Example 5.16 - Formaldehyde from Methanol-Fueled Vehicles in Tunnels

Given: Methanol-fueled autos receive increasing attention because of their potential to reduce ozone levels in urban areas. While methanol combustion produces fewer unburned hydrocarbons that ultimately produce ozone, combustion of methanol produces more *formaldehyde* than does combustion of gasoline. The PEL for formaldehyde is currently 0.75 PPM (920 $\mu g/m^3$), but the EPA is concerned that outdoor concentrations as low as 150 $\mu g/m^3$ may cause irritation for some individuals. One may assume that the conditions given by Chang and Rudy (1990) apply to roadway tunnels under severe conditions of traffic congestion, poor tunnel ventilation, and engines with high rates of formaldehyde emission. Four tunnels are analyzed, as shown in Table E5.16. The diameter and amount of traffic are the same in each tunnel, but the tunnels are of various lengths; each tunnel also employs a different type of ventilation:

(a) a short tunnel with natural ventilation
(b) a moderate length tunnel with uniform make-up air ventilation
(c) a long tunnel with balanced transverse ventilation
(d) the same long tunnel, but with unbalanced transverse ventilation

To do: Estimate the formaldehyde concentration in the four tunnels listed above.

Table E5.16 Parameters for the four tunnels of Example 5.16.

parameter (units)	**(a) natural** ($q_m = q_e = 0$)	**(b) uniform make-up air** ($q_e = 0$, q_m = constant)	**(c) balanced transverse** ($q_m = q_e$)	**(d) unbalanced transverse** ($q_m \neq q_e$)
L (m)	300	1000	2000	2000
D (m)	7.57	7.57	7.57	7.57
U(0) (m/min)	60.	60.	60.	60.
q_m (min^{-1})	0	0.20	0.20	0.20
q_e (min^{-1})	0	0	0.20	0.18
c_m ($\mu g/m^3$)	5.0	5.0	5.0	5.0
c(0) ($\mu g/m^3$)	7.4	7.4	7.4	7.4
n_c (autos/km)	100	100	100	100
v_c (km/hr)	8.0	8.0	8.0	8.0
$(EF)_c$ [mg / (auto km)]	100	100	100	100
k (min^{-1})	0.020	0.020	0.020	0.020

Solution: The source term (s) is common to several of the equations above, and can be calculated from Eq. (5-76), using Eq. (5-71),

$$s = \frac{S}{A_c L} = \frac{(EF)_c n_c v_c L}{\frac{\pi D^2}{4} L} = \frac{4(EF)_c n_c v_c}{\pi D^2}$$

which upon substitution of the values provided in the table yields

$$s = \frac{4\left(100.\frac{mg}{auto \cdot km}\right)100.\frac{auto}{km}8.0\frac{km}{hr}}{\pi\left(7.57\ m\right)^2}\left(\frac{hr}{60\ min}\right)\left(\frac{1000\ \mu g}{mg}\right)\left(\frac{km}{1000\ m}\right) = 29.6\frac{\mu g}{m^3\ min}$$

Now the various ventilation cases can be calculated:

(a) <u>Natural ventilation</u> ($q_m = q_e = 0$):
For natural ventilation, Eqs. (5-86) and (5-87) apply. The air velocity through the tunnel is constant (U = U(0)) and the maximum mass concentration of formaldehyde is thus

$$c_{max} = \frac{s}{k} = \frac{29.6\frac{\mu g}{m^3\ min}}{0.020\frac{1}{min}} = 1480\frac{\mu g}{m^3}$$

The reader should note that c increases with x, and that this maximum concentration is predicted for a very *long* tunnel. As will be seen, tunnel (a) is so short that the actual concentration never goes above about 10% of this value. The mass concentration of formaldehyde at any x location along the tunnel is

$$c(x) = c_{max} - \left[c_{max} - c(0)\right]\exp\left(-\frac{k}{U_0}x\right) = 1480\frac{\mu g}{m^3} - \left[1480 - 7.4\right]\frac{\mu g}{m^3}\exp\left(-\frac{0.020\frac{1}{min}}{60.\frac{m}{min}}x\right)$$

where x must be in meters for unit consistency. The concentration at the tunnel exit (x = L = 300 m for this tunnel) is

$$\underline{c(L) = 150 \frac{\mu g}{m^3}}$$

(b) Uniform make-up ventilation, no exhaust (q_m = constant, $q_e = 0$):
When $q_m = 0.20 \text{ min}^{-1}$ and $q_e = 0$, Eq. (5-82) can be used, where the value of c_{max} is obtained from Eq. (5-80),

$$c_{max} = \frac{s + q_m c_m}{k + q_m} = \frac{29.6 \frac{\mu g}{m^3 \text{ min}} + 0.20 \frac{1}{\text{min}} 5.0 \frac{\mu g}{m^3}}{0.020 \frac{1}{\text{min}} + 0.20 \frac{1}{\text{min}}} = 139. \frac{\mu g}{m^3}$$

and the exponent b is obtained from Eq. (5-83),

$$b = \frac{k + q_m}{q_m - q_e} = \frac{(0.020 + 0.20) \frac{1}{\text{min}}}{(0.20 - 0) \frac{1}{\text{min}}} = 1.1$$

