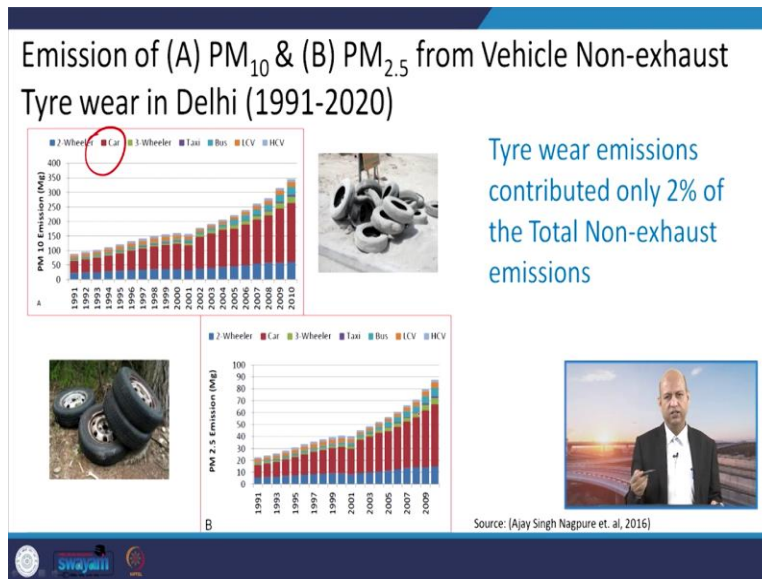


Source: (Ajay Singh Nagpure et. al, 2016)



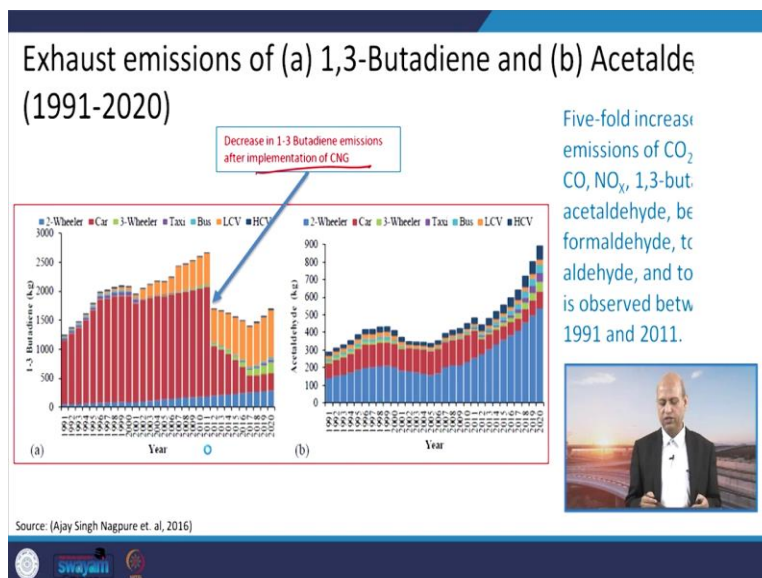
Then we can see the estimations of non exhaust road dust and PM10 emissions from the road dust. So, that was estimated as increasing over the years similarly, PM10 from break wears, it also increased because number of vehicles are increasing. So, naturally it is increasing.

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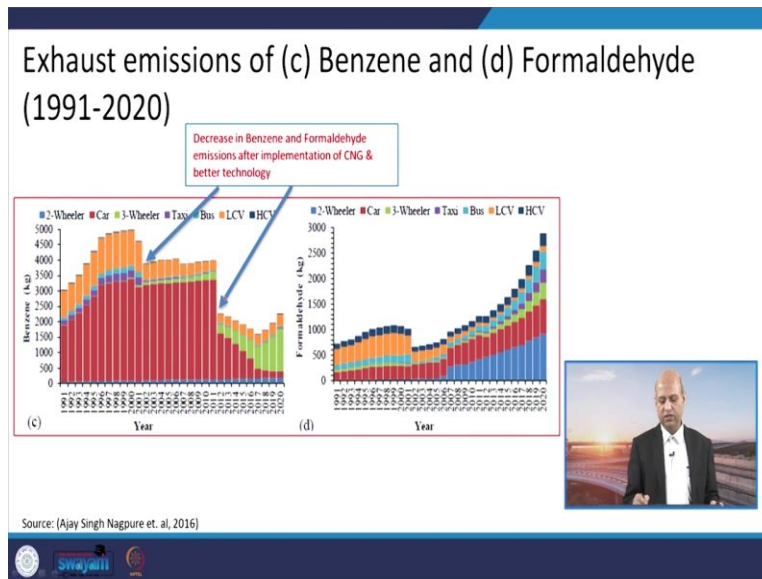
If we see this tire wear and from different vehicle category, then cars are more responsible for the PM₁₀ this particular you can see the number and also these PM_{2.5} this predominant source is car tires basically when we consider these vehicle related non exhaust emissions. So, tires are responsible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

