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 μg/m³

• Parts per million (ppm) = 1 volume of
  – 1 ppm = __1 volume gaseous pollutant__
  \[= \frac{1}{10^6} \text{volumes (pollutant + air)}\]

• μg/m³ = 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
- Assumess 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

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

(4.3)

- \( x = \) mean of the distribution
- \( \sigma = \) 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?

\[ f(x) \]

\[ x_0 = -2 \quad x_0 = 0 \]

\[ \sigma_2 > \sigma_1 \]

\[ \text{Point of inflection} \]

\[ -2 \quad 0 \quad +2 \]

**FIGURE 4-1** The Gaussian or normal distribution function for different values of \( x_0 \) and \( \sigma \).

\[ f(x) \text{ becomes concentration, maximum at center of plume} \]
Gaussian or Normal distribution

- **68%** of the area fall within 1 standard deviation of the mean ($\mu \pm 1 \sigma$).
- **95%** of area fall within 1.96 standard deviation of the mean ($\mu \pm 1.96 \sigma$).
- **99.7%** of the area fall within 3 standard deviations of the mean ($\mu \pm 3 \sigma$).
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, $\Delta h$
  - 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

Z-axis through stack

Y-axis is transverse to wind

X-axis in direction of wind

FIGURE 6.3
Coordinate system and nomenclature for the Gaussian plume idea.
As distance increase so does dispersion

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

Image source: Cooper and Alley, 2002
Figure 20.4
Coordinate system showing Gaussian distributions in the horizontal and vertical.
(Adapted from Turner, 1970.)
Point Source at Elevation H

- Assumes no interference or limitation to dispersion in any direction

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

(4-6)

\(x_0\) 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)**
\(\sigma_y\) and \(\sigma_z\) 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

\[ C(x, y, z) = \frac{Q}{2\pi \mu \sigma_y \sigma_z} \exp \left[ \frac{-(y - y_0)^2}{2\sigma_y^2} \right] \exp \left[ \frac{-(z - z_0)^2}{2\sigma_z^2} \right] \]

(4-6)

- 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 (±y)^2 gives a positive value
  - gives concentration as you move in the vertical direction (±z direction), direction doesn’t matter because (±(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

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

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, $\sigma_y$ and $\sigma_z$ 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

\[ C(x, y, z) = \frac{Q}{2\pi \mu \sigma_y \sigma_z} \exp \left( -\frac{1}{2} \left[ \frac{y^2}{\sigma_y^2} + \frac{(z - H)^2}{\sigma_z^2} \right] \right) \]  

- \( Q = 20 \text{ g/s of SO}_2 \)
- \( u = 3 \text{ m/s (u)} \)
- \( \sigma_y \) and \( \sigma_z \) are 30 m and 20 m
- \( y = 0 \) and \( z = H \)
- So reduces to:
  
  \[ C(x,0,0) = \frac{20 \text{ g/s}}{2(\Pi \times 3 \times 30 \times 20)} = 0.00177 \text{ g/m}^3 = 1770 \mu \text{ g/m}^3 \]

At centerline \( y \) and \( Z \) are 0

So second half of equation goes to 0
What are the SO2 concentrations at a point 60 meters to the side and 20 meters below the centerline?

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

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

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

\[= (0.00177 \text{ g/m}^3) \times (\exp^{-2.5}) = 0.000145 \text{ g/m}^3 \text{ or } 145.23 \mu \text{g/m}^3\]

At 20 and 60 meters
Evaluation of Standard Deviation

• Horizontal and vertical dispersion coefficients -- $\sigma_y$, $\sigma_z$ are a function
  – downwind position $x$
  – Atmospheric stability conditions

• many experimental measurements -- charts have been created
  – Correlated $\sigma_y$ and $\sigma_z$ 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

• $\sigma_z$ less certain than $\sigma_y$
  – 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 $\sigma_y$ and $\sigma_z$ at 1 km downstream (assume urban)

From Tables 4-6 and 4-7
$\sigma_y \sim 220 \text{ m}$

**FIGURE 4-6** Rural and urban horizontal dispersion coefficients ($\sigma_y$) as a function of stability category. (Graph prepared by S.M. Claggett [20].)
$\sigma_z \sim 310 \text{ m}$
Example

