Module 3:
Emission Inventory Fundamentals

The Atmosphere

Usable Air

Apple Skin
Major Regions of the Atmosphere

What is Clean Air?

- Composition of Natural Air in Troposphere:
  - Argon (0.9%)
  - Other (0.1%)
    - Carbon dioxide 330 ppm
    - Neon 18 ppm
    - Helium 5 ppm
    - Methane 1.5 ppm
    - Other Gases 1 ppm
  
- Properties:
  - Exhibits properties of a fluid – occupies space
  - Has mass – weighs more than $4.5 \times 10^{18}$ kg
  - Is a mixture
    - Gases
    - Tiny solid particles
    - Water Droplets
# Air Pollution - Definition

- Presence of substances in the air in concentrations high enough to create health, comfort, and safety problems or to interfere with full use of property
- Air pollutants can be
  - Naturally occurring or man-made gases
  - Liquid droplets
  - Particulate matter

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# Emission Types

- **Anthropogenic**
  - Motor vehicles and nonroad motors
  - Industries and other fuel combustion (residential)
  - Evaporation of solvents and paints
- **Natural**
  - Plants and soils
  - Lightning and volcanoes
  - Wildfires
Scale of Air Pollution Problems

- **Local Scale**
  - Impacts from a single source or group of sources
  - May examine health impacts on specific receptors
- **Regional Scale**
  - 500 to several thousand km²
- **County to Continental Scale**
  - Scale
  - Tens of thousands of km²
  - May address international transboundary pollution
- **Global Scale**
  - Transport of pollutants across globe

What is an Emissions Inventory?

- Comprehensive listing of air pollutant emissions by source type and category
  - Point, nonpoint (area), motor vehicle, nonroad mobile, natural
- Pertinent to a specific geographic area
  - National, Local, district/county, State
- Developed for a specific time interval
  - Hour, day, month, season, year
Why Do We Need Air Emission Inventories?

- Public interest in clean air
- Fundamental Component of Air Quality Management Plan
  > To identify sources and problem areas
  > To establish a baseline for future planning
  > To develop air quality control plans and mitigation strategies
  > To establish regulations and permit conditions for industrial facilities and basis for emissions trading programs

Why Do We Need Air Emission Inventories?

- Fundamental Component of Air Quality Management Plan
  > To measure progress/changes over time to achieve cleaner air (track trends or progress toward air quality goals)
  > To determine compliance with environmental regulations
Class Exercise #1

A first-time national-level emissions inventory is needed for South Africa.

How can this be done to obtain an “order of magnitude” estimate?

Extrapolation Technique

<table>
<thead>
<tr>
<th>U.S. National Emissions Inventory for year 2000 (1,000 metric tons):</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; CO: 112,101</td>
</tr>
<tr>
<td>&gt; NOx: 21,046</td>
</tr>
<tr>
<td>&gt; VOC: 17,875</td>
</tr>
<tr>
<td>&gt; SO2: 14,803</td>
</tr>
<tr>
<td>&gt; PM10: 22,407</td>
</tr>
<tr>
<td>&gt; PM2.5: 7,216</td>
</tr>
<tr>
<td>&gt; NH3: 4,521</td>
</tr>
</tbody>
</table>

<table>
<thead>
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<tbody>
<tr>
<td>&gt; Population = 281,421,906</td>
</tr>
<tr>
<td>&gt; GDP = $9,872.9 billion</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>South African statistics (2000):</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; Population = 43,421,000</td>
</tr>
<tr>
<td>&gt; GDP = $153 billion</td>
</tr>
<tr>
<td>&gt; Electricity consumption = 183.8 billion kWh</td>
</tr>
<tr>
<td>&gt; Annual population growth = 1.9%</td>
</tr>
<tr>
<td>&gt; Annual GDP growth = 3.5%</td>
</tr>
</tbody>
</table>
Extrapolation Technique (continued)

- Ratio of South African to U.S. population = 0.1543
- Ratio of South African to U.S. GDP = 0.0155

