Dispersion for point sources

CE 524

February 2011

Concentration

- Air pollution law in most industrial countries based on concentration of contaminants
  - NAAQS in US
- Need method to predict concentrations at any given location
  - Any given set of pollutant
  - Meteorological conditions
  - At any location
  - For any time period
- But even best currently available concentration models are far from ideal

Concentration

- Commonly express concentration as ppm or $\mu g/m^3$
- Parts per million (ppm) = 1 volume of
  - 1 ppm = $\dfrac{\text{1 volume gaseous pollutant}}{10^6 \text{ volumes (pollutant + air)}}$
- $\mu g/m^3$ = micrograms/cubic meter

Factors that determine Dispersion

- Physical nature of effluents
- Chemical nature of effluents
- Meteorology
- Location of the stack
- Nature of terrain downwind from the stack

Stack Effluents

- Gas and particulate matter
- Particles < 20 μm behave same as gas
  - Low settling velocity
- Particle > 20 μm have significant settling velocity
- Only gases and Particles < 20 μm are treated in dispersion models
- Others are treated as particulate matter
- Assumes effluents leave the stack with sufficient momentum and buoyancy
  - Hot gases continue to rise

Assumptions

- Effluents leave the stack with sufficient momentum and buoyancy
  - Hot gases continue to rise
- Plume is deflected along its axis in proportion to the average wind speed (u)

Gaussian or Normal Distribution

- Gaussian distribution model
- Dispersion in y and z directions uses a double gaussian distribution -- plumes
- Dispersion in (x, y, z) is three-dimensional
- Used to model instantaneous puff of emissions

Gaussian or Normal Distribution

- Pollution dispersion follows a distribution function
- Theoretical form: gaussian distribution function

Gaussian or Normal Distribution

$$f(x) = \frac{1}{\sigma(2\pi)^{1/2}} \exp\left[\frac{-(x - x_0)^2}{2\sigma^2}\right] \qquad (4\text{-}3)$$

- x = mean of the distribution
- σ = standard deviation

Gaussian distribution used to model probabilities, in this context formula used to predict steady state concentration at a point down stream

Gaussian or Normal Distribution

What are some properties of the normal distribution?

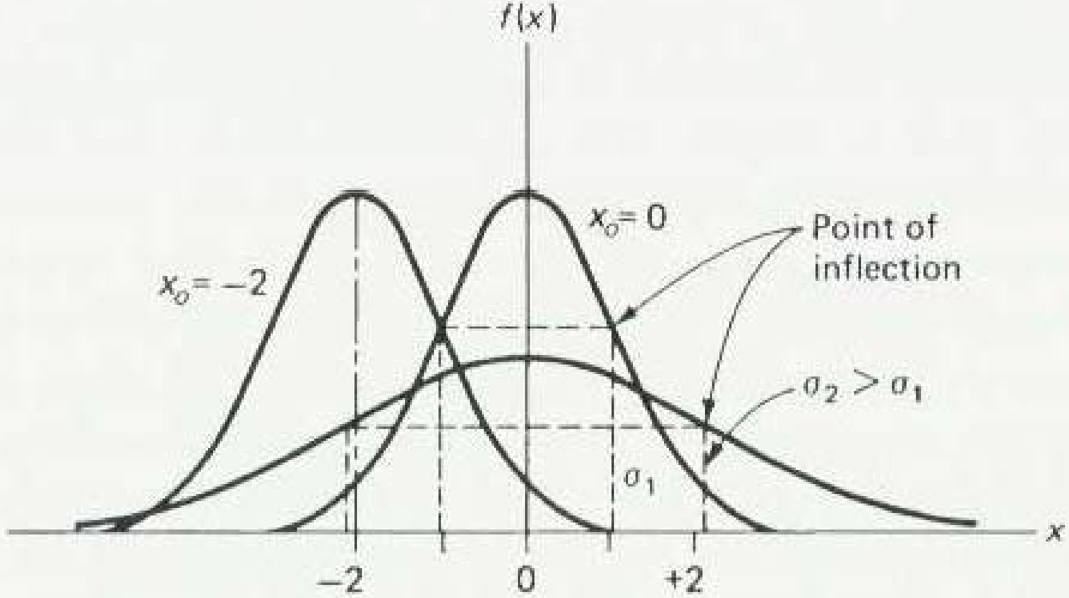


FIGURE 4-1 The Gaussian or normal distribution function for different values of x_o and σ_o

f(x) becomes concentration, maximum at center of plume

Gaussian or Normal distribution

- **68%** of the area fall within 1 standard deviation of the mean **(μ ± 1** σ).
- **95%** of area fall within 1.96 standard deviation of the mean **(μ ± 1.96** σ).
- **99.7%** of the area fall within 3 standard deviations of the mean **(μ ± 3** σ)

Gaussian dispersion model

- Dispersion in y and z directions are modeled as Gaussian
- Becomes double Gaussian model
- Why doesn't it follow a Gaussian distribution in the x direction?
  - Direction of wind

Gaussian Dispersion Model

- For localized point sources – stacks
- General appearance
- Plume exits at height, h_s
- Rises an additional distance, Δh
  - buoyancy of hot gases
  - called plume rise
  - reaches distance where buoyancy and upward momentum cease
- Exit velocity, V_s
- Plume appears as a point source emitted at height $H = h_s + \Delta h$
- Emission rate Q (g/s)
- Assume wind blows in x direction at speed u
  - u is independent of time, elevation, or location (not really true)

Gaussian Dispersion Model

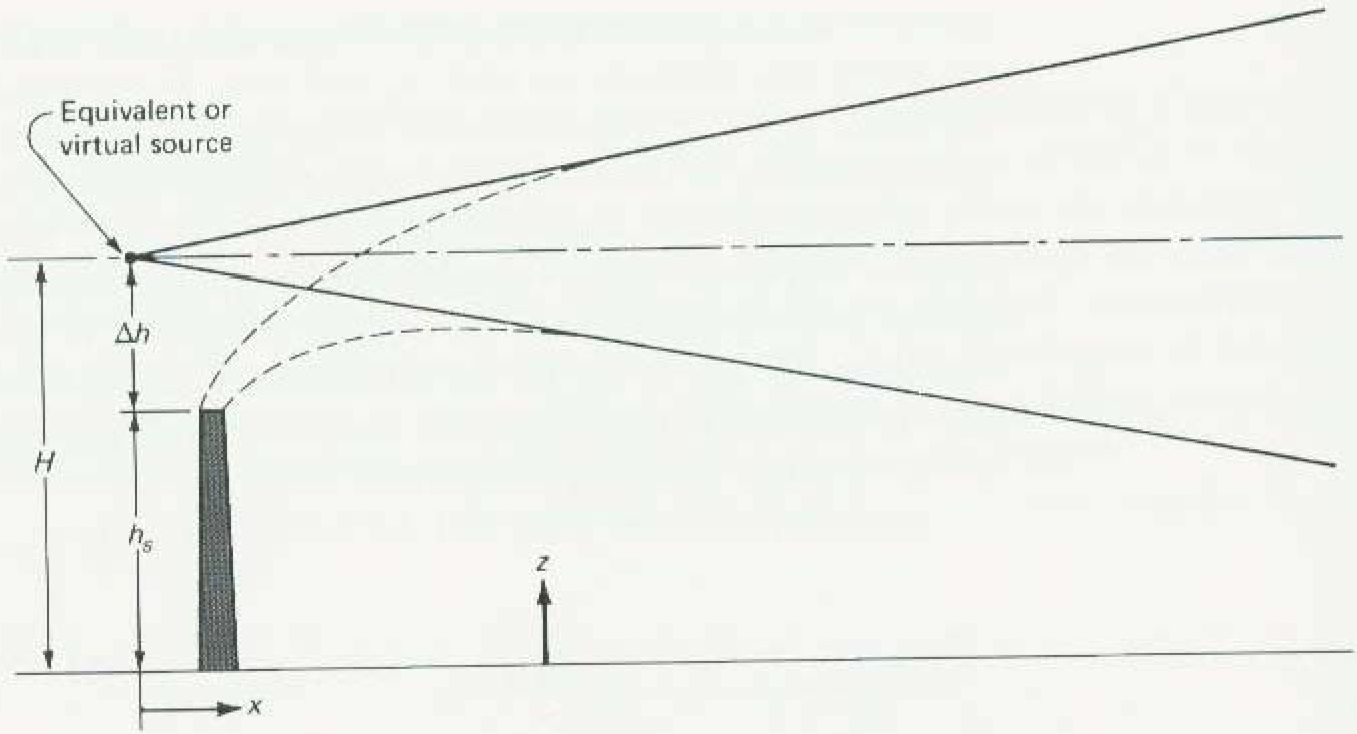


FIGURE 4-2 A dispersion model with virtual source at an effective stack height *H*.