The concentration at any location x inside the tunnel, $0 \le x \le L$, is obtained by substituting these values into Eq. (5-82):

$$c(x) = 139. \frac{\mu g}{m^3} - [139. - 7.4] \frac{\mu g}{m^3} \left[1 + \frac{0.20 \frac{1}{\text{min}}}{60. \frac{m}{\text{min}}} x \right]^{-1.1}$$

where Eq. (5-74) has been used for $U(x)/U(0)$, and x must be in meters in order for the units to be consistent. At the tunnel exit ($x = L = 1000$ m for this tunnel), the above yields

$$\underline{c(L) = 110 \frac{\mu g}{m^3}}$$

Again, as in tunnel (a), this tunnel is too short for the concentration to reach the predicted maximum value.

(c) Balanced transverse ventilation ($q_m = q_e$ = const):
When the system is *balanced*, $q_m = q_e = 0.20 \text{ min}^{-1}$; Eqs. (5-84) and (5-85) apply, and can be used to calculate the concentration at any x location. The maximum concentration (c_{max}) is the same as that calculated in Part (b) above, i.e. $c_{max} = 139.\ \mu g/m^3$, and

$$c(x) = 139. \frac{\mu g}{m^3} - [139. - 7.4] \frac{\mu g}{m^3} \exp\left(- \frac{(0.020 + 0.20) \frac{1}{\text{min}}}{60. \frac{m}{\text{min}}} x \right)$$

where again x must be in meters in order for the units to be consistent. At the tunnel exit ($x = L = 2000$ m for this tunnel), the above yields

$$\underline{c(L) = 138.9 \frac{\mu g}{m^3} \cong 139. \frac{\mu g}{m^3}}$$

In this case, the tunnel is long enough that the mass concentration of formaldehyde at the tunnel exit has nearly reached its maximum possible value (the exponential term in the above equation is negligibly small).

(d) Unbalanced transverse ventilation ($q_m \neq q_e$) (q_m = const, q_e = const):
If $q_e = 0.18\ \text{min}^{-1}$ and $q_m = 0.20\ \text{min}^{-1}$, the system is *unbalanced* and Eq. (5-82) can be used, with exponent b determined from Eq. (5-83),

$$b = \frac{k + q_m}{q_m - q_e} = \frac{(0.020 + 0.20)\frac{1}{\text{min}}}{(0.20 - 0.18)\frac{1}{\text{min}}} = 11.0$$

The maximum concentration (c_{max}) is obtained from Eq. (5-80), and is the same as that calculated in Part (b) above, i.e. $c_{max} = 139.\ \mu\text{g/m}^3$. Thus, at any x location in the tunnel,

$$c(x) = 139.\frac{\mu g}{m^3} - [139. - 7.4]\frac{\mu g}{m^3}\left[1 + \frac{(0.20 - 0.18)\frac{1}{\text{min}}}{60.\frac{m}{\text{min}}} x\right]^{-11.0}$$

At the tunnel exit (x = L = 2000 m for this tunnel), the above yields

$$\underline{c(L) = 138.5\frac{\mu g}{m^3} \cong 139.\frac{\mu g}{m^3}}$$

Again, as in Part (c) above, the tunnel is long enough that the mass concentration of formaldehyde at the tunnel exit has nearly reached its maximum possible value.

Discussion: Comparing the four tunnels, the maximum concentration (at the end of the tunnel in each case) lies between 110 and 150 $\mu\text{g/m}^3$. This is below the value of 150 $\mu\text{g/m}^3$, the concentration at which the EPA expressed concern. Thus, one can conclude that workers in the tunnel are not in any great danger from formaldehyde vapors. Drivers moving through the tunnel are only inside the tunnel for a short period, and should have even less concern.

It is straightforward to generate plots of formaldehyde concentration as a function of tunnel length (x or L), using the above values and equations for each of the four ventilation cases. A plot generated by Mathcad is shown in Figure E5.18a. The Mathcad file can be downloaded from the book's web site. It is clear from the plot that as the tunnel length increases, natural ventilation (curve a) becomes inadequate. The plot clearly shows why it is necessary to use some type of tunnel ventilation scheme to supply fresh make-up air for long tunnels. There is not much difference between balanced and unbalanced transverse ventilation (curves c and d respectively), and both yield somewhat higher concentrations than does uniform make-up air ventilation with no exhaust. For the values in the above example problem, ventilation scheme (b), i.e. uniform make-up air ventilation with no exhaust appears to be the best scheme for any tunnel length. However, as mentioned above, there is a physical limit to the length of a tunnel with this ventilation scheme. Namely, without forced exhaust, the only place for all of the make-up air to go is out the end of the tunnel; thus U(x) grows linearly with x as given by Eq. (5-74).

