Lecture 7

Air Quality:

Air Pollution Control

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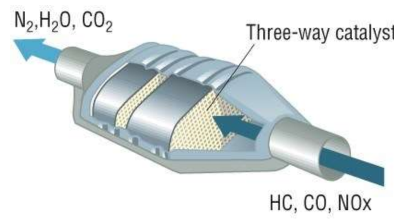
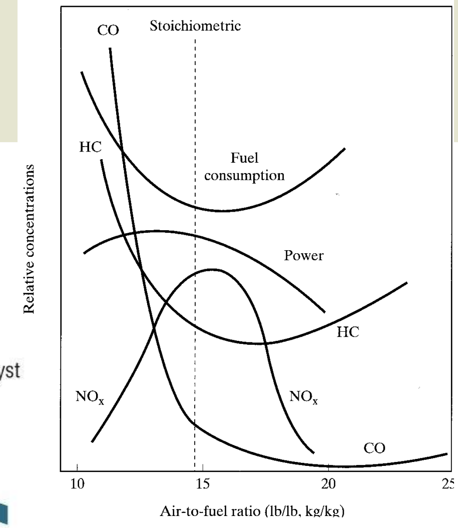
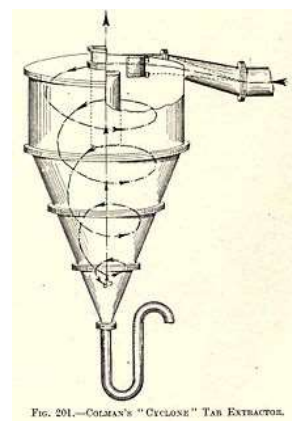
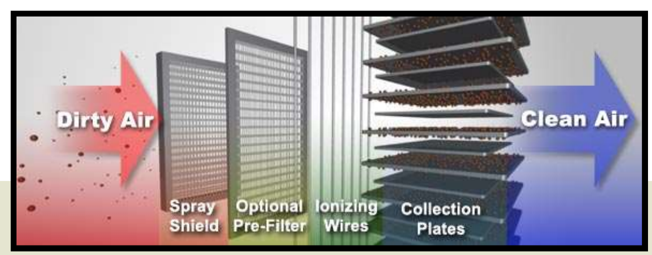
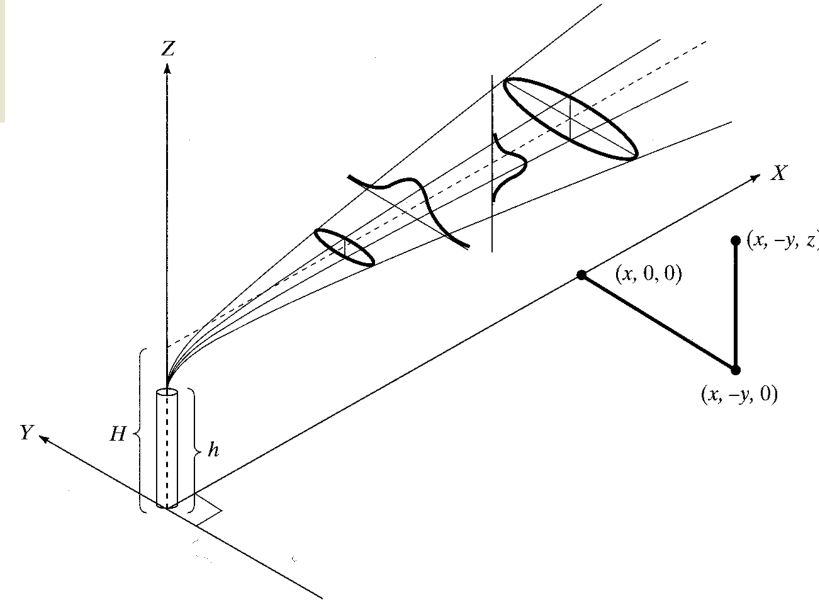








Recap 1



- Air pollution monitoring is crucial for true understanding of the state of the environment but impossible to have wide spatial coverage, hence air quality modeling is needed

- Gaussian Plume (Dispersion) Model (GPM) is used to estimate the ground level concentrations for pollutants coming from a chimney/point source

- Inputs to GPM are: height of chimney; source emission strength; wind rose data; atmospheric stability of the region

$$\chi(x, y, 0, H) = \left[\frac{Q}{\pi s_y s_z u}\right]\left[\exp\left[-\frac{1}{2}\left(\frac{y}{s_y}\right)^2\right]\right]\left[\exp\left[-\frac{1}{2}\left(\frac{H}{s_z}\right)^2\right]\right]$$

Recap 2

- Assumptions in GPM
  - pollutants released from a “virtual point source”
  - advective transport by wind
  - dispersive transport (spreading) follows normal (Gaussian) distribution away from trajectory
  - constant source emission rate
  - wind speed constant with time and elevation
  - pollutant is conservative (no reaction)
  - terrain is flat and unobstructed
  - uniform atmospheric stability
- Effective stack height

$$H = h + \Delta H$$

$$\Delta H = \frac{v_s d}{u}\left[1.5 + \left(2.68\times10^{-3}(P)\left(\frac{T_s - T_a}{T_s}\right)d\right)\right]$$

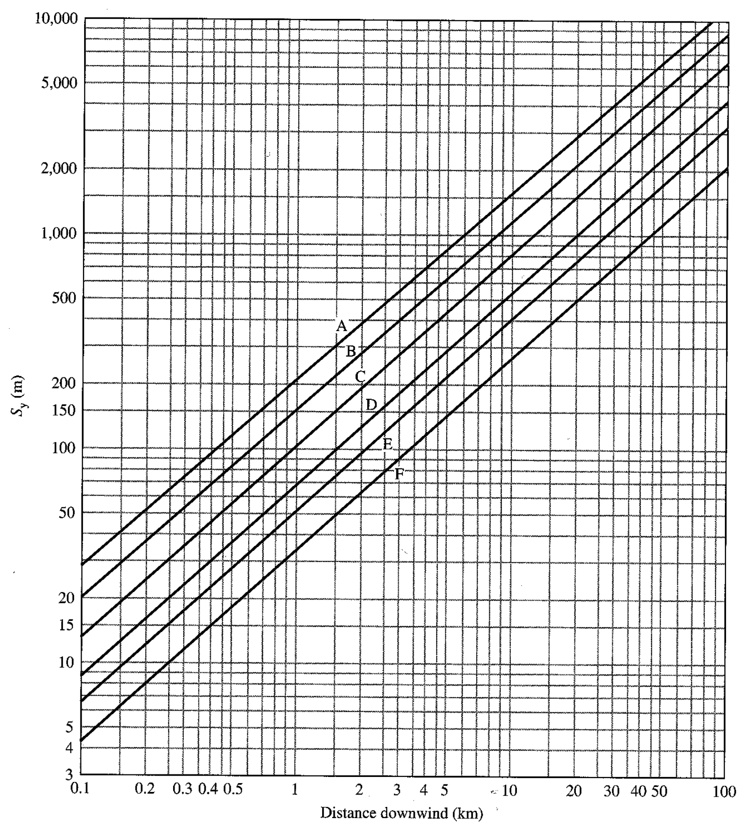
Holland’s formula

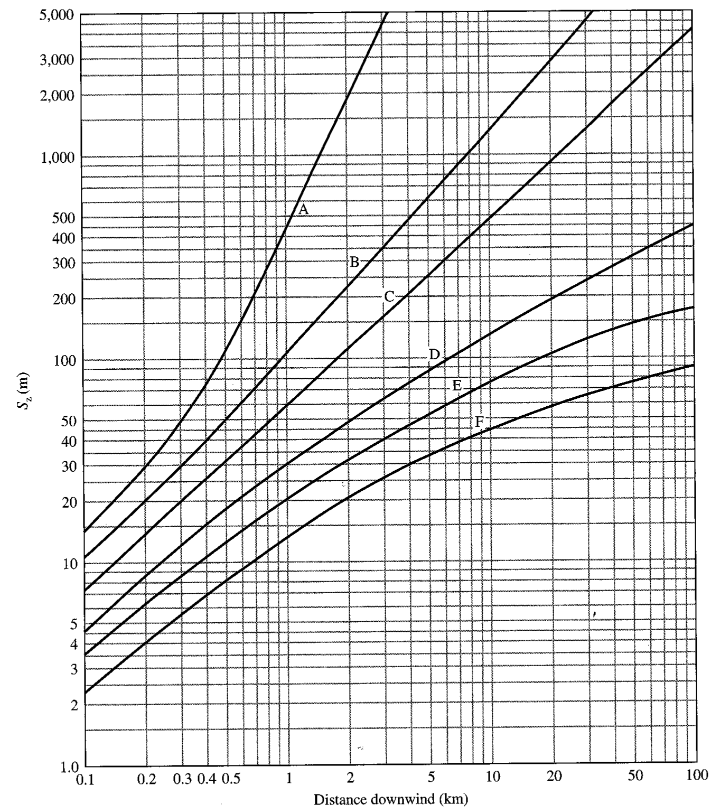
Recap 3

$$\sigma_y = a\,x^{0.894}$$

$$\sigma_z = cx^d + f$$

- Estimation of horizontal dispersion (s_y and s_z)