For stability class A, what are the values of \( \sigma_y \) and \( \sigma_z \) at 1 km downstream

From Tables 4-6 and 4-7

\[ \sigma_y = 220 \text{ m} \]

\[ \sigma_z = 310 \text{ m} \]
Empirical Equations

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

\[ \sigma_y = cx^d \]
\[ \sigma_z = ax^b \]

Where

\( x = \text{downwind distance (kilometers)} \)
\( a, b, c, d = \text{coefficients from Tables 4-1 and 4-2} \)
**Example:** what are values of $\sigma_y$ and $\sigma_z$ at 1 km downstream for stability class A using equations rather than charts?

$\sigma_y = cx^d$

$\sigma_z = ax^b$

Using table 4-1 for stability class A

- $c = 24.1670$
- $d = 2.5334$
**Example:** what are values of $\sigma_y$ and $\sigma_z$ 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

- $a = 453.850$
- $b = 2.11660$
Example: what are values of $\sigma_y$ and $\sigma_z$ at 1 km downstream for stability class A using equations rather than charts?

\[ \sigma_y = cx^d \]
\[ \sigma_z = ax^b \]

\begin{align*}
    c &= 24.1670 \\
    a &= 453.850 \\
    d &= 2.5334 \\
    b &= 2.11660
\end{align*}

Solution

\[ \sigma_y = cx^d = 24.1670(1 \text{ km})^{2.5334} = 24.17 \text{ m} \]
\[ \sigma_z = ax^b = 453.85(1 \text{ km})^{2.11660} = 453.9 \text{ m} \]
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

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

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

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

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

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

\[(4-8)\]

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

\sigma_y = 126 m \quad \text{and} \quad \sigma_z = 51 m

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

\sigma_y = 126 m \quad \text{and} \quad \sigma_z = 51 m

Solving in pieces \quad \underline{100 \text{ g/s}} = 0.000496

\[2\pi \times 5 \times 126 \times 51\]
Example: Point Source at Elevation H with Reflection

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

(4-8)

\[
\begin{align*}
Q &= 110 \text{ g/s} \quad H = 80 \text{ m} \quad u = 5 \text{ m/s} \quad \Delta h = 20 \text{ m} \quad y = 100 \text{ m} \\
\sigma_y &= 126 \text{ m} \quad \text{and} \quad \sigma_z = 51 \text{ m} \\
\end{align*}
\]

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

\[ \exp \left[ -\frac{100^2}{2*125^2} \right] = 0.726149 \]
Example: Point Source at Elevation H with Reflection

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

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

\( \sigma_y = 126 \text{ m and } \sigma_z = 51 \text{ m} \)

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

\[ c = 0.000496 \times 0.726149 \times (2 \times 0.14625) = 0.000116 \text{ g/m}^3 \text{ or } 116.4 \mu g/m^3 \]
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
- \( Z = 0 \)

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

(4-8)

1 + 1 cancels 2

Reduces to at ground level

\[
C(x, y, 0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp \left( -\frac{H^2}{2\sigma_z^2} \right) \exp \left( -\frac{y^2}{2\sigma_y^2} \right) 
\]

(4-9)
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, $\sigma_y = 90$ m,
From Figure 4-7, $\sigma_z = 32$ m

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

\[
\left( \frac{C_u}{Q} \right)_{\text{max}} = \exp[a + b(\ln H) + c(\ln H)^2 + d(\ln H)^3]
\]

(4-15)

Values for a, b, c, d are in Table 4-5
Alternative to Eq. 4-15

• For moderately unstable to neutral conditions

\[ \sigma_z = 0.707H \]

\[ C_{\text{max, reflection}} = \frac{0.1171Q}{u \sigma_y \sigma_z} \]
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 µg/s

Solution:

\[ \sigma_z = 0.707H = 0.707(71\text{m}) = 50.2 \text{ m} \]

From Figure 4-7, this occurs at \( x = 500 \text{ m} \)
\[ \sigma_z = 50.2 \text{ m} \]

From Figure 4-7, this occurs at \( x = 500 \text{ m} \)
At 500 m, $\sigma_y = 120$ m
Max. Concentration Example

