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AUTOMOBILE PASSENGER COMPARTMENT VENTILATION

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ABSTRACT

A sequential box model (SBM) is proposed that predicts the instantaneous contaminant concentration at arbitrary points in a three-dimensional enclosure when the contaminant generation rate varies with time and location. The method can also accommodate time-varying ventilation flow rates and contaminant concentrations in the makeup air supply. The method is used to predict the passenger breathing zone concentrations of (a) cigarette smoke, when passengers smoke following some describable schedule, and (b) carbon monoxide, when the exhaust from a vehicle is drawn into the air intake of the vehicle behind it. The critical parameter affecting the accuracy of the method is the selection of exchange coefficients that describe the transport of air and contaminants from one box to another.

INTRODUCTION

Automotive ventilation systems heat, air-condition, or circulate fresh air. The driver chooses to use outdoor air or air withdrawn from the compartment. While there are no professional standards or governmental regulations affecting the design of vehicle ventilation systems, guidance can be gained from ASHRAE Standard 62-1989 (ASHRAE 1989), which recommends 15 ft^3/min per person for transportation vehicles in general and 15-25 ft^3/min per person for commercial aircraft (ASHRAE 1991). Of course, merely specifying a volumetric flow rate or the number of compartment air changes per unit time is no guarantee that well-mixed conditions exist or that fresh air is available for each passenger under a variety of conditions in which contaminants enter the compartment or are generated within the compartment.

The purpose of this paper is to describe a method to predict the time-varying contaminant concentrations at arbitrary points inside the passenger compartment of a 1989 four-door, mid-sized sedan for two situations:

(a) different combinations of passengers who smoke cigarettes,

(b) carbon monoxide (CO) entering the automobile's fresh air intake while cars are in a queue.

Ventilation air enters the compartment through four registers in the instrument panel. The volume of air in the compartment containing five passengers is 67.75 ft^3 (1.92 m^3). It is assumed that compartment air leaks through cracks around doors and windows. Recirculated compartment air was withdrawn from registers under the instrument panel.

REVIEW OF THE LITERATURE

Peterson and Sabersky (1975) measured O_3, CO, NO_2, and NO_x inside and outside automobiles driven in Los Angles during the summer months. They concluded that with the windows closed, the ozone concentration would be below the ambient concentration (c_a) because ozone reacts with materials inside the compartment. Using a single well-mixed model, they expressed the ozone concentration as

$$V dc/dt = Qc_a - Qc - c(kA) \qquad (1)$$

where V and A are the compartment volume and surface area, k is a contaminant decay constant they found on average to be equal to 0.17 min^{-1}, and Q is the volumetric flow rate of air seeping into the vehicle. The authors found that (Q/V) was proportional to the vehicle speed, reaching a value of 0.6 min^{-1} at 50 miles/hour

Hayes (1989, 1991) analyzed compartment ventilation using a single-box indoor air quality (IAQ) model and found that the peak indoor/outside ozone concentration ratio was approximately 0.33. Parameters used in the model were not given. Hayes (1991) found that as the vehicle speed increases, the infiltration rate and indoor ozone concentration increase. Keeping the windows closed provides the best protection against outside ozone.

Chan *et al.* (1991) measured the driver's exposure to 24 gasoline-related volatile organic compounds (VOC) and three criteria pollutants (O_3, CO, and NO_2) in four-door sedans under different traffic patterns, vehicle ventilation conditions, and driving periods. The ventilation volumetric flow rate was not reported. No differences in VOC concentrations