Gaussian Dispersion Model

- Stack gas transported downstream
- Dispersion in vertical direction governed by atmospheric stability
- Dispersion in horizontal plane governed by molecular and eddy diffusion
- x-axis oriented to wind direction
- z-axis oriented vertically upwards
- y-direction oriented transverse to the wind
- Concentrations are symmetric about y-axis and z-axis

Gaussian Dispersion Model

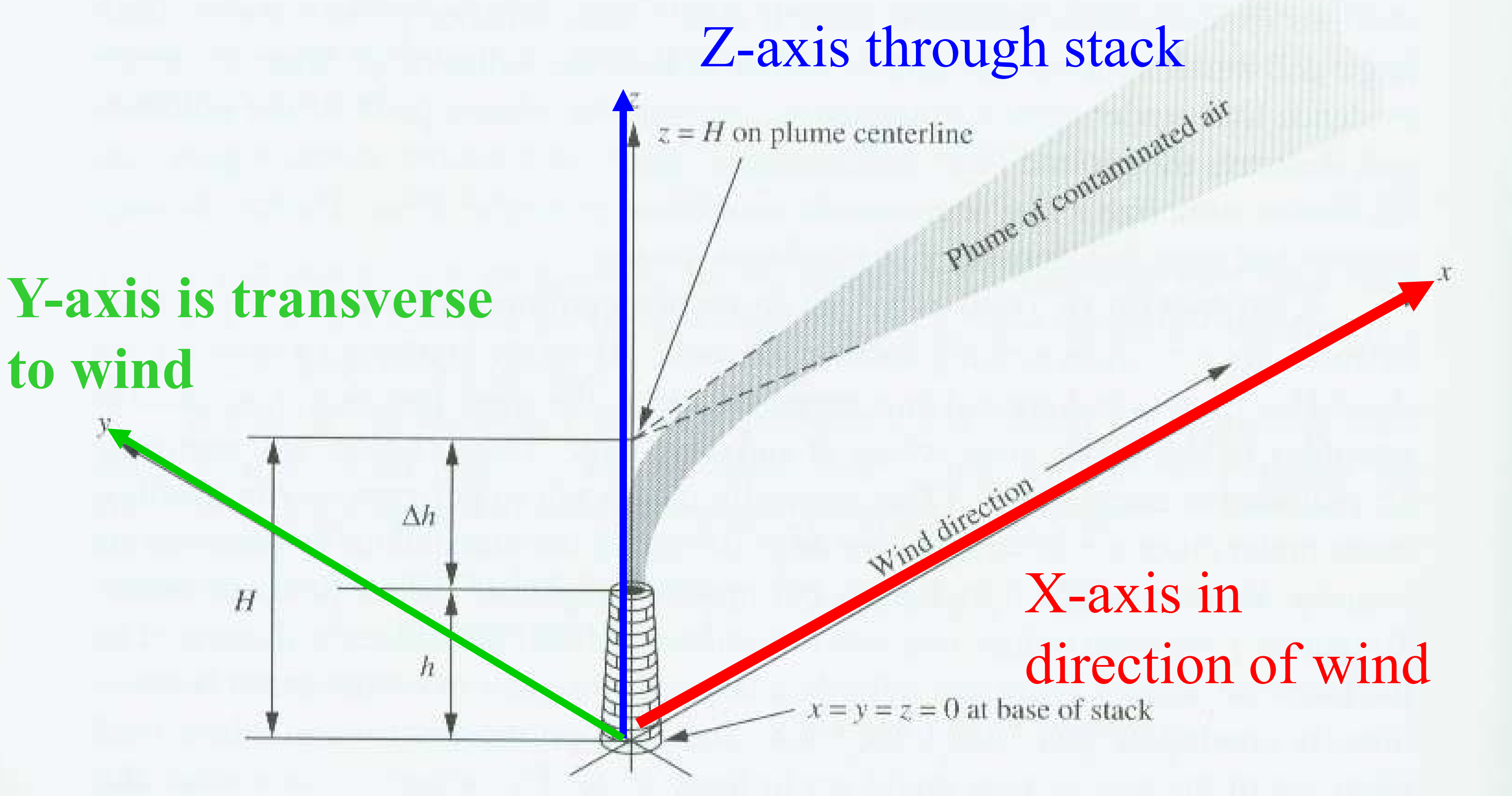


FIGURE 6.3
Coordinate system and nomenclature for the Gaussian plume idea.

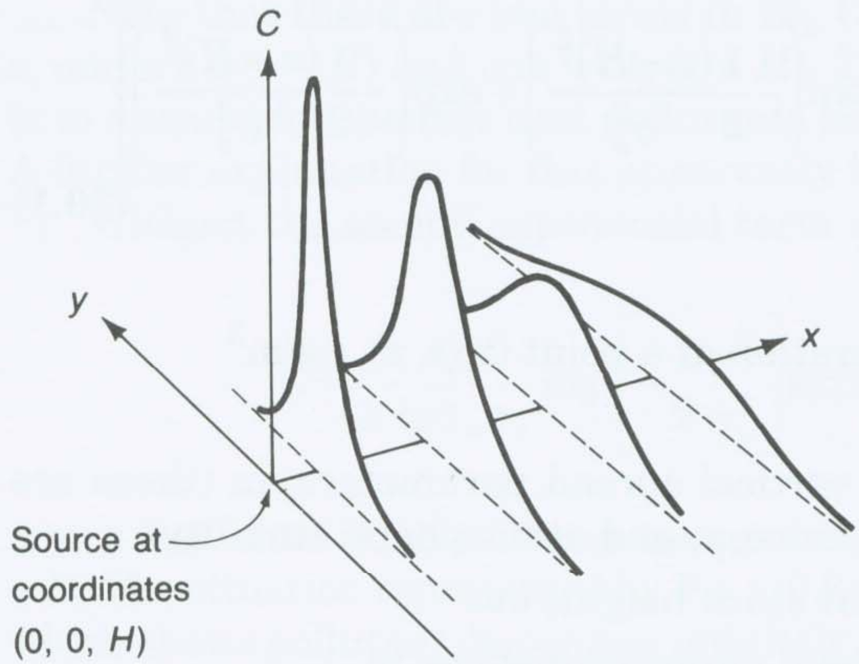


Figure 20.3
Behavior of the downwind, elevated transverse concentration profiles as a function of distance downward.