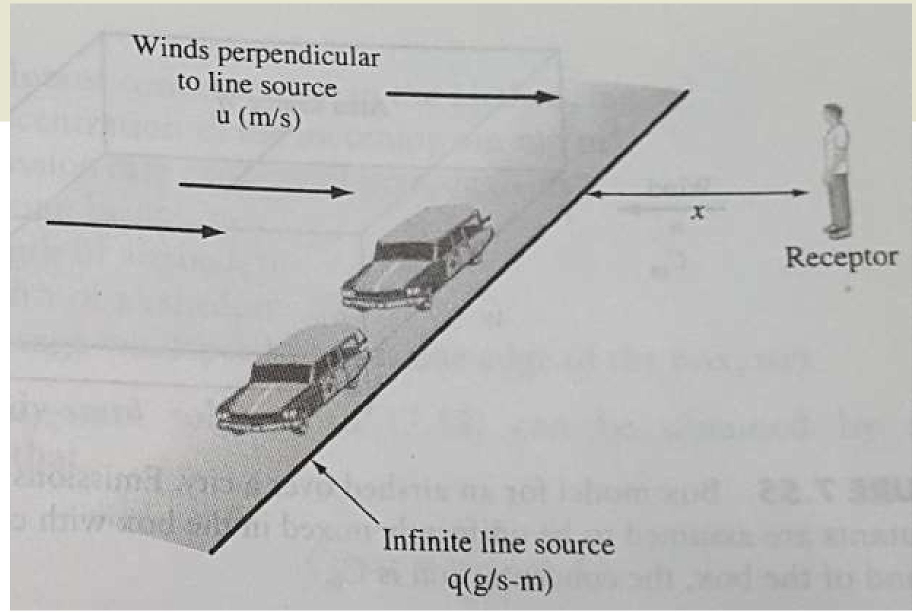




- Estimation of wind speed at <u>stack height</u>
- Model uncertainty could be up to 50%

$$u_2 = u_1\left(\frac{z_2}{z_1}\right)^p$$

Recap 4

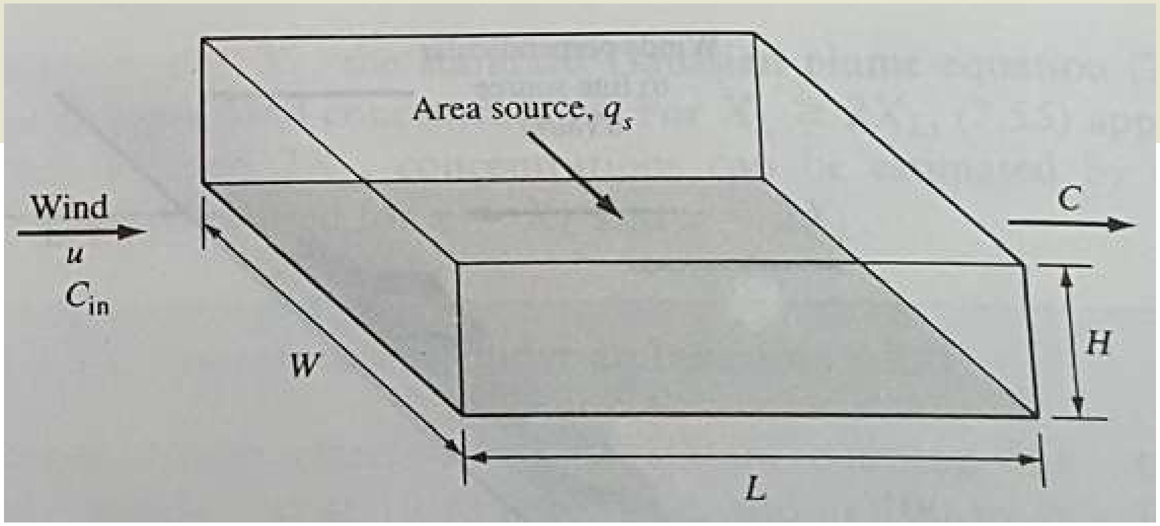


- When source is distributed along a <u>line</u> with continuous emissions, similar approach can be used
- Ground level conc. of pollutants at a perpendicular distance x can be obtained by:

$$C(x) = \frac{2q}{\sqrt{2\pi}\,\sigma_z u}$$

$$\chi(x,y,0,H)=\left[\frac{Q}{\pi s_y s_z u}\right]\left[\exp\left[-\frac{1}{2}\left(\frac{y}{s_y}\right)^2\right]\right]\left[\exp\left[-\frac{1}{2}\left(\frac{H}{s_z}\right)^2\right]\right]$$

Recap 5



- For distributed sources spread over an area, box model can be used

- Assuming uniform mixing in the box, and a conservative pollutants, rate of change of pollutants in the box:

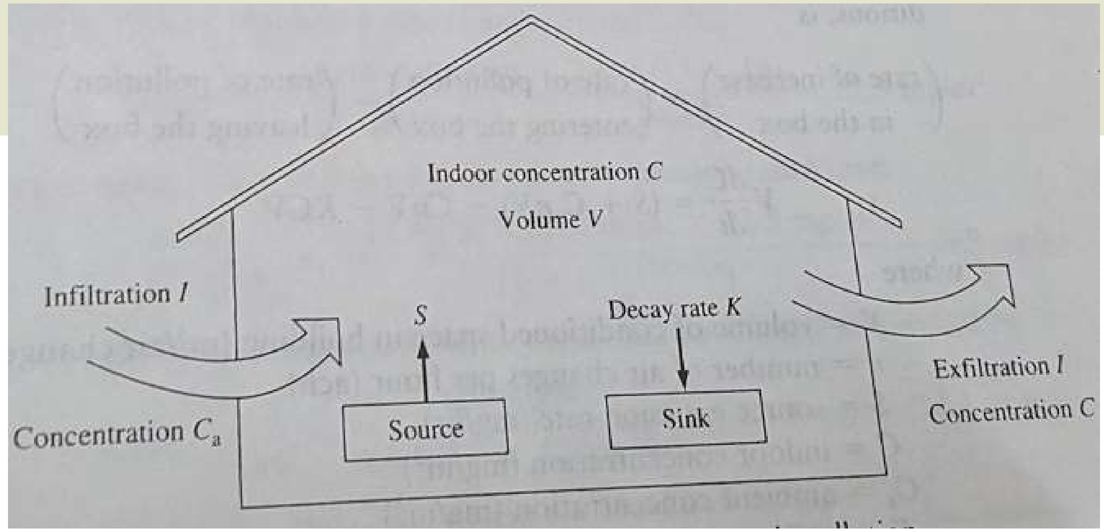
$$\begin{pmatrix}\text{Rate of change of} \\ \text{pollution in the box}\end{pmatrix} = \begin{pmatrix}\text{Rate of pollution} \\ \text{entering the box}\end{pmatrix} - \begin{pmatrix}\text{Rate of pollution} \\ \text{leaving the box}\end{pmatrix}$$

$$LWH\frac{dC}{dt} = q_sLW + WHuC_{in} - WHuC$$

$$C(t) = \left(\frac{q_sL}{uH} + C_{in}\right)(1 - e^{-ut/L}) + C(0)e^{-ut/L}$$

$$C(\infty) = \frac{q_sL}{uH} + C_{in}$$

Recap 6



- Similar to urban airshed, an indoor box model can be built
- e.g. a basic mass balance for pollution in the building/ room, assuming well-mixed conditions:

$$\begin{pmatrix}\text{rate of increase}\\ \text{in the box}\end{pmatrix} = \begin{pmatrix}\text{rate of pollution}\\ \text{entering the box}\end{pmatrix} - \begin{pmatrix}\text{rate of pollution}\\ \text{leaving the box}\end{pmatrix} - \begin{pmatrix}\text{rate of decay}\\ \text{in the box}\end{pmatrix}$$

$$V\frac{dC}{dt} = (S + C_a nV) - CnV - KCV$$

where, *n* is number of air changes per hour

$$C(t) = \left[\frac{(S/V) + C_a n}{n + K}\right]\left[1 - e^{-(n+K)t}\right] + C(0)e^{-(n+K)t}$$

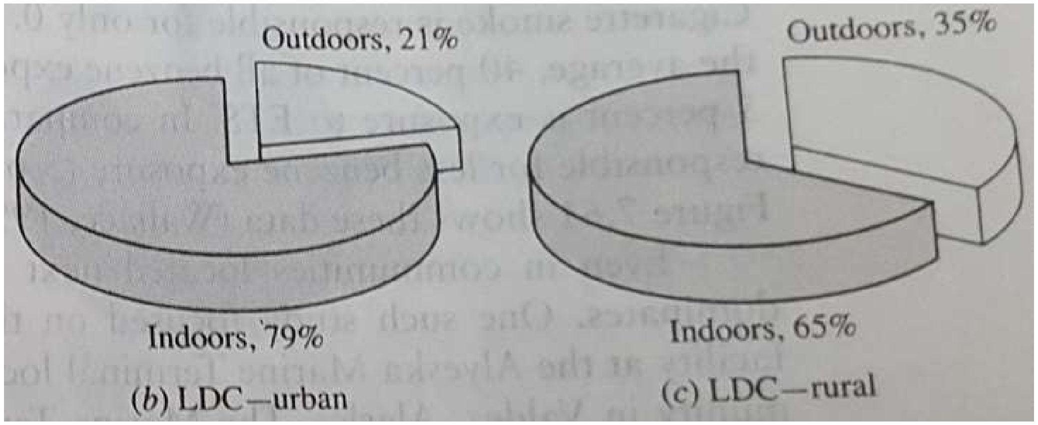
$$C(\infty) = \frac{(S/V) + C_a n}{n + K}$$