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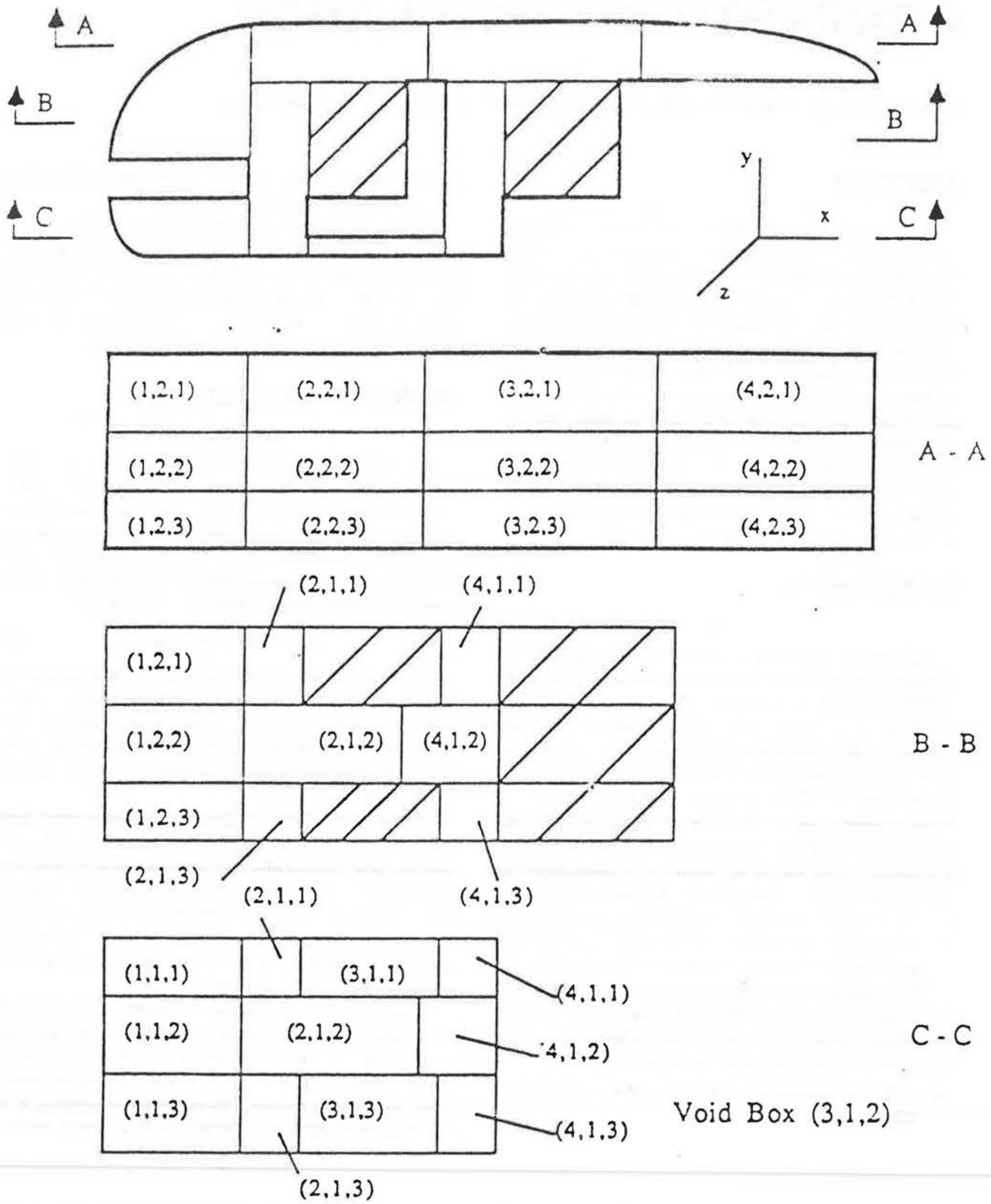


Figure 1 *Box arrangement in vehicle compartment, shaded regions correspond to passengers*

were found between morning and afternoon rush hour driving, but higher O_3 and NO_2 concentrations were found during afternoon driving. Compartment VOC levels were lowest with the air conditioner on and highest when the vent was open with the fan on. Contrary to Hayes (1991), the indoor/outdoor concentration ratio for VOC, CO, and NO_2 was slightly greater than unity.

MATHEMATICAL MODELING

Predicting the velocity and concentration fields inside the compartment can be accomplished by using any one of several commercial computer programs (Lueptow 1988; Jameson 1989) available for purchase or lease that solve the Navier Stokes equations. Not everyone has access to these programs nor the temperament and experience to use them, and fewer yet are inclined to write such a program from scratch. A useful alternative to Navier Stokes solvers is the less accurate but conceptually simple technique called the multicell well-mixed model or sequential box model (SBM) developed years ago to study the movement of air and contaminants in buildings. One- and two-dimensional sequential box models have been described elsewhere (Skaret and Mathisen 1983; Heinsohn 1991, 1993; Skaret 1986; Rock *et al.* 1991; Yamamoto *et al.* 1989; Bruno and Heinsohn 1992; Ryan *et al.* 1988) but the description of a three-dimensional SBM has not received attention. To begin the analysis, the user must know the following:

(1) Dimensions of the passenger compartment, hereafter called the control volume, V(t), The surface of the control volume is called the control surface

(2) Volumetric flow rate of air entering and leaving specific points on the control surface, Q(t), Such volumetric flow rate includes inlet and outlet flow rates through well-defined registers and leakage (infiltration and exfiltration) around doors, windows, etc

(3) The contaminant concentration in the separate airstreams entering the control volume, $c_a(t)$

(4) Locations of contaminant sources (and sinks) within the control volume and emission rate of each source, $S_{i,j,k}(t)$.

The SBM analysis can accommodate time variations in any or all of the parameters above.

The first step in the analysis is to divide the passenger compartment by a series of mutually perpendicular planes that define a set of smaller volumes called boxes. Each box is defined by a set of coordinates (i,j,k). There are 24 boxes in the passenger compartment (Figure 1). The planes can be arranged to define boxes that coincide with seats, passengers, and their breathing zones. It should be emphasized that each box does not have to be the same size and that the SBM method accommodates any number of boxes the user desires. Users need only know the dimensions, location, and volume of each box. Define $k_{i,j,k}$:

$$k_{i,j,k} = V_{i,j,k}/V \qquad (2)$$

where V is the volume of the passenger compartment and $V_{i,j,k}$ is the volume of box (i,j,k).

In order to execute the DO loops in the computer program, the indices i, j, and k must be continuous integers. It may be necessary to accommodate solid interior furnishings and a complicated control surface by using a technique called the void box. A void box is an imaginary box possessing a set of indices but a tiny value of $V_{i,j,k}$.

Consider the volumetric flow rate of air entering and leaving the passenger compartment that passes through boxes sharing a common surface with the control surface, i.e., air registers and infiltration and exfiltration around windows and doors. The following terms are defined to account for air entering and leaving these boxes:

$$x_{i,j,k} = Q(in)_{i,j,k}/Q(in), \qquad (3)$$

$$y_{i,j,k} = Q(out)_{i,j,k}/Q(out), \qquad (4)$$

where Q(in) is the total volumetric flow rate of air into the passenger compartment defined by

$$Q(in) = SUM_i\ SUM_j\ SUM_k\ Q(in)_{i,j,k} \qquad (5)$$

and Q(out) is defined in a similar fashion. It will be assumed that the volume of the passenger compartment is constant and that the temperature and pressure inside the passenger compartment do not change. Thus, the conservation of mass for air requires

$$Q(in) = Q(out) = Q \qquad (6)$$

It must be emphasized that $x_{i,j,k}$ and $y_{i,j,k}$ refer to air flowing into and out of boxes that share a common boundary with the control surface. Thus these parameters are zero for boxes interior to the control surface and for boxes laying on the surface of the control surface through which no air flows.

Lastly, consider the rate of generation of contaminant within the passenger compartment. Define the term $g_{i,j,k}$:

$$g_{i,j,k} = S_{i,j,k}/S \qquad (7)$$

where S is the total contaminant generation rate within the passenger compartment and $S_{i,j,k}$ is the contaminant generation rate within box (i,j,k). Since various passengers smoked at different times, $S_{i,j,k}$ varies with location and time.

It must be emphasized that the parameters $x_{i,j,k}$, $y_{i,j,k}$, $k_{i,j,k}$, and $g_{i,j,k}$ have numerical values defined by the user at the beginning of the analysis. The parameters may vary with time, in which case the user substitutes the appropriate values at each instant of time. Values of $g_{i,j,k}$ can be positive, negative, or zero. Negative values represent contaminant sinks such as adsorption.