As distance increase so does dispersion

Image source: Cooper and Alley, 2002

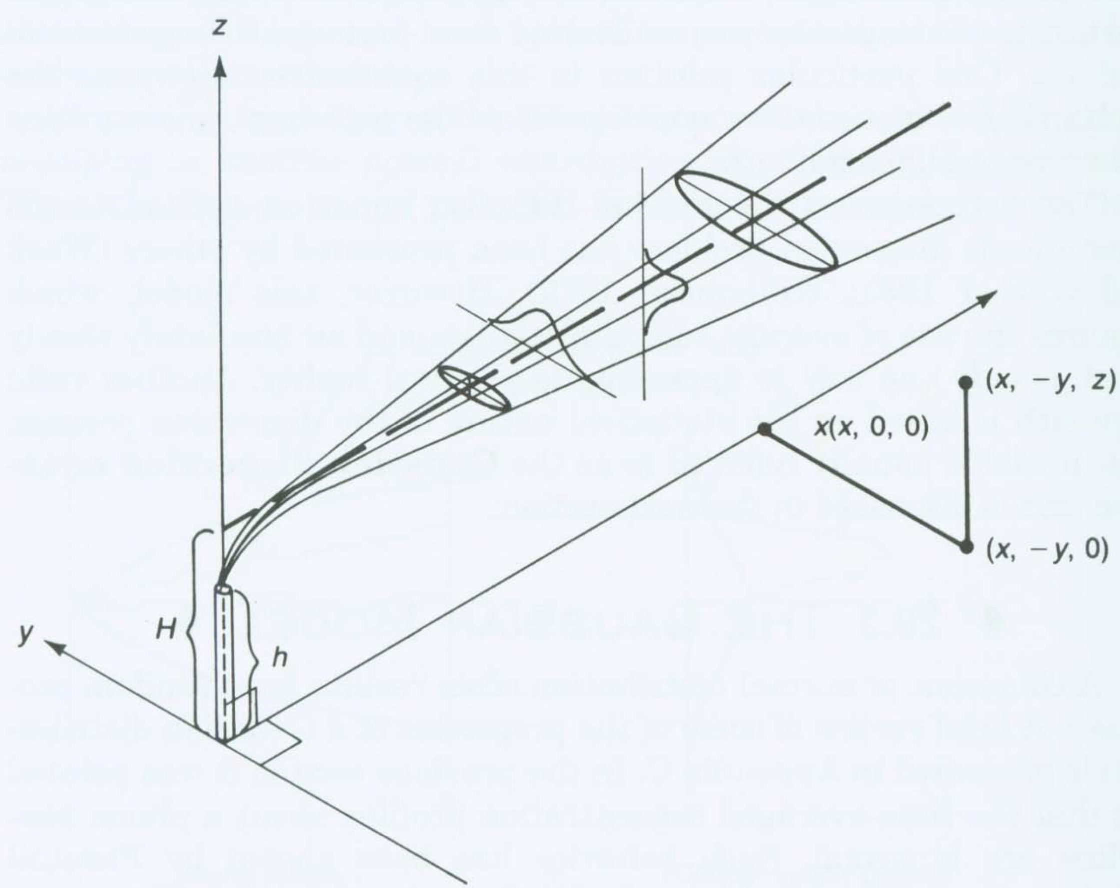


Figure 20.4
Coordinate system showing Gaussian distributions in the horizontal and vertical.
(Adapted from Turner, 1970.)

Image source: Cooper and Alley, 2002

Point Source at Elevation H

- Assumes no interference or limitation to dispersion in any direction

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-(y - y_o)^2}{2\sigma_y^2}\right] \exp\left[\frac{-(z - z_o)^2}{2\sigma_z^2}\right] \qquad (4\text{-}6)$$

x_0 and z_0 are location of centerline of plume

y_0 taken as base of the stack

z_0 is H

Q = emission strength of source (mass/time) – g/s

u = average wind speed thru the plume – m/s

C = concentration – g/m^3 **(Notice this is not ppm)**

σ_y and σ_z are horizontal and vertical standard deviations in meters

Wind Velocity Profile

- Wind speed varies by height
- International standard height for wind-speed measurements is 10 m
- Dispersion of pollutant is a function of wind speed at the height where pollution is emitted
- But difficult to develop relationship between height and wind speed

Point Source at Elevation H without Reflection

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-(y - y_o)^2}{2\sigma_y^2}\right] \exp\left[\frac{-(z - z_o)^2}{2\sigma_z^2}\right] \qquad (4\text{-}6)$$

- 3 terms
  - gives concentration on the centerline of the plume
  - gives concentration as you move in the sideways direction (± y direction), direction doesn't matter because $(\pm y)^2$ gives a positive value
  - gives concentration as you move in the vertical direction (± z direction), direction doesn't matter because $(\pm (z - H))^2$ gives a positive value
- Concentrations are symmetric about y-axis and z-axis
- Same concentration at (z-H) = 10 m as (z-H) =10 m
- Close to ground symmetry is disturbed

Point Source at elevation H without reflection

- Equation 4-6 reduces to

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left[\frac{y^2}{\sigma_y^2} + \frac{(z-H)^2}{\sigma_z^2}\right]\right) \qquad (4\text{-}8)$$

Note in the book there are 2 equation 4-8s (2 different equations just labeled wrong)

This is the first one

Gaussian Plume Example

- A factory emits 20 g/s of SO_2 at height H (includes plume rise)
- Wind speed = 3 m/s (u)
- At a distance of 1 km downstream, σ_y and σ_z are 30 m and 20 m (given, otherwise we would have to look up)
- What are the SO_2 concentrations at the centerline of the plume and at a point 60 meters to the side and 20 meters below the centerline

Gaussian Plume Example

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left[\frac{y^2}{\sigma_y^2} + \frac{(z-H)^2}{\sigma_z^2}\right]\right) \qquad (4\text{-}8)$$

0

Z – H = 0

- Q = 20 g/s of SO_2
- u = 3 m/s (u)
- σ_y and σ_z are 30 m and 20 m
- y = 0 and z = H
- So reduces to:

$$C(x,0,0) = \frac{20\ g/s}{2(\Pi*3*30*20)} = \mathbf{0.00177\ g/m^3 = 1770\ \mu\ g/m^3}$$

So second half of equation goes to 0

At centerline y and Z are 0

Gaussian Plume Example

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{1}{2}\left[\frac{y^2}{\sigma_y^2} + \frac{(z-H)^2}{\sigma_z^2}\right]\right) \quad (4\text{-}8)$$

$$c = \frac{Q}{2\Pi u\, \sigma_y\, \sigma_z} \exp{-1/2}\left[\frac{(-y^2)}{[\sigma_y^2} + (\frac{(z-H)^2)}{\sigma_z^2]}\right]$$

$$= \frac{20\ g/s}{2\Pi\ 3*(30)(20)} \exp{-1/2}\ \left[\frac{(-60m)^2}{[(30m)^2} + \frac{(-20m)^2]}{(20^2m)]}\right] =$$

$(0.00177\ g/m^3) * (\exp^{-2.5}) =$ **$0.000145\ g/m^3$ or $145.23\ \mu\ g/m^3$**

At 20 and 60 meters

Evaluation of Standard Deviation

- Horizontal and vertical dispersion coefficients -- σ_y σ_z are a function
  - downwind position *x*
  - Atmospheric stability conditions
- many experimental measurements –charts have been created
  - Correlated σ_y and σ_z to atmospheric stability and x

Pasquill-Gifford Curves

- Concentrations correspond to sampling times of approx. 10 minutes
- Regulatory models assume that the concentrations predicted represent 1-hour averages
- Solid curves represent rural values
- Dashed lines represent urban values
- Estimated concentrations represent only the lowest several hundred meters of the atmosphere