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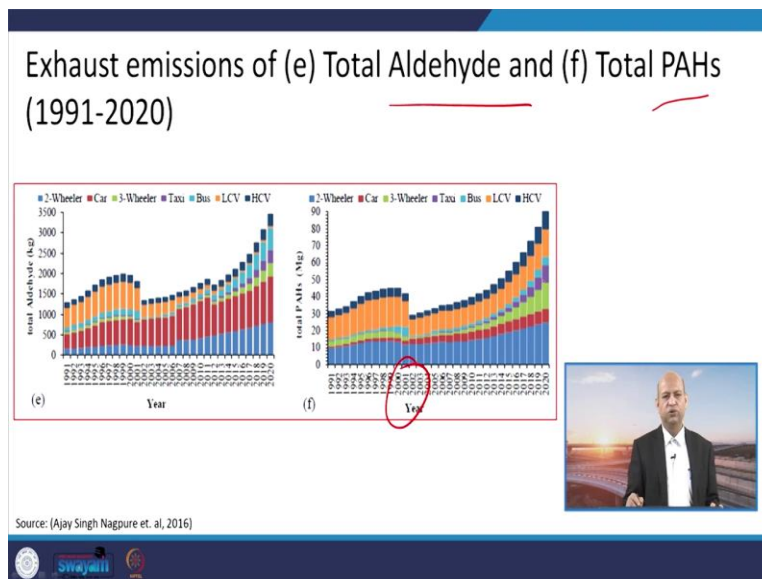
If we consider butadiene acetaldehyde then you know this decrease was there due to implementation of CNG in 2001. Otherwise, the later on then because of number of year population of the vehicles it increased.

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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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Case study 4 Results (1/2)

- The private vehicle emissions (two wheelers and cars) were estimated to increase by 2-18 times in 2020 over the 1991 levels.
- Two wheelers were dominating the emissions of CO (29-51%), HC (45-73%), acetaldehyde (46-51%) and total poly aromatic hydrocarbons (PAHs, 37-42%).
- Private cars were responsible for the majority of the CO₂ (24-42%), 1,3-butadiene (72-89%), benzene (60-82%), formaldehyde (23-44%) and total aldehyde (27-52%) between 1991 and 2011.




Source: [Ajay Singh Nagpure et. al, 2016]

Swayam

Case study 4 Results (2/2)

- The heavy-duty commercial vehicles (HCVs) contributed to majority of the NO_x (48-41%) and PM₁₀ (33-43%) emissions during the years 1991-2011.
- Vehicular exhausts were responsible for (21-55%) PM₁₀ emissions, road dust (42-73%) and brake wear (3-5%) between 1991 and 2011.
- After 2002, non-exhaust emissions (e.g. road dust, brake wear and tyre wear) indicates higher accountability for PM₁₀ emissions (66-86%) than the exhaust emissions (14-34%).



Source: [Ajay Singh Nagpure et. al, 2016]

Swayam

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 NO_x 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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Limitations of IVE Model

- IVE model was designed for developing countries similar to India.
 - However, the complexity of the model is similar to the US and European models, which needs extensive data requirements.
 - Difficult to compile such complex datasets in Indian scenario.



Source: (Ajay Singh Nagpure, 2011)

swayam


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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Limitations of VAPI model ✓

- Speed related Correction factor not used in the model.
- Cumulative registered vehicle population data required for model calculations.
- Model is designed to estimate for 1991 to 2030 only.
- Only two climatic (Temperature and Humidity) and one geographical (Altitude) correction factor is considered.
- Number of vehicle categories in model is based on Indian conditions, which restricts International scope of VAPI model.

Source: (Ajay Singh Nagpure, 2011)



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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Conclusions

- Using complex vehicular emission models is **difficult in Indian scenario** due to lack of complex datasets and thus may **give erroneous results**.
- **The VAPI model** is a simple vehicular emission model designed for developing countries like India.
- India is a country with **varying road traffic characteristics and vehicle categories, which pose additional challenge**.
 - Ex., Apart from the cities, Indian villages use unregistered and modified motorized vehicles, which are locally developed for their local needs.




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.