An equation for the conservation of contaminant is written for each box (i,j,k):

Table 1
Exchange Coefficients

Box	F	F′	Value
1,1,1	1,1,1,2,1,1		0.380
1,1,1	1,1,1,1,1,2		0.400
1,1,1		1,1,1,1,1,2	0.235
1,1,1		1,1,1,2,1,1	0.400
1,1,2	1,1,2,1,1,1		0.235
1,1,2	1,1,2,2,1,2		1.000
1,1,2	1,1,2,1,1,3		0.235
1,1,2		1,1,2,1,1,1	0.400
1,1,2		1,1,2,2,1,2	0.500
1,1,3	1,1,3,2,1,3		0.380
1,1,3	1,1,3,1,1,2		0.400
1,1,3		1,1,3,1,1,2	0.235
1,1,3		1,1,1,2,1,3	0.400
1,2,1	1,2,1,2,2,1		0.320
1,2,1	1,2,1,1,2,2		0.350
1,2,1	1,2,1,2,1,1		0.300
1,2,1		1,2,1,2,2,1	0.400
1,2,1		1,2,1,1,2,2	0.250
1,2,1		1,2,1,2,1,1	0.300
1,2,2	1,2,2,1,2,1		0.250
1,2,2	1,2,2,2,2,2		0.800
1,2,2	1,2,2,1,2,3		0.250
1,2,2	1,2,2,2,1,2		0.400
1,2,2		1,2,2,1,2,1	0.350
1,2,2		1,2,2,2,2,2	0.400
1,2,2		1,2,2,1,2,3	0.350
1,2,2		1,2,2,2,1,2	0.600
1,2,3	1,2,3,2,2,3		0.320
1,2,3	1,2,3,1,2,2		0.350
1,2,3	1,2,3,2,1,3		0.300
1,2,3		1,2,3,2,2,3	0.400
1,2,3		1,2,3,1,2,2	0.250
1,2,3		1,2,3,2,1,3	0.300
2,1,1	2,1,1,1,1,1		0.400
2,1,1	2,1,1,3,1,1		0.190
2,1,1	2,1,1,2,1,2		1.220
2,1,1	2,1,1,1,2,1		0.300
2,1,1	2,1,1,2,2,1		0.340
2,1,1		2,1,1,1,1,1	0.380
2,1,1		2,1,1,3,1,1	0.820
2,1,1		2,1,1,2,1,2	0.700
2,1,1		2,1,1,1,2,1	0.300
2,1,1		2,1,1,2,2,1	0.450
2,1,2	2,1,2,1,1,2		0.500
2,1,2	2,1,2,2,1,3		0.700
2,1,2	2,1,2,3,1,3		0.700
2,1,2	2,1,2,2,1,1		0.700
2,1,2	2,1,2,3,1,1		0.700
2,1,2	2,1,2,4,1,2		1.220
2,1,2	2,1,2,1,2,2		0.600
2,1,2	2,1,2,2,2,2		0.400
2,1,2		2,1,2,1,1,2	1.000
2,1,2		2,1,2,2,1,3	1.000
2,1,2		2,1,2,3,1,3	0.500
2,1,2		2,1,2,2,1,1	1.220
2,1,2		2,1,2,3,1,1	0.500
2,1,2		2,1,2,4,1,2	0.800
2,1,2		2,1,2,1,2,2	0.400
2,1,2		2,1,2,2,2,2	0.600
2,1,3	2,1,3,1,1,3		0.400
2,1,3	2,1,3,3,1,3		0.190
2,1,3	2,1,3,2,1,2		1.220
2,1,3	2,1,3,1,2,3		0.300
2,1,3	2,1,3,2,2,3		0.340
2,1,3		2,1,3,1,1,3	0.380
2,1,3		2,1,3,3,1,3	0.820
2,1,3		2,1,3,2,1,2	0.700
2,1,3		2,1,3,1,2,3	0.300
2,1,3		2,1,3,2,2,3	0.450
2,2,1	2,2,1,1,2,1		0.400
2,2,1	2,2,1,3,2,1		0.450
2,2,1	2,2,1,2,2,2		0.700
2,2,1	2,2,1,2,1,1		0.450
2,2,1		2,2,1,1,2,1	0.320
2,2,1		2,2,1,3,2,1	0.600
2,2,1		2,2,1,2,2,2	0.700
2,2,1		2,2,1,2,1,1	0.340
2,2,2	2,2,2,1,2,2		0.400
2,2,2	2,2,2,2,2,1		0.700
2,2,2	2,2,2,2,2,3		0.700
2,2,2	2,2,2,2,1,2		0.600
2,2,2	2,2,2,3,2,2		0.600
2,2,2		2,2,2,1,2,2	0.800
2,2,2		2,2,2,2,2,1	0.700
2,2,2		2,2,2,2,2,3	0.700
2,2,2		2,2,2,2,1,2	0.400
2,2,2		2,2,2,3,2,2	0.400
2,2,3	2,2,3,1,2,3		0.400
2,2,3	2,2,3,3,2,3		0.450
2,2,3	2,2,3,2,2,2		0.700
2,2,3	2,2,3,2,1,3		0.450
2,2,3		2,2,3,1,2,3	0.320
2,2,3		2,2,3,3,2,3	0.600
2,2,3		2,2,3,2,2,2	0.700
2,2,3		2,2,3,2,1,3	0.340
3,1,1	3,1,1,2,1,2		0.500
3,1,1	3,1,1,2,1,1		0.820
3,1,1	3,1,1,4,1,1		0.260
3,1,1	3,1,1,4,1,2		0.300
3,1,1		3,1,1,2,1,2	0.700
3,1,1		3,1,1,2,1,1	0.190
3,1,1		3,1,1,4,1,1	0.240
3,1,1		3,1,1,4,1,2	0.600
3,1,2	void box		
3,1,3	3,1,2,1,1,2		0.500
3,1,3	3,1,3,2,1,3		0.820
3,1,3	3,1,3,4,1,3		0.260
3,1,3	3,1,3,4,1,2		0.300
3,1,3		3,1,3,2,1,2	0.700
3,1,3		3,1,3,2,1,3	0.190
3,1,3		3,1,3,4,1,3	0.240
3,1,3		3,1,3,4,1,2	0.600