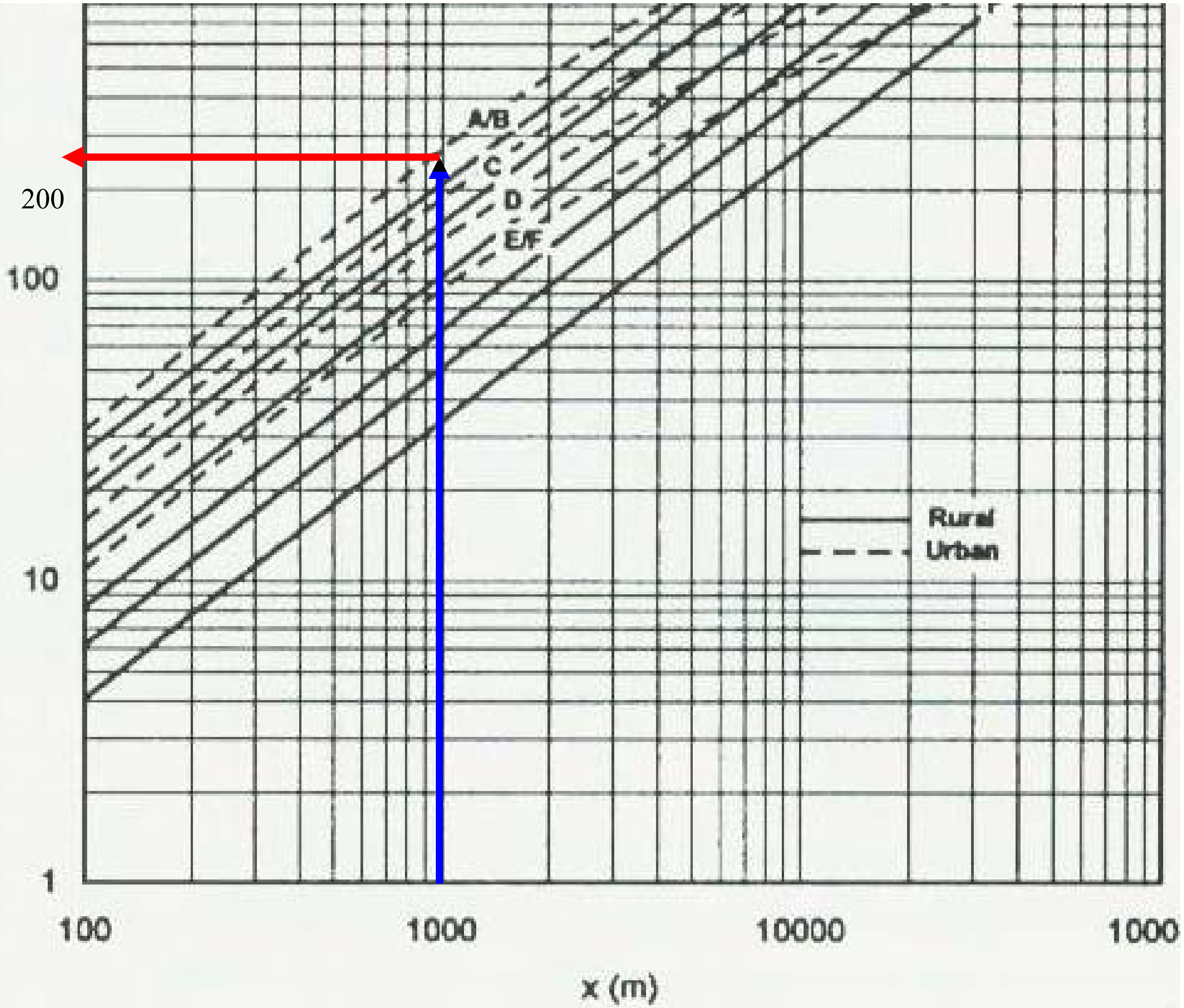
Pasquill-Gifford Curves

- σ_z less certain than σ_y
  - Especially for $x > 1$ km
- For neutral to moderately unstable atmospheric conditions and distances out to a few kilometers, concentrations should be within a factor of 2 or 3 of actual values
- Tables 3-1: Key to stability classes

Example

For stability class A, what are the values of σ_y and σ_z at 1 km downstream (assume urban)

From Tables 4-6 and 4-7



$\sigma_y \sim 220$ m

FIGURE 4-6 Rural and urban horizontal dispersion coefficients (σ_y) as a function of stability category. (Graph prepared by S.M. Claggett [20].)

$\sigma_z \sim 310$ m

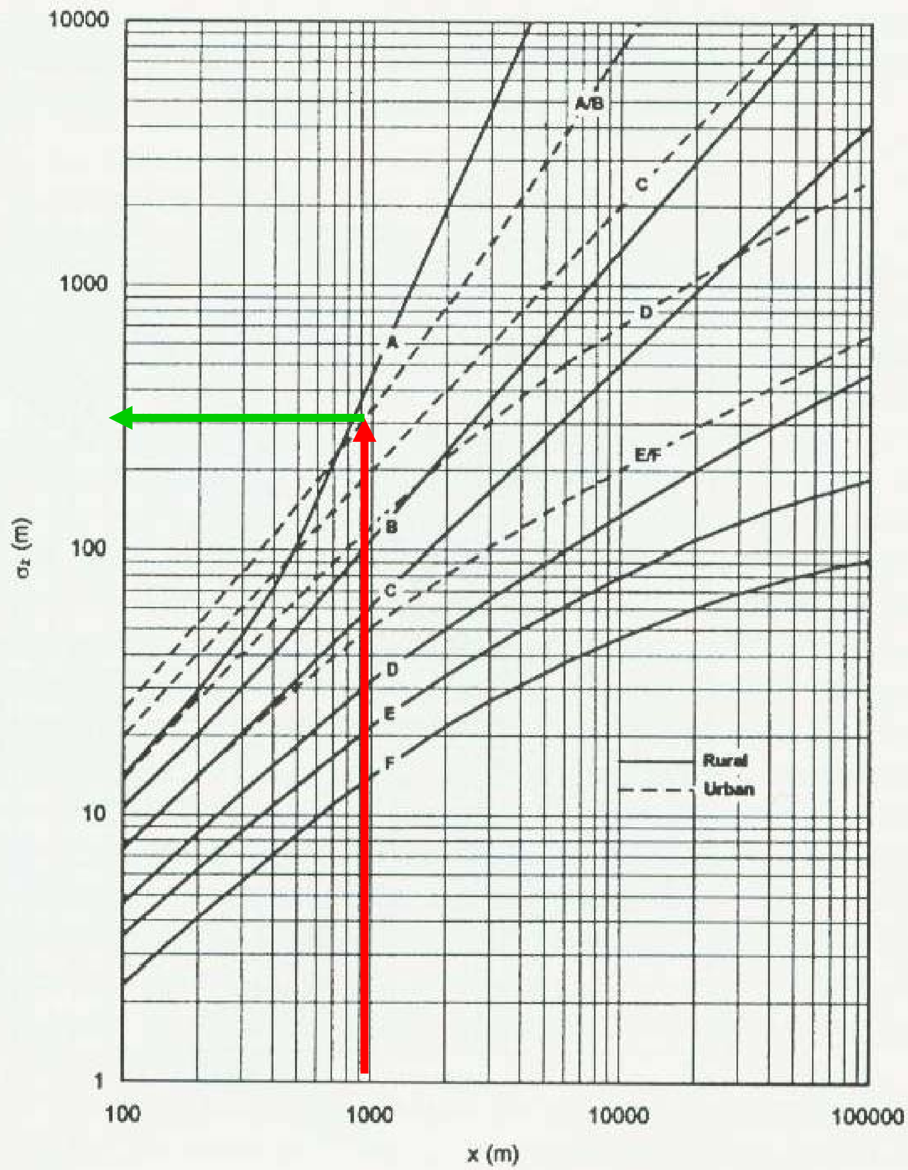


FIGURE 4-7 Rural and urban vertical dispersion coefficients (σ_z) as a function of stability category. (Graph prepared by S.M. Claggett [20].)