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

- Wind speed = 2 m/s
- \( H = 71 \text{ m} \)
- Stability Class B
- \( Q = 2,500,000 \mu g/s \)

Solution:

\( \sigma_z = 0.707H = 0.707(71\text{m}) = 50.2 \text{ m} \)

From Figure 4-7, this occurs at \( x = 500 \text{ m} \)

From Figure 4-6, \( \sigma_y = 120 \text{ m} \)

\[
C_{\text{max, reflection}} = \frac{0.1171Q}{u \sigma_y \sigma_z} = \frac{0.1171(2500000)}{(2)(120)(50.2)} = 24.3 \mu g/m^3
\]
Calculation of Effective Stack Height

- $H = h_s + \Delta h$
- $\Delta h$ 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

\[
\Delta h = - 0.029 \frac{V_s d_s}{u_s} + 2.62 \left( \frac{Q_h}{u_s} \right)^{1/2}
\]  \hspace{1cm} (4.18)

Where:
\( \Delta h \) = 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 \text{ kj/s}
Wind speed = 5 \text{ mph}
Stack gas velocity = 15 \text{ m/s}
Stack diameter at top is 2 m
Estimate plume rise

\[ \Delta h = -0.029 \left[ \frac{15(2)}{5} \right] + 2.62 \left[ \frac{(4800)^{1/2}}{5} \right] = -0.1 + 36.3 \]
\[ = 36.2 \text{ m} \quad \text{(Carson and Moses)} \]
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

\[ C(x,0) = \frac{2q}{(2\pi)^{0.5} \sigma_z u} \exp(-0.5H^2) \frac{\sigma_z^2}{\sigma_z} \]

\( q = \text{source strength per unit distance (g/s * m)} \)

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

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

\[
C(x,0) = \frac{2q}{(2\pi)^{0.5} \sigma_z u} \exp(-0.5H^2) \sigma_z^2
\]
Roadway Emissions and Mixing

From Guensler, 2000
Instantaneous Release of a Puff

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

$$C = \frac{Q_p}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \exp \left( -\frac{1}{2} \left( \frac{y - y_0}{\sigma_y} \right)^2 \right) \exp \left( -\frac{1}{2} \left( \frac{x - x_0}{\sigma_x} \right)^2 \right) \left[ \exp \left( -\frac{1}{2} \left( \frac{z - z_0}{\sigma_z} \right)^2 \right) + \exp \left( -\frac{1}{2} \left( \frac{z + z_0}{\sigma_z} \right)^2 \right) \right]$$

(4-39)
Instantaneous Release of a Puff

- Equation 4-41 to predict maximum ground level concentration

\[ C_{\text{max}} = \frac{2Qp}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} \]

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>
<thead>
<tr>
<th>Parameter</th>
<th>Stability Condition</th>
<th>Equation*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_y$</td>
<td>Unstable</td>
<td>$\sigma_y = 0.14 \ (x)^{0.92}$</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>$\sigma_y = 0.06 \ (x)^{0.92}$</td>
</tr>
<tr>
<td></td>
<td>Very Stable</td>
<td>$\sigma_y = 0.02 \ (x)^{0.89}$</td>
</tr>
<tr>
<td>$\sigma_z$</td>
<td>Unstable</td>
<td>$\sigma_z = 0.53 \ (x)^{0.73}$</td>
</tr>
<tr>
<td></td>
<td>Neutral</td>
<td>$\sigma_z = 0.15 \ (x)^{0.70}$</td>
</tr>
<tr>
<td></td>
<td>Very Stable</td>
<td>$\sigma_z = 0.05 \ (x)^{0.61}$</td>
</tr>
</tbody>
</table>

* $x$ 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

### TABLE 4.7
Instantaneous Values for $\sigma_y$ and $\sigma_z$ in meters [11]

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<td></td>
<td>Very Stable</td>
<td>$\sigma_z = 0.05 , (x)^{0.61}$</td>
</tr>
</tbody>
</table>

* $x$ 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 \( x = 100 \text{ m} \)? Assume very stable conditions.

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

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\[
C_{\text{max}} = \frac{2Q_p}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} = \frac{2(400000 \text{ g})}{(2\pi)^{3/2}(1.21)(1.21)(0.83)} = 42,181 \text{ g/m}^3
\]