Table 1
Exchange Coefficients

Box	F	F′	Value
3,2,1	3,2,1,2,2,1		0.600
3,2,1	3,2,1,3,2,2		0.550
3,2,1	3,2,1,4,2,1		0.250
3,2,1	3,2,1,4,1,1		0.240
3,2,1		3,2,1,2,2,1	0.450
3,2,1		3,2,1,3,2,2	0.450
3,2,1		3,2,1,4,2,1	0.300
3,2,1		3,2,1,4,1,1	0.400
3,2,2	3,2,2,3,2,1		0.450
3,2,2	3,2,2,2,2,2		0.400
3,2,2	3,2,2,4,2,2		0.850
3,2,2	3,2,2,3,2,3		0.450
3,2,2	3,2,2,4,1,2		0.400
3,2,2		3,2,2,3,2,1	0.550
3,2,2		3,2,2,2,2,2	0.600
3,2,2		3,2,2,4,2,2	0.450
3,2,2		3,2,2,3,2,3	0.550
3,2,2		3,2,2,4,1,2	0.400
3,2,3	3,2,3,2,2,3		0.600
3,2,3	3,2,3,3,2,2		0.550
3,2,3	3,2,3,4,2,3		0.250
3,2,3	3,2,3,4,1,3		0.240
3,2,3		3,2,3,2,2,3	0.450
3,2,3		3,2,3,3,2,2	0.450
3,2,3		3,2,3,4,2,3	0.300
3,2,3		3,2,3,4,1,3	0.400
4,1,1	4,1,1,3,2,1		0.400
4,1,1	4,1,1,3,1,1		0.240
4,1,1	4,1,1,4,1,2		0.800
4,1,1		4,1,1,3,2,1	0.240
4,1,1		4,1,1,3,1,1	0.260
4,1,1		4,1,1,4,1,2	0.900
4,1,2	4,1,2,4,1,1		0.900
4,1,2	4,1,2,4,1,3		0.600
4,1,2	4,1,2,2,1,2		0.800
4,1,2	4,1,2,3,2,2		0.400
4,1,2	4,1,2,3,1,1		0.600
4,1,2	4,1,2,3,1,3		0.600
4,1,2		4,1,2,4,1,1	0.800
4,1,2		4,1,2,4,1,3	0.800
4,1,2		4,1,2,2,1,2	1.220
4,1,2		4,1,2,3,2,2	0.400
4,1,2		4,1,2,3,1,1	0.300
4,1,2		4,1,2,3,1,3	0.300
4,1,3	4,1,3,3,2,3		0.400
4,1,3	4,1,3,3,1,3		0.240
4,1,3	4,1,3,4,1,2		0.800
4,1,3		4,1,3,3,2,3	0.240
4,1,3		4,1,3,3,1,3	0.260
4,1,3		4,1,3,4,1,2	0.900
4,2,1	4,2,1,3,2,1		0.300
4,2,1	4,2,1,3,2,1		0.500
4,2,1		4,2,1,3,2,1	0.250
4,2,1		4,2,1,4,2,2	0.500
4,2,2	4,2,2,3,2,2		0.450
4,2,2	4,2,2,4,2,1		0.500
4,2,2	4,2,2,4,2,3		0.500
4,2,2		4,2,2,3,2,2	0.850
4,2,2		4,2,2,4,2,1	0.500
4,2,2		4,2,2,4,2,3	0.100
4,2,3	4,2,3,3,2,3		0.300
4,2,3	4,2,3,4,2,2		0.500
4,2,3		4,2,3,3,2,3	0.250
4,2,3		4,2,3,4,2,2	0.500