Estimate South African Emissions Inventory for the Year 2000

Class Exercise #1 – Solution

- Year 2000 S. African National Emissions Inventory based on population (1,000 metric tons):
  > CO: 17,296
  > NO$_x$: 3,247
  > VOC: 2,758
  > SO$_2$: 2,248
  > PM$_{10}$: 3,457
  > PM$_{2.5}$: 1,113
  > NH$_3$: 698

- Year 2000 S. African National Emissions Inventory based on GDP (1,000 metric tons):
  > CO: 1,737
  > NO$_x$: 326
  > VOC: 277
  > SO$_2$: 229
  > PM$_{10}$: 347
  > PM$_{2.5}$: 112
  > NH$_3$: 70
Class Exercise #2

Estimate South African Emissions Inventory for the Year 2002, by using the year 2000 data and assuming
- annual population growth of 1.9% and
- 3.5% GWP growth.

Class Exercise #2 - Solution

- 2002 Emissions = Year 2000 Emissions (population-based) x (1.019)^2
- Year 2002 S. African National Emissions Inventory (1,000 metric tons):
  > CO: 17,959
  > NO\textsubscript{x}: 3,372
  > VOC: 2,864
  > SO\textsubscript{2}: 2,372
  > PM\textsubscript{10}: 3,590
  > PM\textsubscript{2.5}: 1,156
  > NH\textsubscript{3}: 725

- 2002 Emissions = Year 2000 Emissions (GDP-based) x (1.035)^2
- Year 2002 S. African National Emissions Inventory (1,000 metric tons):
  > CO: 1,861
  > NO\textsubscript{x}: 349
  > VOC: 297
  > SO\textsubscript{2}: 245
  > PM\textsubscript{10}: 372
  > PM\textsubscript{2.5}: 120
  > NH\textsubscript{3}: 75
Emission Source Types

- There are 5 basic source types for purposes of emissions inventory development in this course
  - Point sources
  - Nonpoint (or area) sources
  - Onroad (Motor vehicle) sources
  - Nonroad mobile sources
  - Natural sources

Emission Source Types: Point Sources

- Stationary industrial facilities
  - Examples: Chemical manufacturing, electricity generation, primary and secondary metal processing
  - May be defined as emitting an amount above a certain threshold (e.g., 12 metric tons per year NO₂)
  - May be defined based on location or regulatory jurisdiction (e.g., regulated by city, state, or federal government)
  - May be specifically defined by legal statute (e.g., all petroleum refineries are point sources)
Emission Source Types: Nonpoint Sources

- Stationary industrial, commercial, institutional facilities and businesses that are too small or numerous to be categorized as a point source
  - Examples: dry cleaners, gasoline stations

- Nonpoint sources emit over a geographic “area” versus point sources that emit over a geographic “point”
  - Examples: residential cooking and heating, wind erosion of vacant lots and agricultural lands, dust from vehicle travel over paved and unpaved roads, consumer solvent use, wildfires

Point and Nonpoint Source Emissions Double Counting

- Due to differences in source type definitions and inventory procedures used, potential for double counting of point and nonpoint source emissions exists
- As required, point source contributions to some nonpoint source categories must be removed
- Adjust the activity level of the nonpoint source category if possible (as opposed to subtracting off emissions)
- Prevalent categories to check for double counting potential include: auto body refinishing, chrome electroplating, gasoline distribution, graphic arts printing, industrial and institutional/commercial boilers, drycleaners, and wastewater treatment plants
## Point/Nonpoint Sources
### Double Counting Example

### Assumptions
- Nonpoint source category is coal-fired commercial/institutional boilers
- Province-wide activity level = 300,000 MT/yr of coal
- Province-wide category emissions = 8,550 MT PM/yr
- Three point source comm/Inst boilers (2 at universities and 1 at hospital) identified for inventory, their activity levels are as follows:
  - University boiler #1 activity = 10,000 MT/yr coal
  - University boiler #2 activity = 14,000 MT/yr coal
  - Hospital boiler #1 activity = 15,000 MT/yr coal
  - Total point source activity = 39,000 MT/yr coal

### Calculations
300,000 MT/yr (Nonpoint activity) – 39,000 MT/yr (point source activity) = 261,000 MT/yr as the actual coal consumption nonpoint source activity for comm/inst boilers.