Example

For stability class A, what are the values of σ_y and σ_z at 1 km downstream

From Tables 4-6 and 4-7

$\sigma_y = 220$ m

$\sigma_z = 310$ m

Empirical Equations

- Often difficult to read charts
- Curves fit to empirical equations

$$\sigma_y = cx^d$$

$$\sigma_z = ax^b$$

Where

x = downwind distance (kilometers)

a, b, c, d = coefficients from Tables 4-1 and 4-2

Example: what are values of σ_y and σ_z at 1 km downstream for stability class A using equations rather than charts?

$\sigma_y = cx^d$

$\sigma_z = ax^b$

TABLE 4-1 Parameters Used to Calculate Pasquill-Gifford σ_y

Pasquill Stability Category	c	d
A	24.1670	2.5334
B	18.3330	1.8096
C	12.5000	1.0857
D	8.3330	0.72382
E	6.2500	0.54287
F	4.1667	0.36191

Using table 4-1 for stability class A

c = 24.1670

d = 2.5334

Example: what are values of σ_y and σ_z at 1 km downstream for stability class A using equations rather than charts?

$\sigma_y = cx^d$

$\sigma_z = ax^b$

Using table 4-2 where x = 1 km

a = 453.850

b = 2.11660

TABLE 4-2 Parameters Used to Calculate Pasquill-Gifford σ_z

Pasquill Stability Category	x (km)	a	b
A*	<.10	122.800	0.94470
	0.10 – 0.15	158.080	1.05420
	0.16 – 0.20	170.220	1.09320
	0.21 – 0.25	179.520	1.12620
	0.26 – 0.30	217.410	1.26440
	0.31 – 0.40	258.890	1.40940
	0.41 – 0.50	346.750	1.72830
	0.51 – 3.11	453.850	2.11660
	>3.11	**	**

Example: what are values of σ_y and σ_z at 1 km downstream for stability class A using equations rather than charts?

$\sigma_y = cx^d$

$\sigma_z = ax^b$

c = 24.1670 a = 453.850

d = 2.5334 b = 2.11660

Solution

$\sigma_y = cx^d = 24.1670(1\ \text{km})^{2.5334} = \underline{24.17\ \text{m}}$

$\sigma_z = ax^b = 453.85(1\ \text{km})^{2.11660} = \underline{453.9\ \text{m}}$

Point Source at Elevation H with Reflection

- Previous equation for concentration of plumes a considerable distance above ground
- Ground damps out vertical dispersion
- Pollutants “reflect” back up from ground

Point Source at Elevation H with Reflection

- Accounts for reflection of gaseous pollutants back into the atmosphere
- Reflection at some distance *x* is mathematically equivalent to having a mirror image of the source at –H
- Concentration is equal to contribution of both plumes at ground level

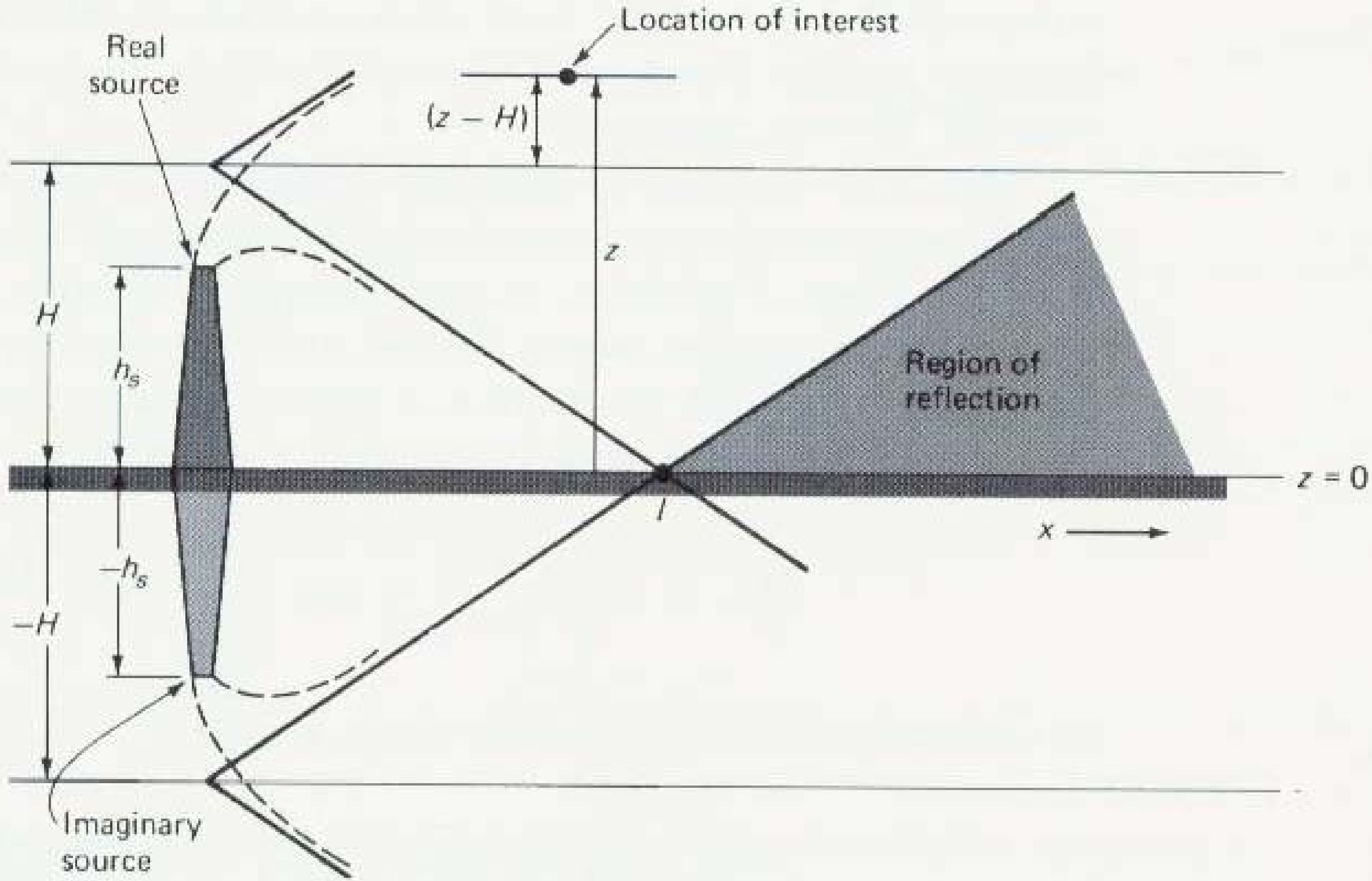


FIGURE 4-3 Use of an imaginary source to describe mathematically gaseous reflection at the surface of the earth.

Point Source at Elevation H with Reflection

$$C(x,\ y,\ z) = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp -\left(\frac{y^2}{2\sigma_y{}^2}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z{}^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z{}^2}\right]\right\} \tag{4-8}$$

Notice this is also equation 4-8 in text, it is the second equation 4-8 on the bottom of page 149

Example: Point Source at Elevation H with Reflection

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp - \left(\frac{y^2}{2\sigma_y^2}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\} \quad (4\text{-}8)$$

Nitrogen dioxide is emitted at 110 g/s from stack with H = 80 m

Wind speed = 5 m/s

Plume rise is 20 m

Calculate ground level concentration 100 meter from centerline of plume (y)

Assume stability class D so $\sigma_y = 126$ m and $\sigma_z = 51$ m

Example: Point Source at Elevation H with Reflection

$$C(x,\ y,\ z) = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp - \left(\frac{y^2}{2\sigma_y{}^2}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z{}^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z{}^2}\right]\right\} \tag{4-8}$$

Q = 110 g/s H = 80 m u = 5 m/s Δh = 20 m y = 100 m

σ_y = 126 m and σ_z = 51 m

Effective stack height =80 m + 20 m = 100 m

σ_y = 126 m and σ_z = 51 m

Solving in pieces $\frac{100\ g/s}{2\Pi*5*126*51} = 0.000496$

Example: Point Source at Elevation H with Reflection

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp -\left(\frac{y^2}{2\sigma_y^{\,2}}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^{\,2}}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^{\,2}}\right]\right\} \qquad (4\text{-}8)$$