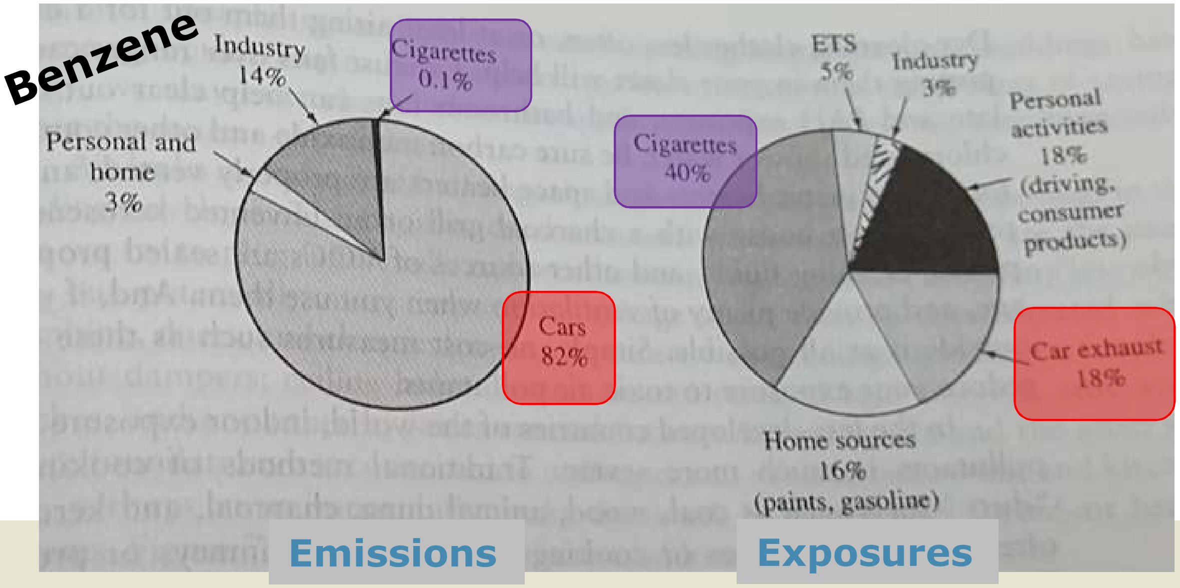
$$C(t) = \left(\frac{S}{nV}\right)(1 - e^{-nt})$$

Recap 6

Exposure = *concentration x duration of time in contact*

- Contact duration depends on where people spend their time
- Some of the largest emissions may have lowest exposures and vice-versa





Today's Learning Objective !

- To learn about air pollution control methods from mobile and stationary sources

Air Pollution Control: Mobile Sources

India Emission Standards

Standard	Reference	Date	Region
India 2000	Euro 1	2000	Nationwide
Bharat Stage II	Euro 2	2001	NCR*, Mumbai, Kolkata, Chennai
		2003.04	NCR*, 11 cities†
		2005.04	Nationwide
Bharat Stage III	Euro 3	2005.04	NCR*, 11 cities†
		2010.04	Nationwide
Bharat Stage IV	Euro 4	2010.04	NCR*, 13 cities‡
		2015.07	Above plus 29 cities mainly in the states of Haryana, Uttar Pradesh, Rajasthan and Maharastra [3231]
		2015.10	North India plus bordering districts of Rajasthan (9 States) [3232]
		2016.04	Western India plus parts of South and East India (10 States and Territories) [3232]
		2017.04	Nationwide [3232]
Bharat Stage V	Euro 5	n/a [a]	
Bharat Stage VI	Euro 6	2020.04	Nationwide [3349]

* National Capital Region (Delhi)
† Mumbai, Kolkata, Chennai, Bangalore, Hyderabad, Secunderabad, Ahmedabad, Pune, Surat, Kanpur and Agra
‡ Above cities plus Solapur and Lucknow. The program was later expanded with the aim of including 50 additional cities by March 2015
[a] Initially proposed in 2015.11 [3297][3298] but removed from a 2016.02 proposal [3349]

www.dieselnet.com/standards/in/

Emission control of IC engines

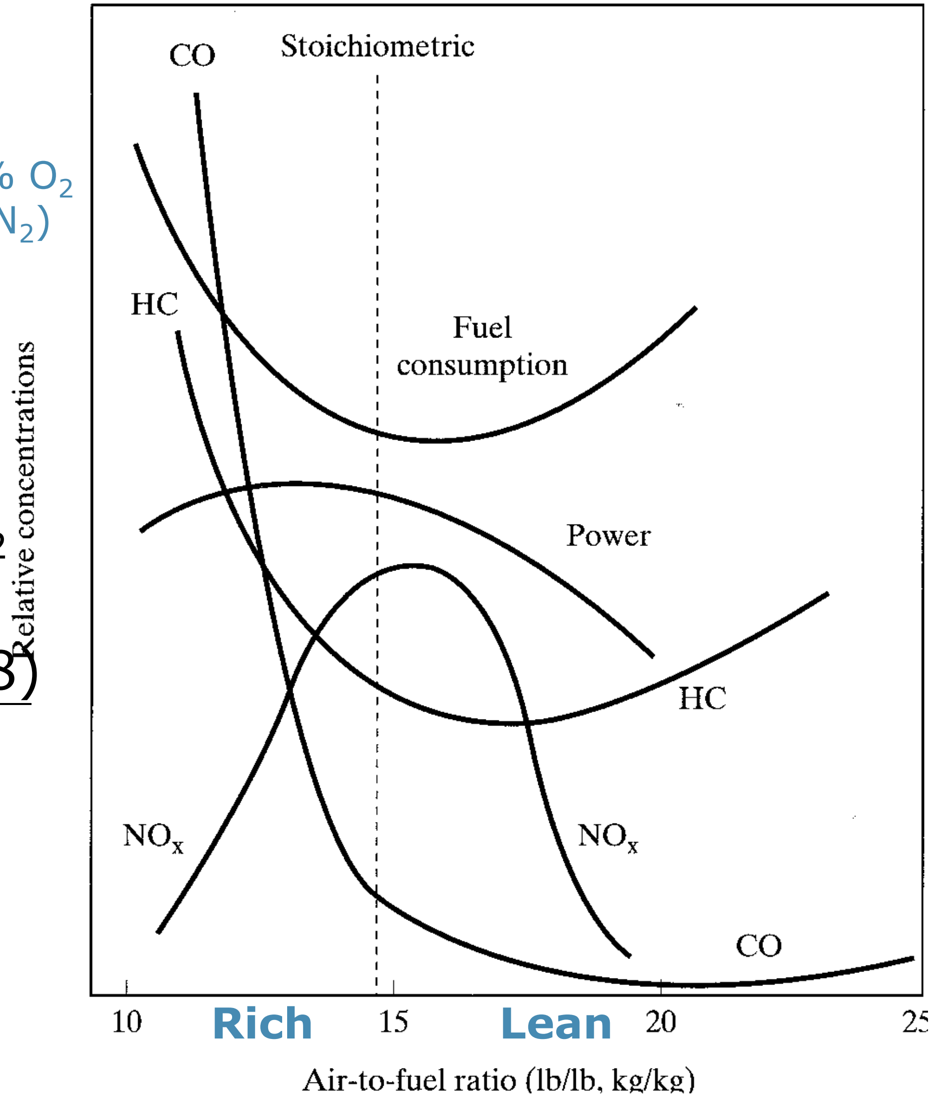
- Maintaining a stoichiometric air/fuel ratio

Air (20.9% O_2 + 78.1% N_2)

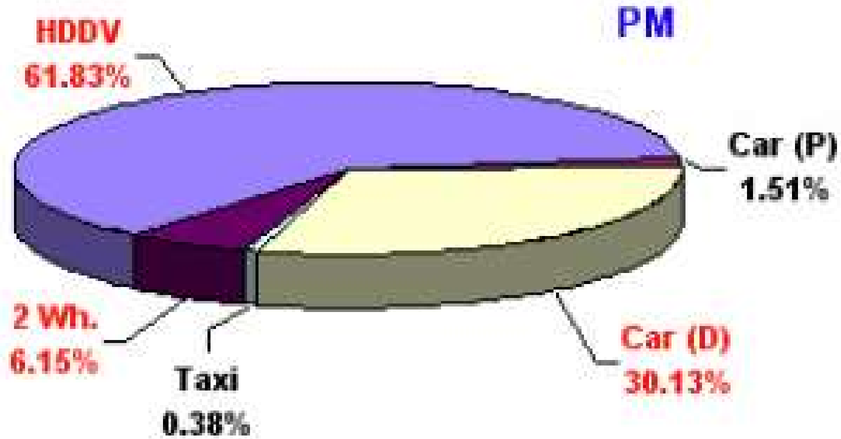
- $C_7H_{13} + 10.25O_2 \longrightarrow 7CO_2 + 6.5H_2O$
- $C_7H_{13} + 10.25O_2 + 38.5N_2 \longrightarrow 7CO_2 + 6.5H_2O + 38.5N_2$
- Air/Fuel = $\frac{(10.25 \times 32 + 38.5 \times 28)}{(12 \times 7 + 1 \times 13)}$