$$k_{i,j,k} V dc_{i,j,k}/dt = g_{i,j,k} S + c_a x_{i,j,k} Q(1\text{-}f) - c_{i,j,k} y_{i,j,k} Q +$$

$$\mathrm{SUM}_{i-1}{}^{i+1}\ \mathrm{SUM}_{j-1}{}^{j+1}\ \mathrm{SUM}_{k-1}{}^{k+1}\ c_{l,m,n} F_{i,j,k,l,m,n} Q\ -$$

$$\mathrm{SUM}_{i-1}{}^{i+1}\ \mathrm{SUM}_{j-1}{}^{j+1}\ \mathrm{SUM}_{k-1}{}^{k+1}\ c_{i,j,k} F'_{i,j,k,l,m,n} Q\ +$$

$$\mathrm{SUM}_{1-1}{}^{1+1}\ \mathrm{SUM}_{j-1}{}^{j+1}\ \mathrm{SUM}_{k-1}{}^{k+1} d_{i,j,k} y_{i,j,k} c_{i,j,k} (1\text{-}E) fQ \qquad (8)$$

where c_a is the contaminant concentration in the outside air, (fQ) is the volumetric flow rate of recirculated air, (E) is the efficiency of an air cleaner for the recirculated air, and $d_{i,j,k}$ is a parameter that is unity if an air return is located in box (i,j,k) or zero if it is not. The subscripts l,m,n are the subscripts of boxes neighboring box i,j,k. While the six subscripts in Eq 8 seem inordinately complex, they lend themselves to instructions in a computer program.

The dimensionless coefficients $F_{i,j,k,l,m,n}$ and $F'_{i,j,k,l,m,n}$ are called exchange coefficients. For the three-dimensional configuration in Figure 1, there will be up to six values of $F_{i,j,k,l,m,n}$ and up to six values of $F'_{i,j,k,l,m,n}$ for each box. The quantity $F_{i,j,k,l,m,n}Q$ is the volumetric flow rate of air transferred into box (i,j,k) from its neighbor (l,m,n) with which it shares a common face, and $F'_{i,j,k,l,m,n}Q$ is the volumetric flow rate of air flowing from box (i,j,k) into its neighbor (l,m,n). Values of $F_{i,j,k,l,m,n}$ and $F'_{i,j,k,l,m,n}$ that are zero or very small denote adjacent boxes that are virtually isolated from each other. It must be emphasized that while $F_{i,j,k,l,m,n}$ and $F'_{i,j,k,l,m,n}$ are never negative, they can exceed unity. Values of $F_{i,j,k,l,m,n}$ and $F'_{i,j,k,l,m,n}$ much greater than unity denote vigorous air movement.

The exchange coefficients account for the transfer of air between boxes (i,j,k) and (l,m,n). Thus repeated indices are meaningless:

$$F_{i,j,k,l,m,n} = 0, \text{ if } l = i,\ m = j,\ n = k; \qquad (9)$$

$$F'_{i,j,k,l,m,n} = 0, \text{ if } l = i,\ m = j,\ n = k. \qquad (10)$$

Because air flowing into box (l,m,n) from box (i,j,k) is the same as air flowing out of box (i,j,k) into box (l,m,n), the following identity holds:

$$F'_{i,j,k,l,m,n} = F_{l,m,n,i,j,k}. \qquad (11)$$

An equation similar to Equation 8 is written for each box within the passenger compartment. Aside from the concentrations, the exchange coefficients are the only unknowns in Equation 8. The SBM does not compute exchange coefficients and users must input selected values.