Q = 110 g/s H = 80 m u = 5 m/s Δh = 20 m y = 100 m

σ_y = 126 m and σ_z = 51 m

Solving in pieces $\exp -\left[\frac{100^2}{[2*125^2]}\right] = 0.726149$

Solving in pieces $\exp -\left[\frac{(0-100m)^2}{[2*51^2]}\right] = 0.146265$

Example: Point Source at Elevation H with Reflection

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp -\left(\frac{y^2}{2\sigma_y^2}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\} \quad (4\text{-}8)$$

$Q = 110$ g/s $H = 80$ m $u = 5$ m/s $\Delta h = 20$ m $y = 100$ m

$\sigma_y = 126$ m and $\sigma_z = 51$ m

Solving in pieces both sides of z portion are same so add

c = 0.000496 * 0.726149 * (2 * 0.14625) = 0.000116 g/m^3 or 116.4 µg/m^3

Ground Level Concentration with reflection

- Often want ground level
  - People, property exposed to pollutants
- Previous eq. gives misleadingly low results near ground
- Pollutants “reflect” back up from ground

Ground Level Concentration

- Equation for ground level concentration
- Z = 0

1 1

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z}\left[\exp -\left(\frac{y^2}{2\sigma_y^2}\right)\right]\left\{\exp\left[\frac{-(z-H)^2}{2\sigma_z^2}\right] + \exp\left[\frac{-(z+H)^2}{2\sigma_z^2}\right]\right\} \quad (4\text{-}8)$$

1 + 1 cancels 2

Reduces to at ground level

$$C(x, y, 0) = \frac{Q}{\pi u \sigma_y \sigma_z}\exp\left(\frac{-H^2}{2\sigma_z^2}\right)\exp\left(\frac{-y^2}{2\sigma_y^2}\right) \quad (4\text{-}9)$$

Ground Level Example

C- stability class

H = 50 m

Q = 95 g/s

Wind speed is 3 m/s

What is ground level concentration at 0.5 km downwind, along the centerline?

From Figure 4-6, σ_y = 90 m,

From Figure 4-7, σ_z = 32 m

$$C = \frac{95 \times 10^6\ \mu g/s}{\Pi\ (3\ m/s)(90\ m)(32\ m)} * \exp\left[\frac{-(50^2)}{2(32)^2}\right] \exp\,[0] = \mathbf{1023.3\ \mu g/m^3}$$

Maximum Ground Level Concentration

- Effect of ground reflection increases ground concentration
- Does not continue indefinitely
- Eventually diffusion in y-direction (crosswind) and z-direction decreases concentration

Maximum Ground Level Concentration

$$\left(\frac{Cu}{Q}\right)_{\max} = \exp[a + b(\ln H) + c(\ln H)^2 + d(\ln H)^3] \qquad (4\text{-}15)$$

Values for a, b, c, d are in Table 4-5

Alternative to Eq. 4-15

- For moderately unstable to neutral conditions

$\sigma_z = 0.707H$

$$C_{max,\ reflection} = \frac{0.1171Q}{u\ \sigma_y\ \sigma_z}$$

Max. Concentration Example

What is maximum ground level concentration and where is it located downstream for the following?

- Wind speed = 2 m/s
- H = 71 m
- Stability Class B
- Q = 2,500,000 <u>μg/s</u>

Solution:

$\sigma_z = 0.707H = 0.707(71m) = 50.2$ m

From Figure 4-7, this occurs at **<u>x = 500 m</u>**

σ_z = 50.2 m

From Figure 4-7, this occurs at **x = 500 m**

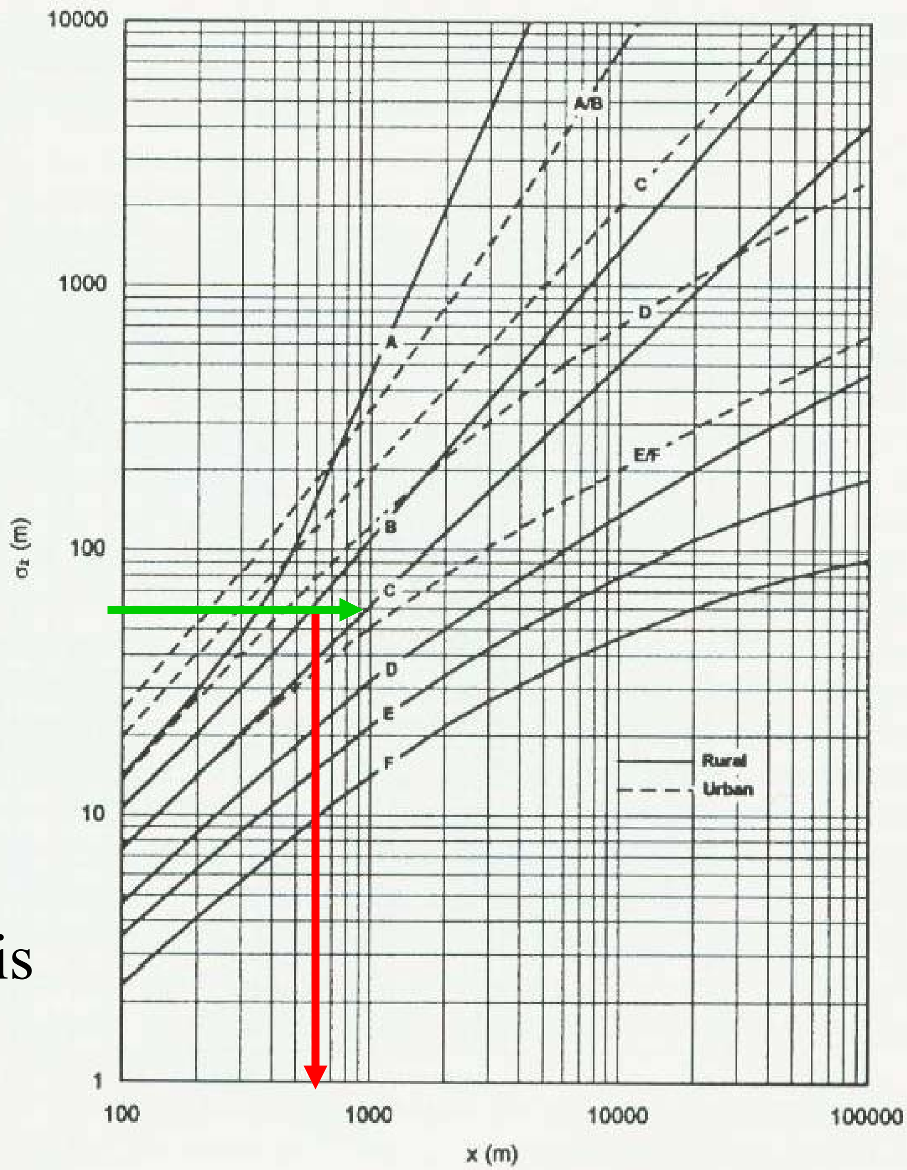


FIGURE 4-7 Rural and urban vertical dispersion coefficients (σ_z) as a function of stability category. (Graph prepared by S.M. Claggett [20].)