The 261,000 MT/yr figure is then multiplied by the appropriate commercial/institutional boiler emission factor to determine the correct nonpoint source emissions total for comm/inst boilers.
Emission Source Types: Onroad Motor Vehicle Sources

- Onroad motor vehicles
  - Exhaust emissions
  - Evaporative emissions
- Various classifications depending on methodology used to estimate emissions:
  - Private automobiles
  - Taxis
  - Buses
  - Heavy-duty diesel trucks
  - Motorcycles/Mopeds

Emission Source Types: Nonroad Mobile Sources

- Mobile sources that do not routinely travel on motor vehicle roadways
- Specific categories of nonroad sources vary between inventories
  - Aircraft (may be included in nonpoint sources)
  - Locomotives (may be included in nonpoint sources)
  - Boats and other marine vessels (may be included in nonpoint sources)
  - Construction, industrial, and agricultural equipment
  - Lawn and garden equipment
Emission Source Types: Natural Sources

- Natural biological and geological phenomenon which generate air emissions (nonanthropogenic)
- Biogenic emissions:
  - VOC emissions from vegetation
- Geogenic emissions:
  - NO\textsubscript{x} emissions from soil (denitrification)
  - SO\textsubscript{x} emissions from volcanoes and geothermal activity
- May include wind erosion, wildfires

Emission Source Types: Indoor Sources

- Indoor air can become contaminated from numerous sources
- Indoor air can have significantly higher concentrations of air pollutants than outdoor air
### Emission Source Types: Other Types of Sources

There are a number of other important sources of air pollutants that aren’t so easy to categorize or count:

- Accidental releases
- Long-range transport of air pollutants
- Historical background (for example, carbon tetrachloride)

### Emission Inventory Characteristics

- Base year
- Geographic area
- Spatial resolution
- Pollutants
- Temporal resolution
- Speciation
- Modeling parameters
**Emission Inventory Characteristics: Base Year**

- Identifies the year for which emissions are estimated
- Provides a benchmark for comparison with previous and subsequent inventories
- Provides a common basis for all the emission estimates
- Determined based on the purpose of the inventory, regulatory requirements, and by data availability

**Emission Inventory Characteristics: Geographic Area**

- Establishes geographic domain for the inventory
- Determines the sources to be included in the inventory based on their location
- Can be based on political boundaries (i.e., city, province, or country borders), airshed boundaries, or other (possibly arbitrary) considerations
- Determined based on the purpose of the inventory
  - City-, district-, province-level analyses of air quality impacts (e.g., 100 to 500 km²)
Emission Inventory Characteristics:
Spatial Resolution

- Establishes the detail of the geographic location of the sources
- Determined based on the purpose of the inventory
  - National-level analysis => Single national estimate for each major source type and pollutant
  - Modeling inventory => Source-specific emissions allocated based on location coordinates, source-category emissions allocated based on "grids" (e.g., 1 to 50 km²)
- Basis varies between point sources and what is used for nonpoint and mobile sources
- Modeling inventories have more specific requirements than other more general tracking inventories

Emission Inventory Characteristics:
Pollutants

- Determined based on the purpose of the inventory
- Particulate matter analysis: PM₁₀ and PM₂.₅, secondary aerosols
- Ozone analysis: NOₓ, VOC primarily (can include other carbon compounds)
- Visibility analysis
  - NOₓ, SOₓ, VOC, CO, PM₁₀, PM₂.₅, NH₃
  - Elemental and organic carbon (EC/OC)
Emission Inventory Characteristics: Pollutants (continued)

- Air toxics analysis
  - Criteria pollutants: Pb
  - Other hazardous air pollutants
- Greenhouse gases assessment
  - CH₄, N₂O, CO₂
  - HFCs, PCFs, and SF₆
- Ozone depleting substances (ODS)
  - CFCs, HCFCs, halons, CCl₄, methyl chloroform \((C₂H₃Cl₃)\), methyl bromide \((CH₃Br)\)