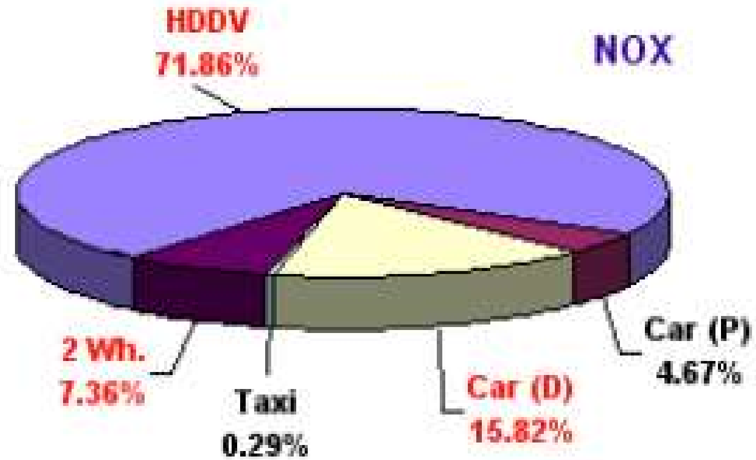
  = 14.5 kg/kg

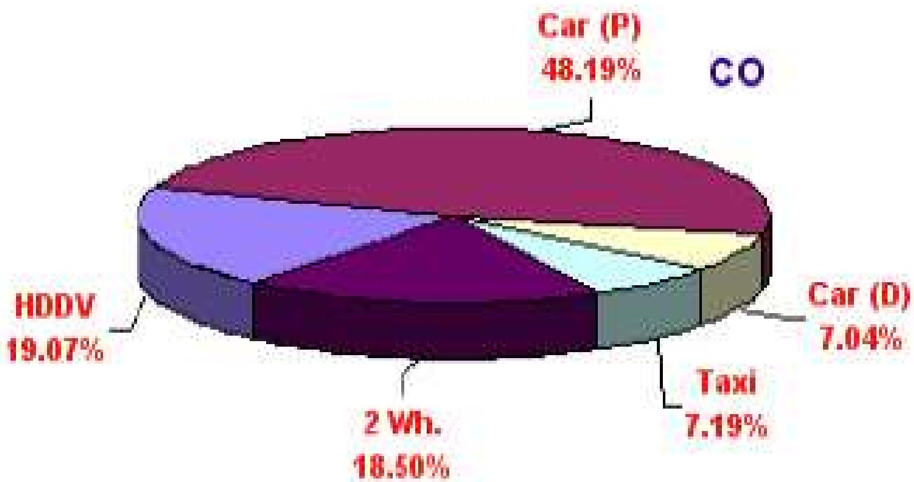
- Petrol vs. Diesel emissions

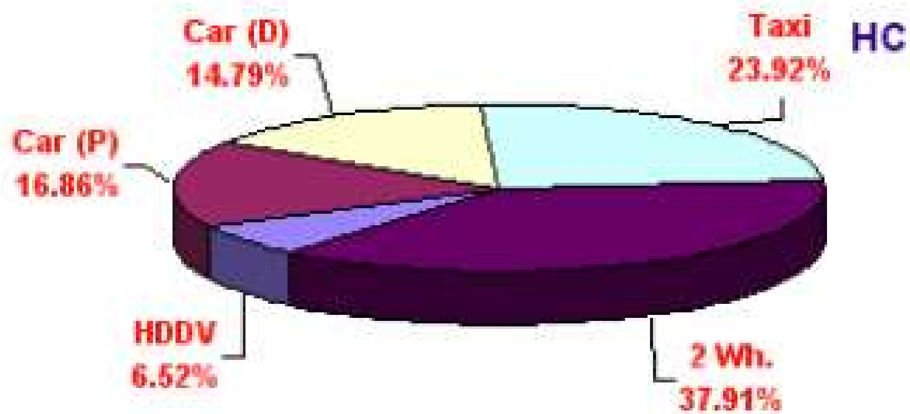


Total emissions from IC engines:
Petrol vs. Diesel





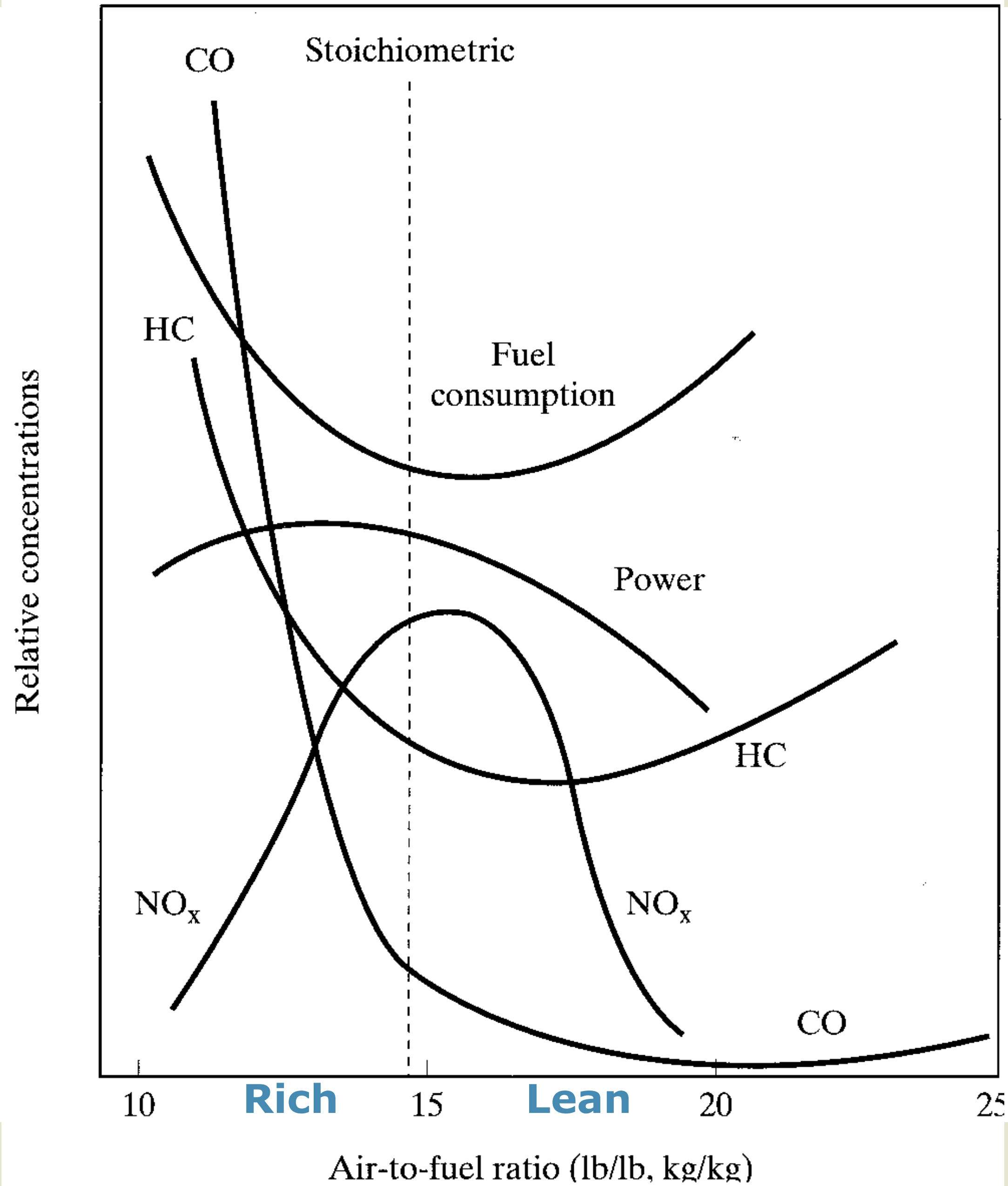




(CPCB report, 2011 & NEERI report, 2010)

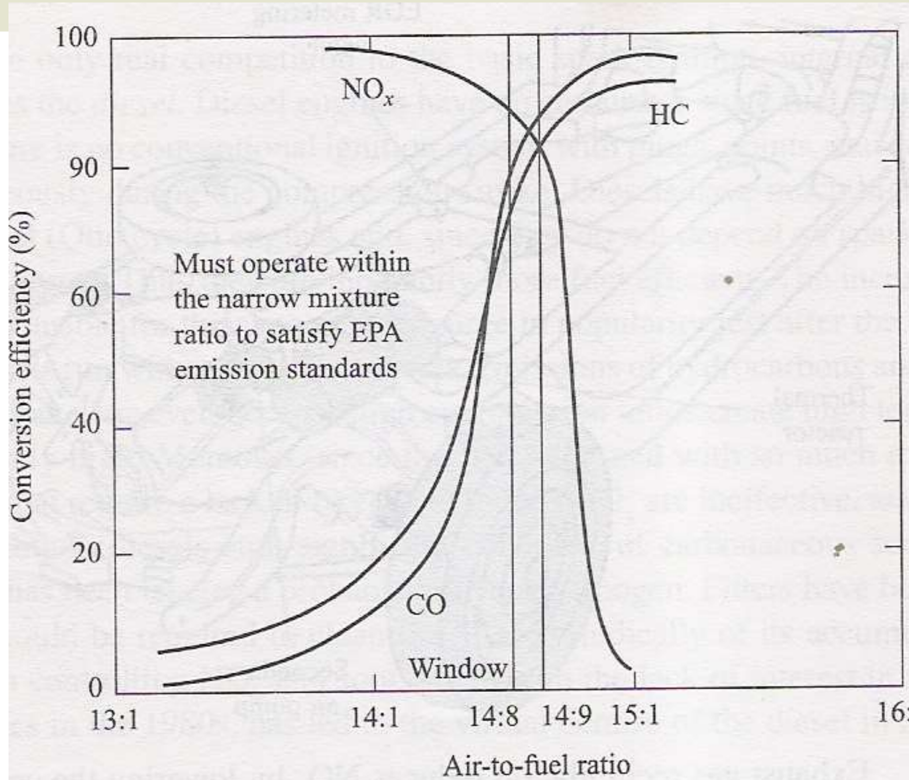
Emission control of IC engines

- Maintaining a stoichiometric air/fuel ratio

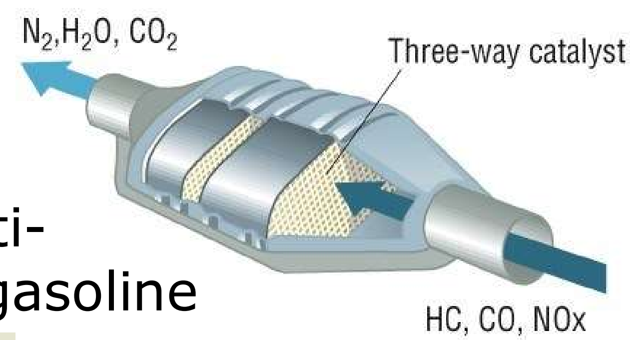


Three-way Catalytic converter

A three-way catalytic converter has three simultaneous tasks:



- Reduction of nitrogen oxides to nitrogen and oxygen:
  $2NO_x \rightarrow xO_2 + N_2$
- Oxidation of carbon monoxide to carbon dioxide:
  $2CO + O_2 \rightarrow 2CO_2$
- Oxidation of unburnt hydrocarbons (HC) to carbon dioxide and water:
  $C_xH_{2x+2} + 2xO_2 \rightarrow xCO_2 + 2_xH_2O$



⇨ Elimination of tetraethyl lead as an anti-knocking agent/ octane booster from gasoline

Cleaner/Alternative fuel

- Vaporization of gasoline should be reduced
- Oxygen containing additives reduce air requirement., e.g. ethanol, MTBE (Hazardous)
  - Methanol: Less photochemically reactive VOC, but emits HCHO (eye irritant), difficult to start in winters: can be overcome by M85 (85% methanol, 15% gasoline)
  - Ethanol: E10 (10% ethanol & 90% gasoline; used as an oxygenate to reduce CO emissions
  - Biodiesel: produced from animal fats, vegetable oils; generally blended with diesel e.g. B2, B5 and B20 are common
  - CNG: Low HC, high NO_x, inconvenient refueling, leakage hazard
  - LPG: Propane, high NO_x
  - Electric /hybrid vehicles

Landmarks dates in Delhi NCR clean up !

- April 1995: Mandatory fitting of catalytic convertors
- April 1996: Low sulphur diesel introduced
- April 1998: Introduction of CNG buses in Delhi
- Sept 1998: Complete removal of lead in petrol
- Dec 1998: Restrict plying of goods vehicles during the day
- Sept 1999: Amendment of Motor Vehicles Act to include CNG
- April 2000: Private vehicles to be registered only if they conform to Euro II standards
- April 2000: Eight-year-old commercial vehicles phased out
- Nov 2002: Conversion of all public transport buses to CNG

Air Pollution Control: Stationary Sources

- Pre-combustion Control
  - Switching to less S and less N fuel
- Combustion Control
  - Improving the combustion process
  - New burners to reduce NO_x
  - Integrated Gasification combined cycle
- Post-Combustion Control
  - Particulate collection devices
  - Flue gas desulfurization

Air Pollution Control: PM

Device selection depends on

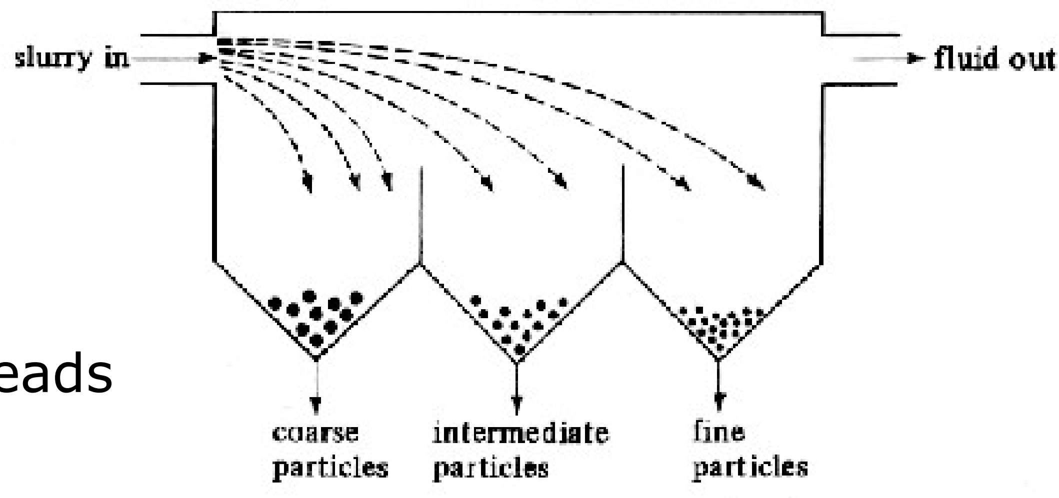
- Particle size
- Concentration
- Corrosivity
- Volumetric flow rate
- Required collection efficiency
- Cost

Air Pollution Control: PM

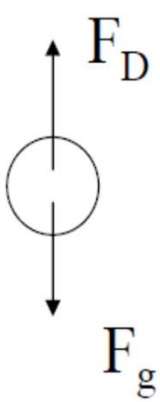
- Mechanical
  - Gravity based: Settling Chambers > 20 μm
  - Inertia based: Cyclones > 10 μm
  - Diffusion based: Filters > 0.1 μm
- Electrical
  - Electrostatic Precipitators > 0.1 μm

Mechanical - Gravity

Gravitational Settlers



- Particle settling:
  Gravitational forces are balanced by drag and buoyancy forces. This leads to Stokes law - settling velocity of particles.



$$\boxed{\begin{aligned} m_p\, g &= \rho_p \frac{\pi}{6} d^3 g \\ F_d &= 3\pi\mu d v \end{aligned}}$$

When $F_d = F_g$, settling velocity is given by

$$\boxed{v_t = g\, d^2 \frac{\rho_p}{18\,\mu}}$$

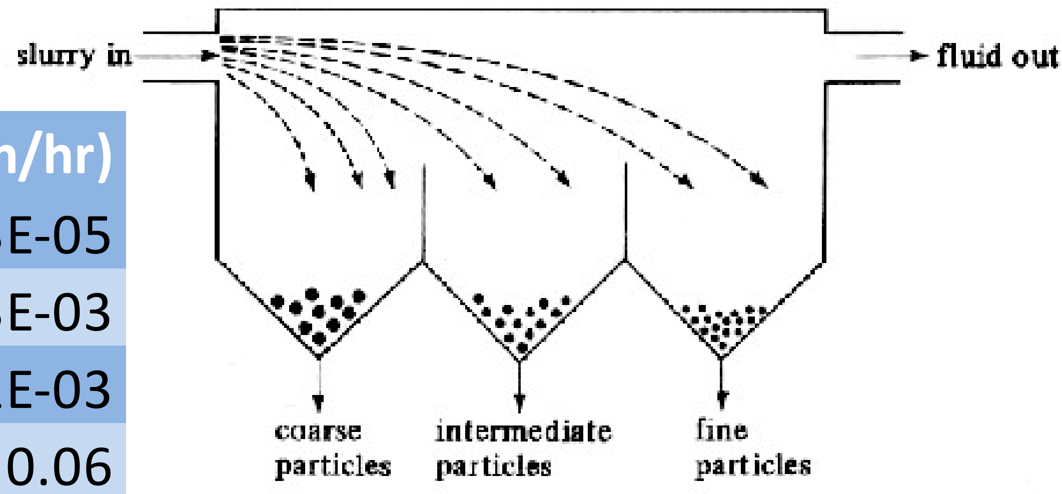
V_t (1μm particle) = 0.006 cm/s

where,
g – gravity acceleration 9.8 m/s^2
d – particle diameter (m)
r_p – particle density (g/m^3)= 2 x 10^6 g/m^3
μ - air viscosity = 0.0172 g/m.s

Mechanical - Gravity

Gravitational Settlers

D_p (μm)	V_t (m/s)	V_t (m/hr)
0.01	6.3E-09	2.3E-05
0.1	6.3E-07	2.3E-03
0.2	2.5E-06	9.1E-03
0.5	1.6E-05	0.06
1	6.3E-05	0.23
2	2.5E-04	0.91
5	0.0016	5.70
10	0.0063	22.79
20	0.0253	91.16
50	0.1583	569.77
100	0.6331	2279.07
200	2.5323	9116.28
500	15.8269	56976.74
1000	63.3075	227906.98