At 500 m, σ_y = 120 m

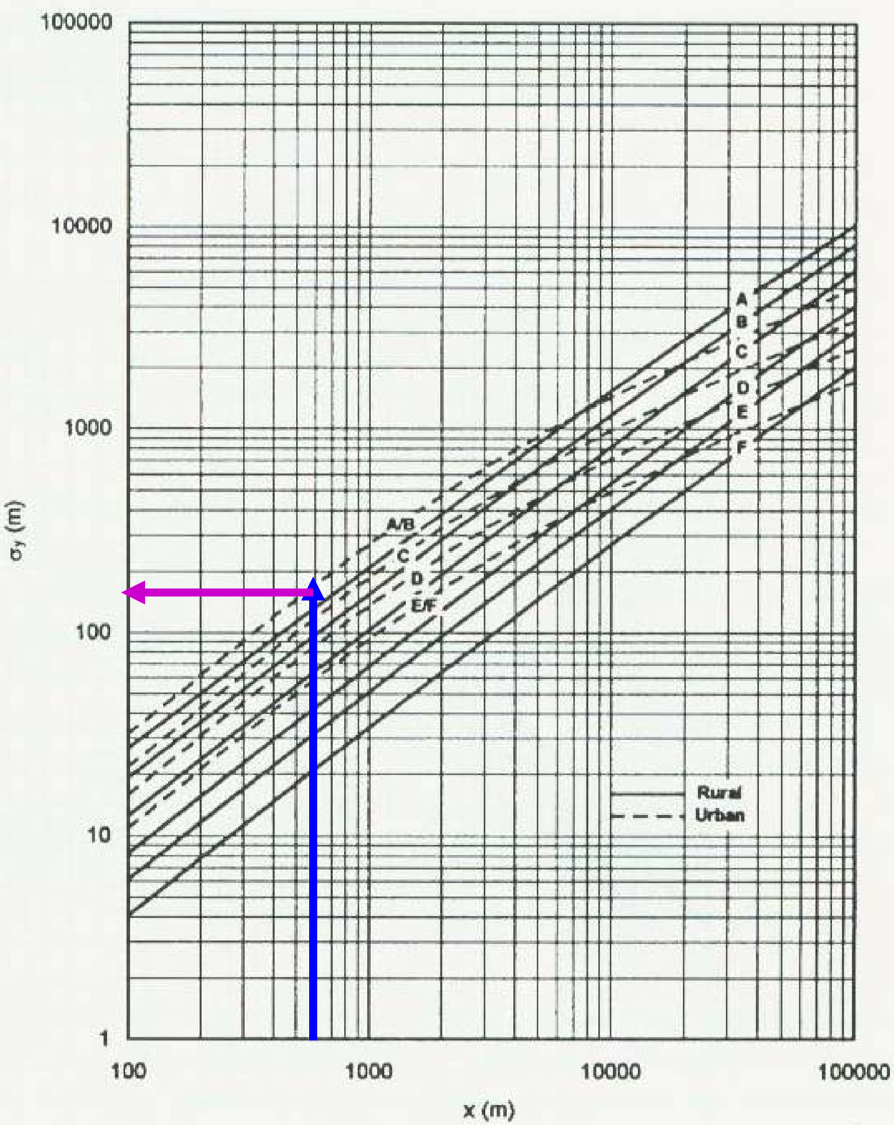


FIGURE 4-6 Rural and urban horizontal dispersion coefficients (σ_y) as a function of stability category. (Graph prepared by S.M. Claggett [20].)

Max. Concentration Example

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- Stability Class B
- Q = 2,500,000 µg/s

Solution:

$\sigma_z = 0.707H = 0.707(71m) = 50.2$ m

From Figure 4-7, this occurs at **x = 500 m**

From Figure 4-6, $\sigma_y = 120$ m

$$C_{max,\ reflection} = \frac{0.1171Q}{u\,\sigma_y\,\sigma_z} = \frac{0.1171(2500000)}{(2)(120)(50.2)} = \mathbf{24.3\ \mu g/m^3}$$

Calculation of Effective Stack Height

- $H = h_s + \Delta h$
- Δh depends on:
  - Stack characteristics
  - Meteorological conditions
  - Physical and chemical nature of effluent
- Various equations based on different characteristics, pages 162 to 166

Carson and Moses

$$\Delta h = -0.029\frac{V_s d_s}{u_s} + 2.62\left(\frac{(Q_h)^{1/2}}{u_s}\right) \qquad (4\text{-}18)$$

Where:

Δh = plume rise (meters)

V_s = stack gas exit velocity (m/s)

d_s = stack exit diameter (meters)

u_s = wind speed at stack exit (m/s)

Q_h = heat emission rate in kilojoules per second

Other basic equations

- Holland
- concawe

Example:

From text

Heat emission rate = 4800 kj/s

Wind speed = 5 mph

Stack gas velocity = 15 m/s

Stack diameter at top is 2 m

Estimate plume rise

$$\Delta h = -0.029\left[\frac{15(2)}{5}\right] + 2.62\left[\frac{(4800)^{1/2}}{5}\right] = -0.1 + 36.3$$

$$= 36.2 \text{ m} \qquad \text{(Carson and Moses)}$$

Concentration Estimates for Different Sampling Times

- Concentrations calculated in previous examples based on averages over 10-minute intervals
- Current regulatory applications use this as 1-hour average concentration
- For other time periods adjust by:
  - 3-hr multiply 1-hr value by 0.9
  - 8-hr multiply 1-hr value by 0.7
  - 24-hr multiply 1-hr value by 0.4
  - annual multiply 1-hr value by 0.03 – 0.08

Concentration Estimates for Different Sampling Times—Example

- For other time periods adjust by:
  - 3-hr multiply 1-hr value by 0.9
  - 8-hr multiply 1-hr value by 0.7
  - 24-hr multiply 1-hr value by 0.4
  - annual multiply 1-hr value by 0.03 – 0.08

Conversion of 1-hr concentration of previous example to an 8-hour average =

$c_{8\text{-hour}} = 36.4\ \mu g/m^3 \times 0.7 = 25.5\ \mu g/m^3$

Line Sources

- Imagine that a line source, such as a highway, consists of an infinite number of point sources
- The roadway can be broken into finite elements, each representing a point source, and contributions from each element are summed to predict net concentration

Line Sources

- When wind direction is normal to line of emission
- Ground level concentration downwind

$$C(x,0) = \frac{2q}{(2\Pi)^{0.5}\,\sigma_z\,u}\;\exp\left(\frac{-0.5H^2}{\sigma_z^{\;2}}\right)$$

q = source strength per unit distance (g/s * m)