Emission Inventory Characteristics: Temporal Resolution

- Describes the variability of emissions over time
- Determined based on the purpose of the inventory
  - Resolution can be annual, seasonal, monthly, daily
  - Modeling inventory => can be hourly or emissions by second
Example of Allocating Annual Emissions to Grams/Second

- A supplemental boiler at a factory is used for increased production in the months of December - February (90 days/year) and emits 500 metric tons/year of CO
- Calculate annual operation in seconds
  \[ \text{Annual operation} = 90 \text{ days} \times 10 \text{ hours/day} \times 3,600 \text{ seconds/hour} \]
  \[ = 3.24 \times 10^6 \text{ seconds} \]
- Calculate CO emissions in grams/second (g/s)
  \[ \text{CO emissions} = \frac{500 \text{ Mg} \times 10^6 \text{ grams}}{3.24 \times 10^6} \]
  \[ = 154.3 \text{ g/s} \]

Emission Inventory Characteristics: Speciation

- Disaggregates inventory pollutants into individual chemical components or groups
- Determined based on the inventory purpose
  > Visibility analysis: elemental carbon/organic carbon
  > Ozone analysis: Aromatics, paraffins, VOCs, etc.
  > Air toxic risk assessment:
    - Hazardous air pollutants
    - VOCs and PM (toxic species)
- Speciation tools exist on EPA's web site (see http://www.epa.gov/ttn/chief/emch/speciation/index.html)
Emission Inventory Characteristics: Modeling Parameters

- Modeling inventories have special needs related to source characterization information
- Data are required to characterize the specific emission parameters occurring at each point of emissions release
- Data include stack heights, stack diameters, flow rates, and temperatures
- Mainly an issue for point sources, but related data also needed for nonpoint and mobile sources

Emissions Inventory Development Approaches

- Top-Down approach
- Bottom-Up approach
Top-Down Approach

- **Methodology:**
  - General emission factors combined with high level (national) activity data (e.g., emission factor x national coal consumption) to estimate emissions in country or region
  - National- or regional-level emissions estimates scaled to the inventory domain based on surrogate data (geographic, demographic, economic data)
- **Typically used when**
  - Local data are not available
  - The cost to gather local information is prohibitive
  - The end use of the data does not justify the cost
- **Advantages:** Requires minimum resources
- **Disadvantages:**
  - Emissions generally have high level of uncertainty
  - Loss of accuracy in emission estimates

Bottom-Up Approach

- **Methodology**
  - Uses source-specific data (for point sources) and category-specific data at the most refined spatial level (for nonpoint and mobile sources)
  - Emission estimates for individual sources (and source categories) are summed to obtain domain-level inventory
- **Typically used when:**
  - Source/category-specific activity or emissions data are available
  - End use of inventory justifies the cost of collecting site-specific data (e.g., for ozone control strategy demonstration)
- **Advantages:** Results in more accurate estimates than a top-down approach
- **Disadvantages:** Requires more resources to collect site-specific information than a top-down approach
Emission Estimation Techniques

How Do I Choose Emission Estimation Methods?

- Choice of methods depends on:
  > Pollutant and source category priorities
  > Intended use of the inventory
  > Resources
  > Availability of data
  > Compromise between method accuracy and cost to implement
Source Category Estimation Methods

- **Point Source Methods**
  - Continuous Emission Monitor (CEM)
  - Source tests
  - Material balance
  - Emission factor x activity factors
  - Fuel analysis
  - Emission estimation models
  - Engineering judgment

- **Nonpoint Source Methods**
  - Surveys and questionnaires
  - Material balance
  - Emission factor x activity factors
  - Emission models