V_t (1μm particle) = 0.006 cm/s

$$v_t = g\, d^2 \frac{\rho_p}{18\,\mu}$$

Mechanical - Inertia

Cyclones

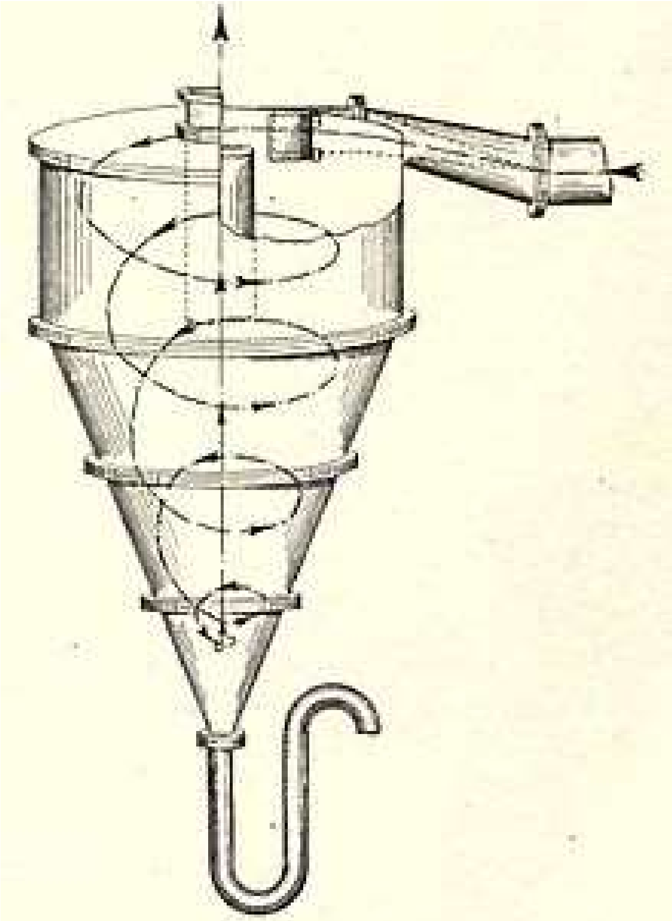
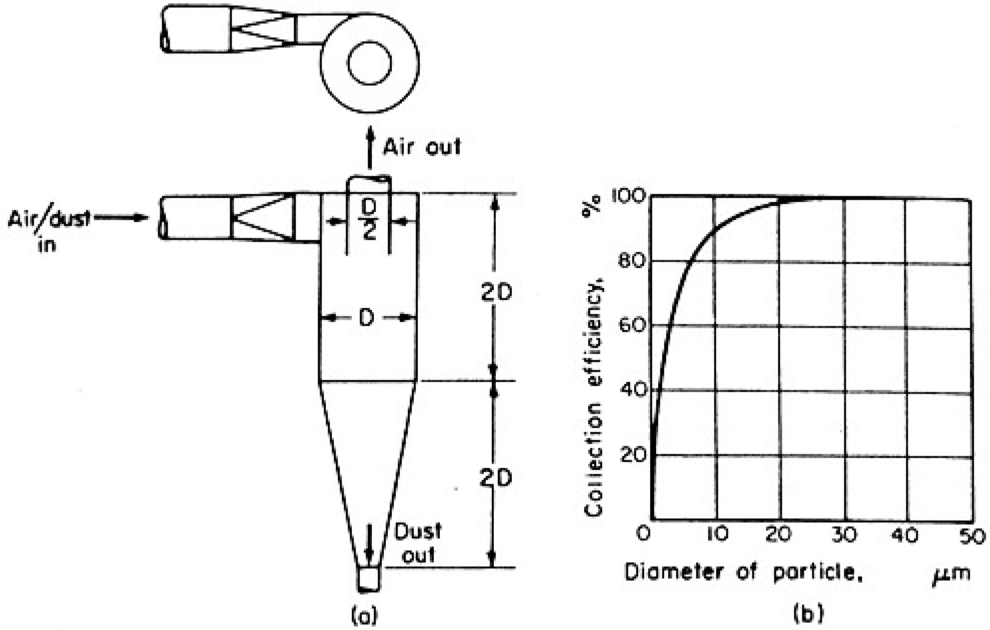


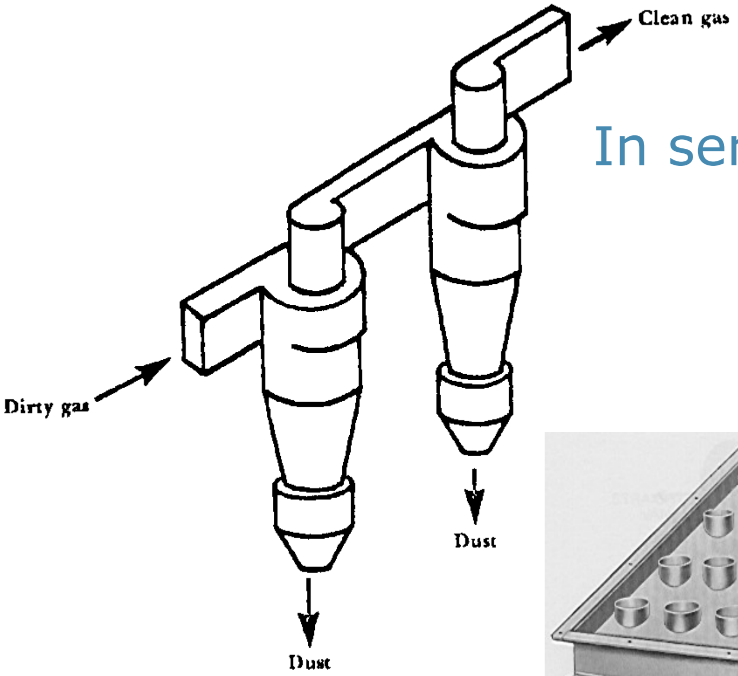
Fig. 201.—Colman's "Cyclone" Tar Extractor.