It is interesting to also plot U(x) for the four cases, as shown in Figure E5.18b. From this plot, it is clear that the two balanced ventilation schemes (cases a and c - natural ventilation and balanced transverse ventilation) maintain a constant U(x) regardless of tunnel length, but U(x) grows with x for the other two (unbalanced) schemes. Ventilation scheme (b) - uniform make-up air ventilation with no exhaust, has the higher slope, and leads to very large air velocities for long tunnels. (At x = 1500 m for the values used in the above example problem, U = 360 m/min, or 6.0 m/s!) Thus, even though the lowest contaminant concentration inside the tunnel is predicted for the uniform make-up air ventilation scheme with no exhaust, *balanced transverse ventilation* (case c) is the best choice for very long automobile tunnels.

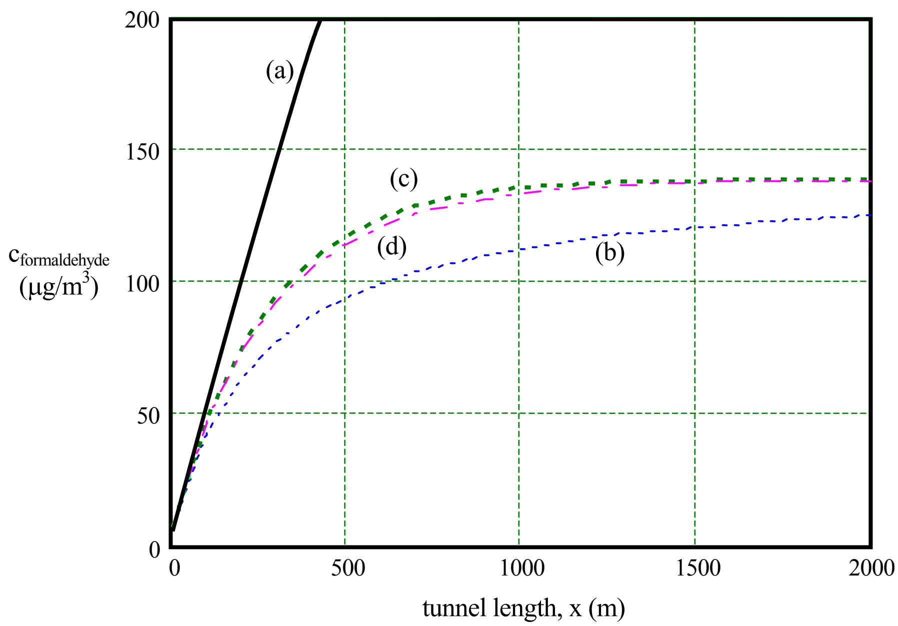

Figure E5.18a Formaldehyde mass concentration versus tunnel length in four types of automobile tunnels: (a) natural, (b) uniform make-up air, (c) balanced transverse, and (d) unbalanced transverse ventilation.

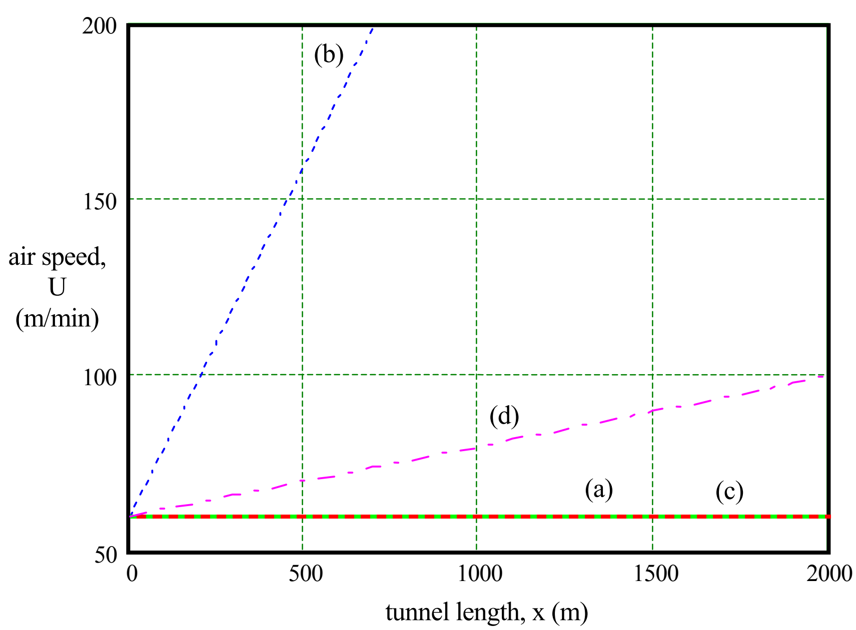

Figure E5.18b Air speed versus tunnel length in four types of automobile tunnels: (a) natural, (b) uniform make-up air, (c) balanced transverse, and (d) unbalanced transverse ventilation.