- **Mobile**
  - Emission models

Estimation Methods: Source Test Sample

- Emission rates generally reported as concentrations which must be converted to mass units for use in emission inventories
- Results depend upon air pollution control device performance and design
- Screening measurements can be indicators of emissions, potential compliance issues
- Sampling can be infrequent (1 stack test every 5 years) or continuous (CEMs)
- Continuous emission monitors (CEMs) can be required by permit conditions for some pollutants
Estimation Methods: Continuous Emission Monitoring (CEM) System

Estimation Methods: Source Sampling

- Emission rates generally reported as concentrations which must be converted to mass units for use in emission inventories
- Summarize emissions for each pollutant in terms of:
  > Mass loading rate
  > Emission factor
  > Flue gas concentration
- Results depend upon air pollution control device performance and design
- Screening measurements can be indicators of emissions, potential compliance issues
Estimation Methods: Source Sampling

Used:
- When source test data, emission factors, or other developed methods are not available
- Where accurate measurements can be made of all process parameters
- For processes where material does not react to form secondary products or does not undergo significant chemical change
- For processes like solvent degreasing operations, and surface coating operations

Estimation Methods: Material Balance
Estimation Methods: Material Balance

- Approach considers all inputs of a material and all possible fates for the material after passing through the process, including direct air emissions, fugitive air emissions, solid and liquid waste streams, and residual product content.
  - Uses measurements of various components of a process to determine air emissions:
    \[
    \text{Air emissions} = \text{Input} - \text{liquid emissions} - \text{solid wastes} - \text{products} - \text{by products} - \text{recycled material}
    \]
- Commonly used to estimate emissions from solvent usage based on contents of various solvents:
  - Solvent degreasing operations
  - Surface coating operations

Examples of Material Balance

- Fresh Solvent
- Waste Solvent
- Solid Waste

VOC Emission

Sulfur Dioxide (SO₂) Emissions

Sulfur (S) in Fuel

Assume all sulfur in a fuel is converted to SO₂ during the combustion process

Paint VOCs

Assume all solvents in paint are evaporated

Assume waste solvent is sent to a reprocessor and solid waste is sent to a treatment facility
Estimation Method: Emission Factors

- Definition: a ratio that relates the quantity of a pollutant released to a unit of activity
  
  > Process based
  > Census based

- Published sources provide emission factors for many source types

Types of Emission Factors

**Process-Based Emission Factors**

- Natural Gas Boiler: kg/10^6 m^3
- Vapor Degreaser: kg/hr/m^2
- Battery Manufacturing: kg/10^3 batteries

**Census-Based Emission Factors**

- Per Capita: kg/person/yr
- Per Employee: kg/employee/yr
### Published Sources of Emission Factors

- U.S. AP-42 Compilation of Air Pollutant Emission Factors
- U. S. Emissions Inventory Improvement Program, EIIP
- U. S. Factor Information REtrieval (FIRE) Data System
  [http://www.epa.gov/ttn/chief/software/fire/index.html](http://www.epa.gov/ttn/chief/software/fire/index.html)
- European Environment Agency – CORINAIR
- Intergovernmental Panel on Climate Change (IPCC) database
  ([http://www.ipcc-nggip.iges.or.jp/](http://www.ipcc-nggip.iges.or.jp/))

### Published Sources of Emission Factors (continued)

- U.S. EPA emission factors are rated A,B,C,D,E
  - “A” considered most reliable for that source type - probably based on source testing
  - Lower ratings indicate that less confidence can be placed in that emission factor
- European Environment Agency – CORINAIR
- Intergovernmental Panel on Climate Change (IPCC) database
  ([http://www.ipcc-nggip.iges.or.jp/](http://www.ipcc-nggip.iges.or.jp/))
Estimation Methods: Fuel Analysis

- Used to predict emissions based on the application of conservation laws
- \[ E = Q_f \times \text{Pollutant in fuel} \times \left( \frac{\text{MW}_p}{\text{MW}_f} \right) \]
  where:
  \[ Q_f \] throughput of the fuel, mass rate (e.g. lb/hr)
  \[ \text{MW}_p \] molecular weight of pollutant emitted (lb/lb-mole)
  \[ \text{MW}_f \] molecular weight of pollutant in fuel (lb/lb-mole)