Concentration should be uniform in the y-direction at a given x

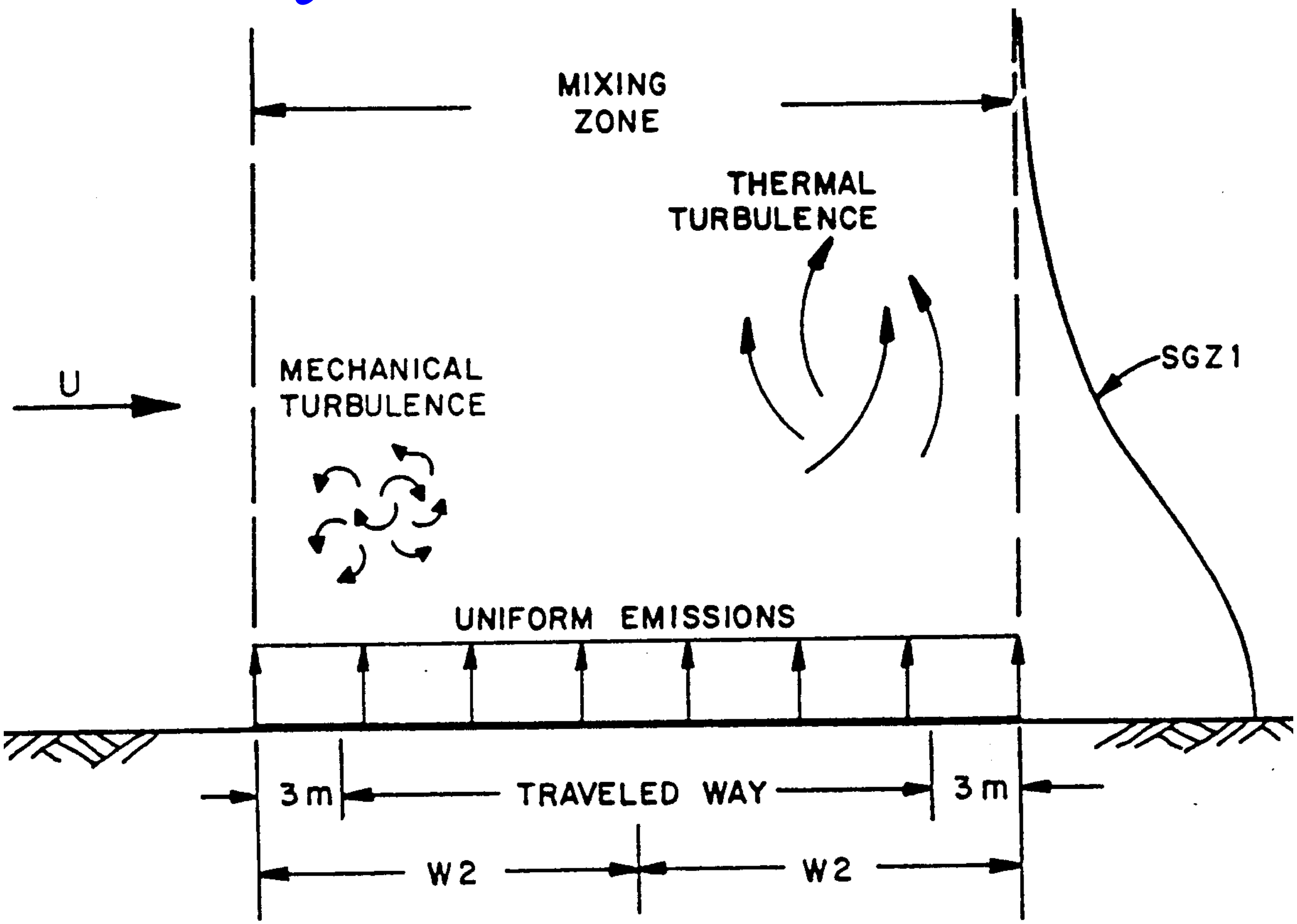
Line Sources

- For ground level (H = 0), could also use breathing height

$$C(x,0) = \frac{2q}{(2\Pi)^{0.5}\,\sigma_z\,u}\;\exp\left(\frac{-0.5H^2}{\sigma_z^2}\right)$$

1

Roadway Emissions and Mixing



from Benson, CALTRANS

u (wind direc

From Guensler, 2000

Instantaneous Release of a Puff

- Pollutant released quickly
- Explosion
- Accidental spill
- Release time << transport time
- Also based on Gaussian distribution function

$$C = \frac{Q_p}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z}\exp\left(-\frac{1}{2}\left(\frac{y-y_o}{\sigma_y}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{x-x_o}{\sigma_x}\right)^2\right)$$

$$\left[\exp\left(-\frac{1}{2}\left(\frac{z-z_o}{\sigma_z}\right)^2\right)+\exp\left(-\frac{1}{2}\left(\frac{z+z_o}{\sigma_z}\right)^2\right)\right] \qquad (4\text{-}39)$$

Instantaneous Release of a Puff

- Equation 4-41 to predict maximum ground level concentration

$$C_{max} = \frac{2Qp}{(2\Pi)^{3/2} \sigma_x \sigma_y \sigma_z}$$

Receptor downwind would see a gradual increase in concentration until center of puff passed and then concentration would decrease

Assume $\sigma_x = \sigma_y$

Figure 4-9 and Table 4-7

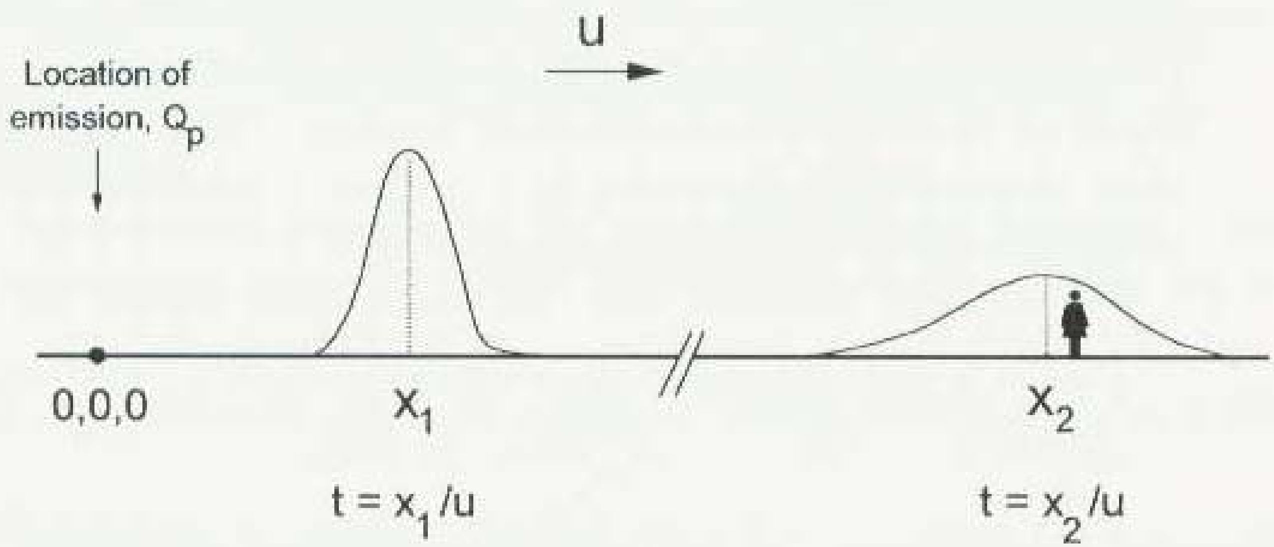


FIGURE 4-9 An instantaneous puff traveling downwind at windspeed, u.

Figure 4-9 and Table 4-7

TABLE 4.7 Instantaneous Values for σ_y and σ_z in meters [11]

Parameter	Stability Condition	Equation*
σ_y	Unstable	$\sigma_y = 0.14\,(x)^{0.92}$
	Neutral	$\sigma_y = 0.06\,(x)^{0.92}$
	Very Stable	$\sigma_y = 0.02\,(x)^{0.89}$
σ_z	Unstable	$\sigma_z = 0.53\,(x)^{0.73}$
	Neutral	$\sigma_z = 0.15\,(x)^{0.70}$
	Very Stable	$\sigma_z = 0.05\,(x)^{0.61}$

*x is the distance downwind in meters.

Puff Example

A tanker spill on the freeway releases 400,000 grams of chlorine. What exposure will vehicles directly behind the tanker (downwind) receive if x =100 m? Assume very stable conditions.

From Table 4-7,

Figure 4-9 and Table 4-7

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Puff Example

A tanker spill on the freeway releases 400,000 grams of chlorine. What exposure will vehicles directly behind the tanker (downwind) receive if x =100 m? Assume very stable conditions.

From Table 4-7, $\sigma_y = 0.02(100\text{m})^{0.89} = 1.21$

From Table 4-7, $\sigma_z = 0.05(100\text{m})^{0.61} = 0.83$

$\sigma_x = \sigma_y = 1.21$

Puff Example

A tanker spill on the freeway releases 400,000 grams of chlorine. What exposure will vehicles directly behind the tanker (downwind) receive if x =100 m? Assume very stable conditions.

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$$C_{max} = \frac{2Q_p}{(2\Pi)^{3/2}\,\sigma_x\,\sigma_y\,\sigma_z} = \frac{2(400000\text{ g})}{(2\Pi)^{3/2}(1.21)(1.21)(0.83)} = \underline{\mathbf{42{,}181\ g/m^3}}$$