The relationship between the exchange coefficients is dictated by the identities, Equations 9-11, and the equations for the conservation of mass for air in each box:

$$x_{i,j,k}Q + \mathrm{SUM}_{i-1}{}^{i+1}\ \mathrm{SUM}_{j-1}{}^{j+1}\ \mathrm{SUM}_{k-1}{}^{K+1}\ F_{i,j,k,l,m,n}\,Q =$$

$$y_{i,j,k}Q + \mathrm{SUM}_{i-1}{}^{i+1}\ \mathrm{SUM}_{j-1}{}^{j+1}\ \mathrm{SUM}_{k-1}{}^{K+1}\ F'_{i,j,k,l,m,n}\,Q. \qquad (12)$$

The crucial parameters in the analysis are the exchange coefficients $F_{i,j,k,l,m,n}$ and $F'_{i,j,k,l,m,n}$. Values are assigned by using one of the following three methods:

1. experimentally measured velocities (using hand-held velocity meters) along surfaces separating boxes,
2. velocities predicted by closed-form analytical solutions to the Navier Stokes equations or numerical techniques from computational fluid dynamics (CFD), or
3. estimates made by the user based on intuition, smoke traverses, or other information.

Irrespective of how values of the exchange coefficients are assigned, the user must be sure that Equation 12 is satisfied for each box. Users cannot assign values in an arbitrary fashion. It is unusual that detailed experiments can be conducted to measure velocities on all planes separating all the boxes, although several velocity measurements may be made at selected points in the passenger compartment. It is assumed that a steady-state velocity field exists within the passenger compartment even though the concentration field and contaminant source generation rates change with time.

If CFD techniques are used to compute all the exchange coefficients, CFD techniques can also compute time-varying concentrations and the SBM will not be necessary. Most likely, users will have to select exchange coefficients based on smoke tests or limited experiments and beliefs of what the velocity field is like, taking into account possible recirculation eddies, dead-air spaces, and inlets, and outlets. To obtain an understanding of the sensitivity of selecting exchange coefficients, users should choose several scenarios using values of exchange coefficients above and below values they believe to be correct.

If the velocity (v) has been measured at several points on the surfaces separating box (i,j,k) from box (l,m,n), the exchange coefficient $F_{i,j,k,l,m,n}$ can be estimated from

$$F_{i,j,k,l,m,n} = \int_{A_{out}} V\,dA/Q \qquad (13)$$

where A_{out} is that portion of the area separating box (i,j,k) from box (l,m,n) where measurements show that the flow leaves the box (i,j,k). In a similar fashion, the exchange coefficient $F'_{i,j,k,l,m,n}$ is

$$F'_{i,j,k,l,m,n} = \int_{A_{in}} V\,dA/Q \qquad (14)$$

where A_{in} is that portion of the area separating box (i,j,k) from box (l,m,n) where measurements show that the flow enters box (i,j,k).

Table 2
Infiltration and exfiltration coefficients

Box	x	y	Description
1,1,1		0.145	withdrawal of compartment air
1,1,2		0.170	withdrawal of compartment air
1,1,3		0.145	withdrawal of compartment air
1,2,1		0.020	door and window leakage
1,2,3		0.020	door and window leakage
2,1,1	0.250	0.050	fresh air inlet & door and window leakage
2,1,2	0.500		fresh air inlet
2,1,3	0.250	0.050	fresh air inlet & door and window leakage
2,2,3		0.040	door and window leakage
3,1,1		0.050	door and window leakage
3,1,3		0.050	door and window leakage
3,2,1		0.040	door and window leakage
3,2,3		0.040	door and window leakage
4,1,1		0.020	door and window leakage
4,1,3		0.020	door and window leakage
4,2,1		0.050	door and window leakage
4,2,3		0.050	door and window leakage