Estimate VOC Emissions from Industrial Fuel Combustion

- Given:
  - Quantity of fuel used = 10,000,000 liters/year
  - VOC emission factor = 88 kg/10^6 m^3
  - CAP = 80% and CON = 90%
- Estimate overall control efficiency
  - CE = (80 x 90)/100 = 72%
- Convert fuel used in liters/year to m^3
  - 10,000,000/1,000 = 10,000 m^3
- Calculate annual emissions
  - 88 kg/10^6 m^3 x (10,000 m^3/10^6) x (1 – 72/100) = 0.25 kg/year
Calculating Emissions Using Emission Factors

- Emissions = EF × AD × (1 – CE/100)
  - EF = emission factor
  - AD = activity data
  - CE = overall control efficiency (%) = (CAP × CON)/100
    - CAP = % of the emissions stream captured by the control
    - CON = % of pollutant removed from the emissions stream

- Activity data
  - Process weight rates = Mg/year, kg/hour, liter/hour
  - Fuel consumption rates = BTU/year, kJ/hour
  - Can be expressed in terms of production rates

Estimation Methods: Emissions Models

- Used when
  - Calculations are very complex
  - Combination of parameters has been identified that affect emissions, but individually, do not provide a direct correlation

- Used to calculate emission factors or mass emissions for specific source categories
  - Examples: Mobile exhaust and evaporative emissions, storage tank evaporation and breathing losses, VOCs from wastewater treatment facilities

- Generally require that a significant amount of information be known about the source(s) being estimated
  - Examples: meteorological conditions in the source area, tank capacity and color, amount and chemical make-up of wastes treated

- Mechanistic and multivariate models
Emissions Models (continued)

- U.S. EPA models include:
  - TANKS (volatile liquid storage tanks) ([http://www.epa.gov/ttn/chief/software/tanks/index.html](http://www.epa.gov/ttn/chief/software/tanks/index.html))
  - MOBILE6 (motor vehicles) and NONROAD ([http://www.epa.gov/otaq/mobile.htm](http://www.epa.gov/otaq/mobile.htm))
  - International Vehicle Emission Model ([http://www.epa.gov/oia/airandclimate/capbuild/ive.html](http://www.epa.gov/oia/airandclimate/capbuild/ive.html))
  - LandGEM (landfills) ([http://www.epa.gov/ttn/catc/products.html#software](http://www.epa.gov/ttn/catc/products.html#software))

Estimation Methods: Engineering Judgment (Extrapolation)

- Last resort to be used only if none of the methods described can be used to generate accurate emission estimates
- Provides an “order of magnitude” estimate with significant uncertainty
- Scaling emissions estimates to create another inventory using scaling parameters
  - Production quantity
  - Material throughput
  - Land area
  - Number of employees
  - Population
Estimation Methods: Surveying

- Questionnaires are used to collect activity, controls, and emissions data from specific source types, categories
- Surveys can be conducted by various means
  - Workshops
  - Telephone
  - Internet
  - Visits to individual facilities by survey staff
- Keys to successful surveys
  - Well planned field effort
  - Well trained survey staff
  - Efficiently designed survey instrument
  - Quality assurance of data at various steps in the process

Point Source Survey Process

1. Develop Questionnaire
2. Survey All Facilities
3. Complete Questionnaires for Each Point Source
4. Estimate Facility Emissions for Surveyed Point Sources
Summary: Emission Inventory Fundamentals

- Inventories are the fundamental building blocks of any air quality management program and are used for a variety of purposes.
- Inventory characteristics (e.g., year, pollutants, sources, spatial and temporal resolution) are determined by the uses of the inventory.
- Modeling inventories have more specific requirements than more general tracking inventories.
- Emission Inventories can be developed using a top-down or bottom-up approach.
- A variety of emission estimation methods exist and are determined by the inventory uses, pollutant and source category priorities, resources, and data available.
  > Compromise between method accuracy and cost to implement.

Questions or Comments?
END

Module 2:
Emission Inventory Fundamentals