- For PM > 5 μm
- Efficiency > 90%
- Maintenance-free
- Low-cost

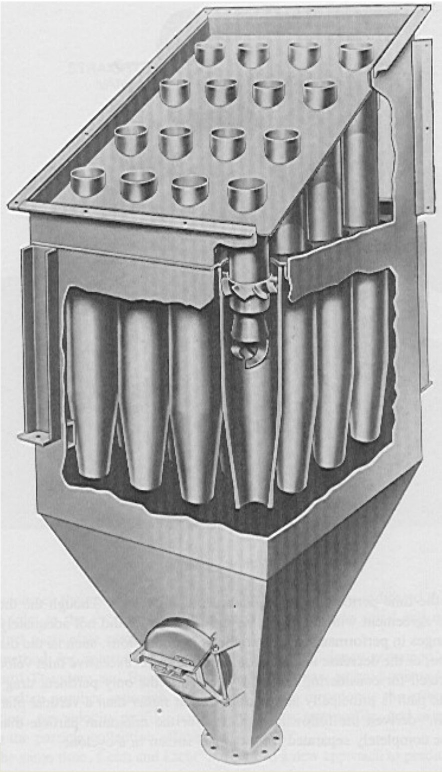
Mechanical - Inertia

Cyclones



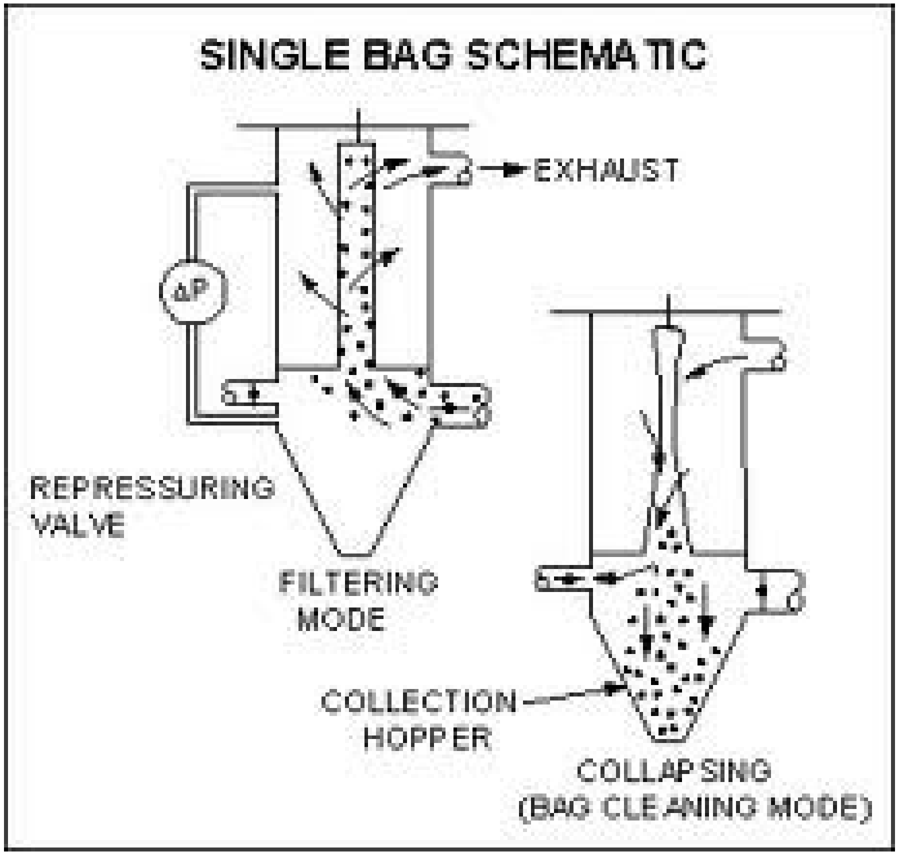
In series

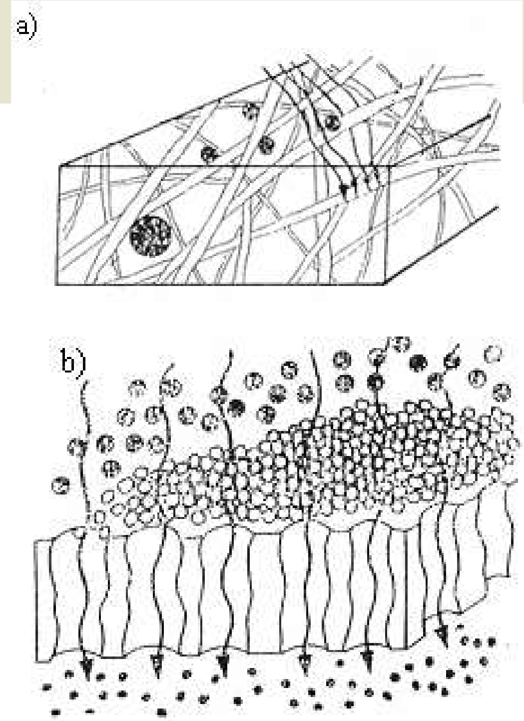
In parallel



Mechanical - Filtration

Bag filters



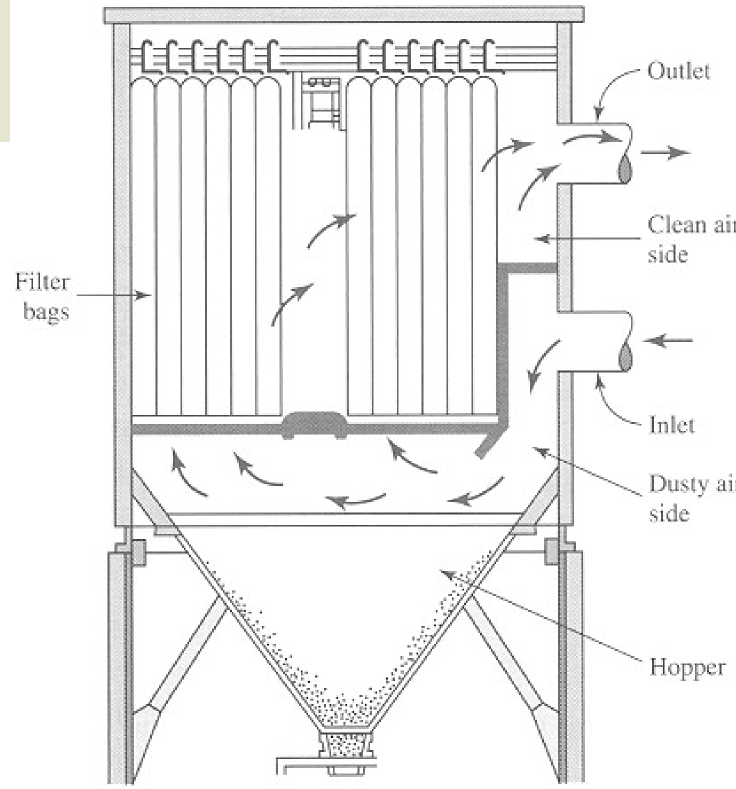


Filtration through fibrous material via:

- Diffusion
- Impaction
- Interception
- (NOT SIEVING)

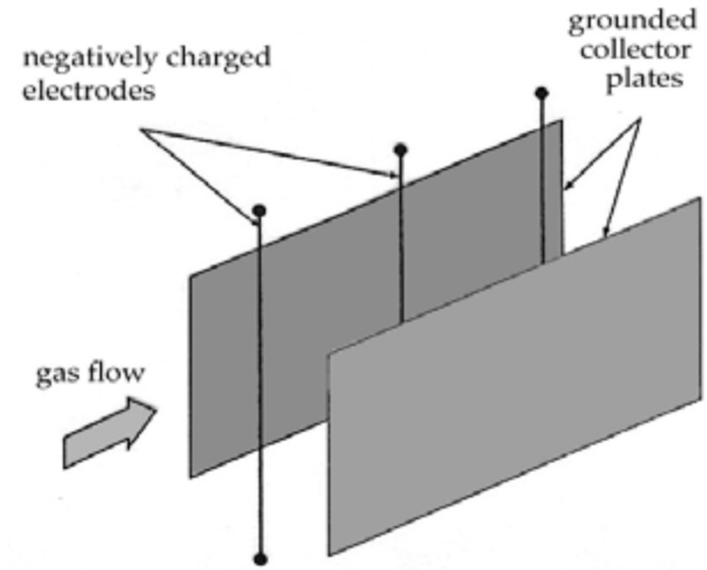
Mechanical - Filtration

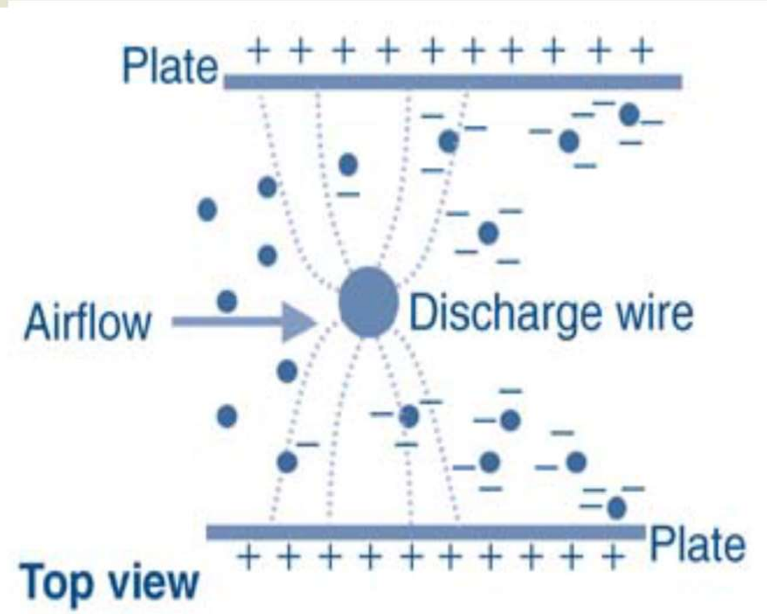
Bag filters



- Efficiency – 100% for particles >0.01-1 μm
- Cannot operate in moist environment
- Large & expensive
- Competitive with ESP

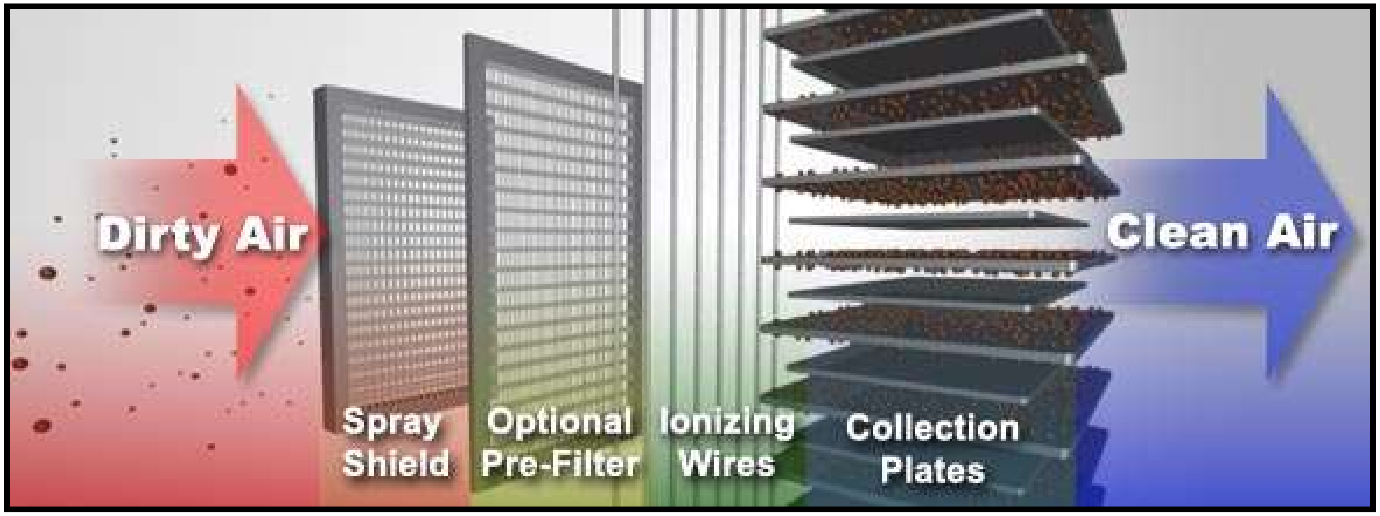
Electrostatic Precipitators (ESP)

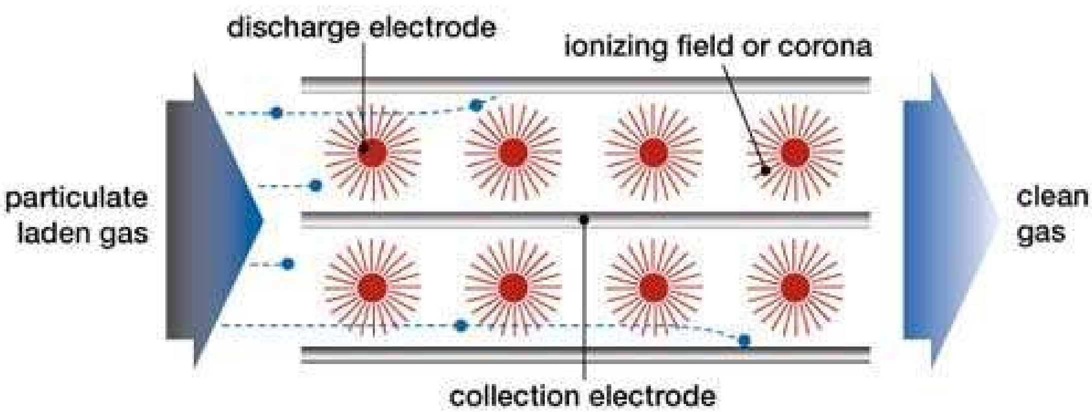




- *Principle*: Electrodes at high voltage create a corona effect (ionized atmosphere) surrounding them
- This charges the passing particles
- Once charged, particles are subject to a transverse electrostatic force that pulls them toward the collecting plates
- Plates are periodically "rapped" (vibrated) to make the collected particles fall down into a receiver basket

Electrostatic Precipitators (ESP)





- Removal>98%, all sizes
- Little pressure drop, low O&M cost, but expensive
- Occupy large space
- Plate area requirement depends on required efficiency

Air Pollution Control - Gases

- Absorption/ Adsorption
- Incineration
- Chemical Reactions
  - Catalysts: e.g. selective catalytic reduction (SCR) for NO_x control; NH_3 is injected into boiler flue gas and the mix is passed through a catalyst bed where NO_x is reduced to N_2:

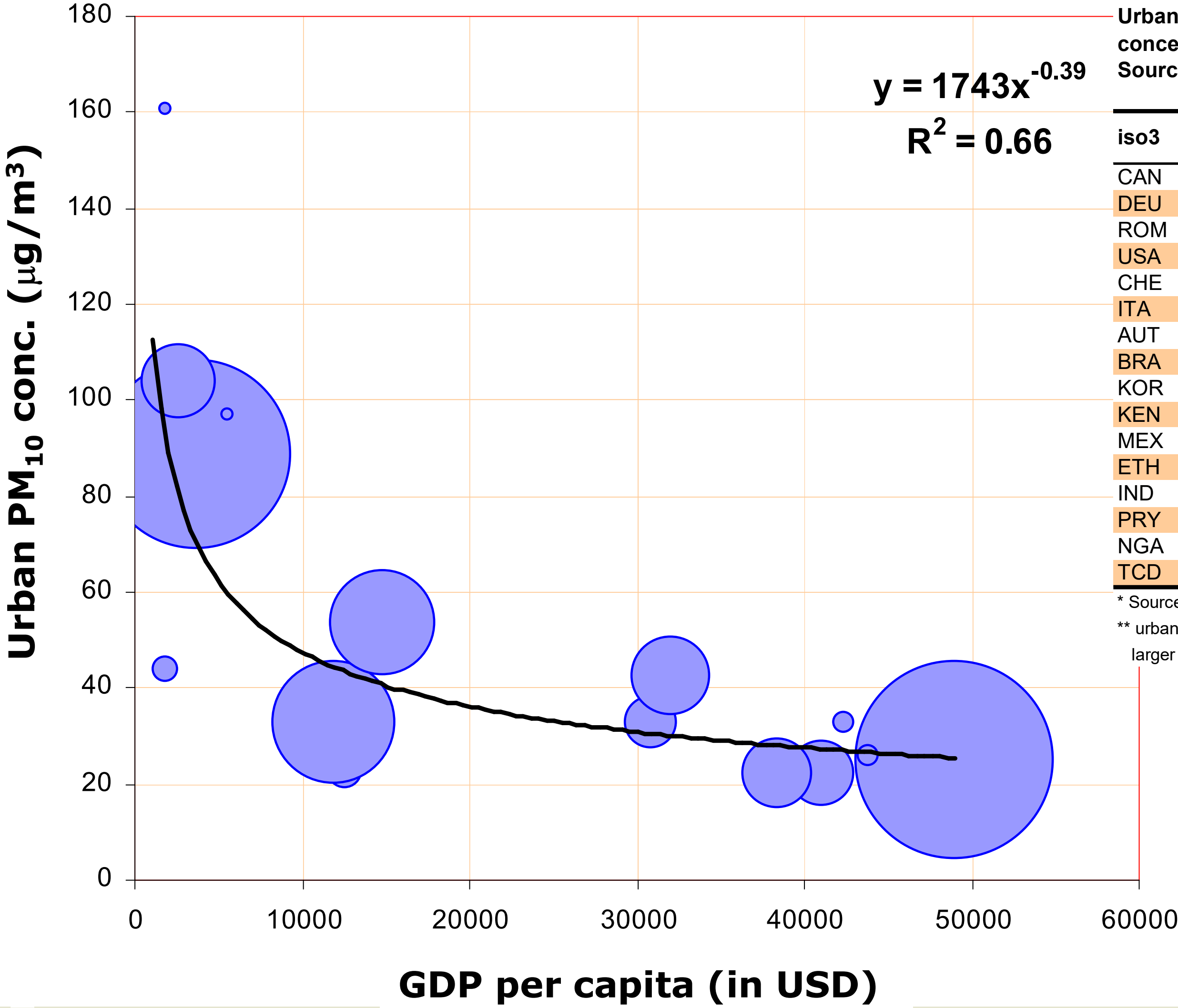
    $$4NO + 4NH_3 + O_2 \longrightarrow 4N_2 + 6H_2O$$

  - Flue gas desulfurisation: Finely pulverized limestone ($CaCO_3$) is mixed with water to create a slurry that is sprayed into the flue gas; about 90% SO_2 can be captured:

    $$CaCO_3 + SO_2 + 2H_2O \longrightarrow CaSO_3.2H_2O + CO_2$$

…a food for thought on air pollution problems!

The two 'E's – Economics & Environment

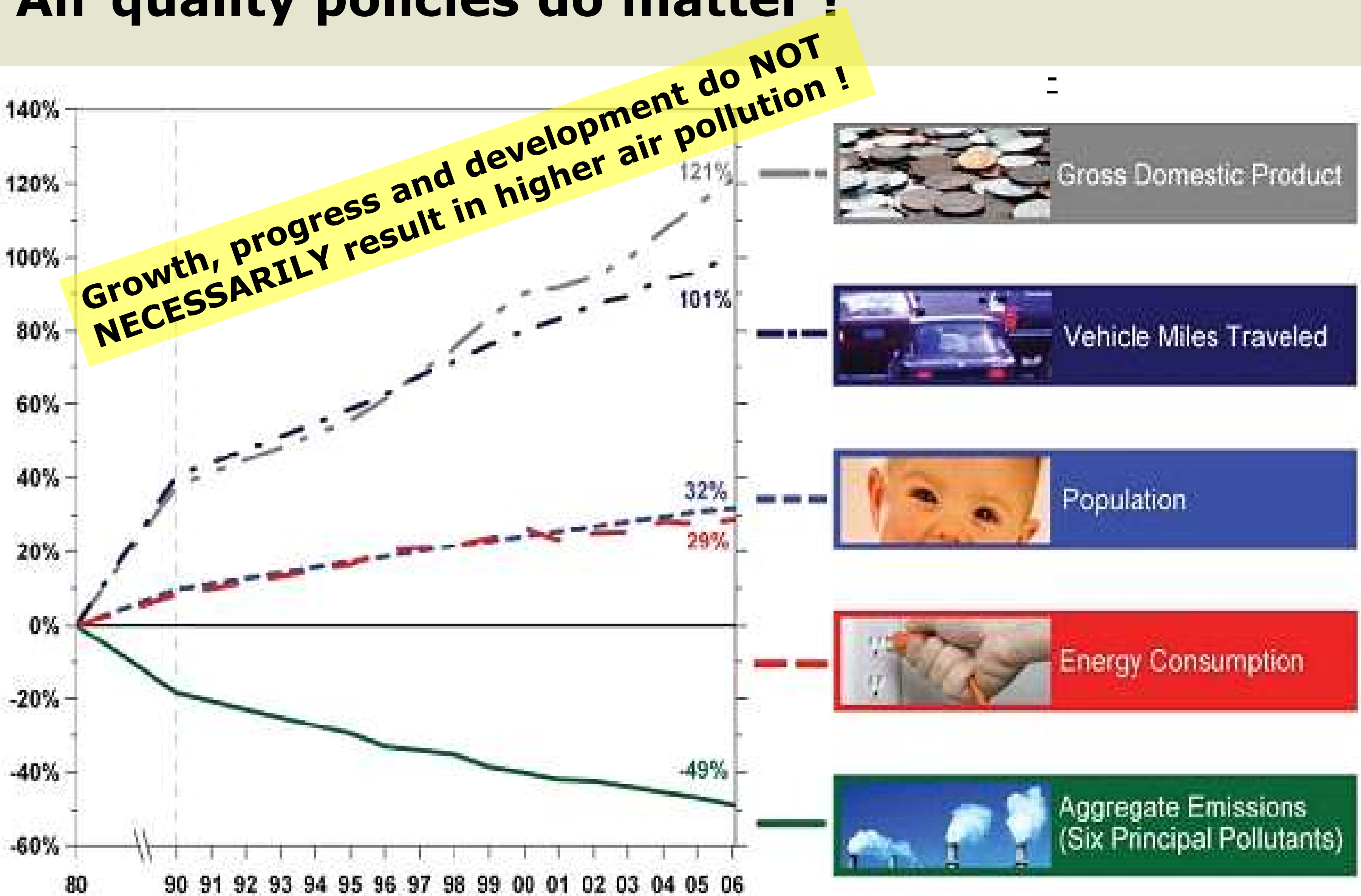


Air Pollution Data by Country
Urban population weighted average PM10 concentrations (micro grams per cubic meter) in
Source: The World Bank, 2000

iso3	country	GDP/capita (in USD)*	PM10 conc. 1999	Urban pop.** 2000
CAN	Canada	41100	22	24088276
DEU	Germany	38400	22	26555040
ROM	Romania	12600	23	7319254
USA	United States	49000	25	201423008
CHE	Switzerland	43900	26	2950271
ITA	Italy	30900	33	15272937
AUT	Austria	42400	33	3008152
BRA	Brazil	11900	33	76136838
KOR	South Korea	32100	43	33956145
KEN	Kenya	1800	44	4600094
MEX	Mexico	14800	53	55341364
ETH	Ethiopia	1100	88	4581946
IND	India	3700	89	183885990
PRY	Paraguay	5500	97	1277983
NGA	Nigeria	2600	104	29416937
TCD	Chad	1900	161	1430623

* Source :CIA World Factbook, 2011
** urban population consists of all residents living in cities larger than 100,000 and national capitals.

Air quality policies do matter !



From Lecture slides, Prof. Nino Künzli, SwissTPH, Basel, 2012
Adapted from Masters and Ela, 2008

Good luck for
ES 200 end-sem exam !!!

Thu, 16.Nov, 14:00-17:00

LA101, LA102, LA301

For ONLY those who missed quiz,

…for a genuine reason

Re-Quiz !

Today, 12:45-13:10

CESE, Seminar Hall, 1st Floor