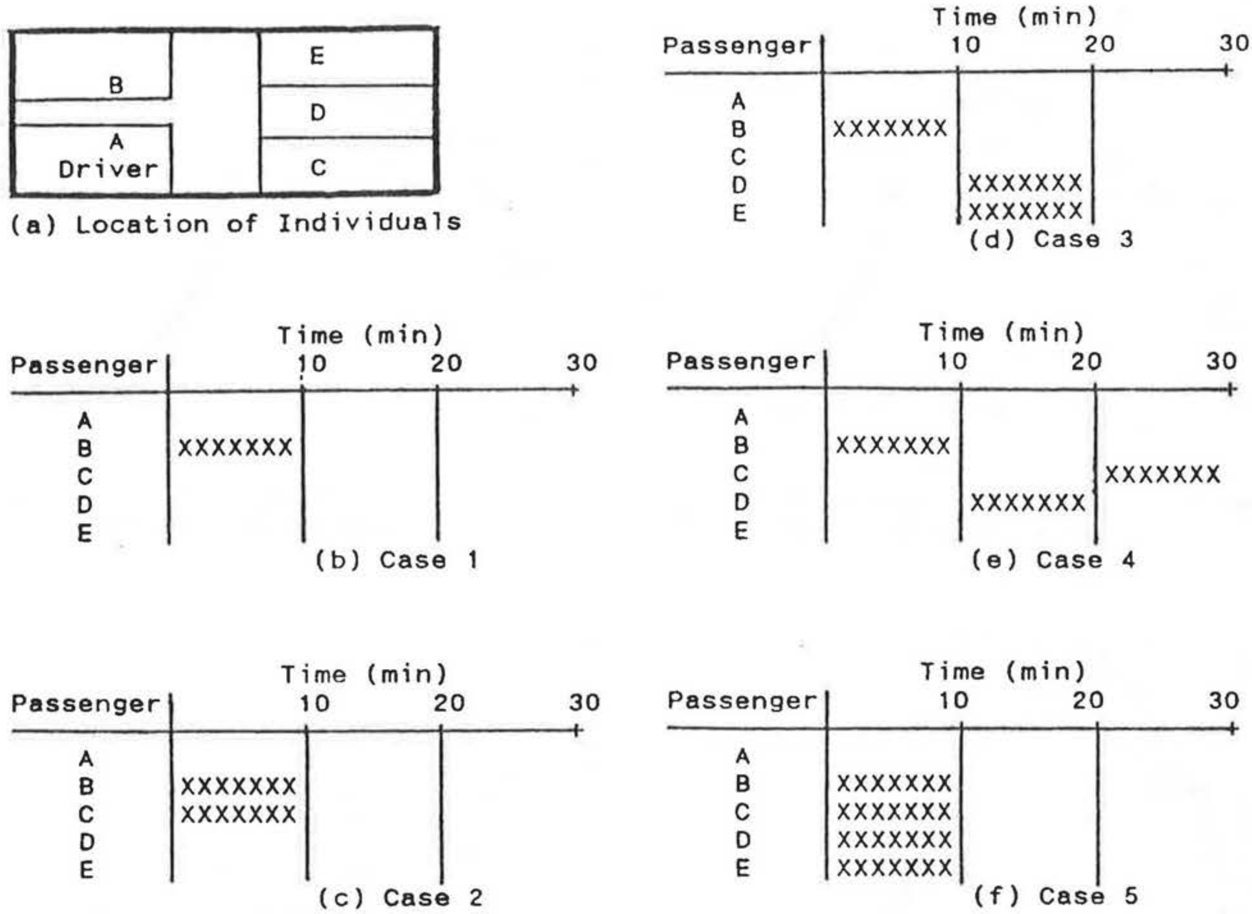
The exchange coefficients selected in this paper are shown in Table 1. The exfiltration coefficients were evaluated from ASHRAE relationships (ASHRAE 1981) and are shown in Table 2. The ratio of the volumetric flow rate of air seeping through openings around windows and doors (0.54Q) divided by the compartment volume (V) is equal to 0.58 min^{-1}, which is in good agreement with values reported by Peterson and Sabersky (1975). Fresh air (0.54Q) enters boxes (211), (212), and (213) and compartment air is removed for recirculation (0.46Q) through boxes (111), (112), and (113).

CONTAMINANT CONCENTRATION

The time-varying concentration in the breathing zones of each passenger was predicted for a ventilation volumetric flow rate (Q) equal to 63.57 ACFM, f = 0.46, and E = 0.85. It was also assumed that

(1) cigarette smoke was generated following the schedules in Figure 2, that each cigarette generated particles at a steady rate of 3 mg/min for 10 minutes (Committee on Indoor Air Pollution 1981), and that $c_a = 0$, and

(2) the car was stuck in a traffic jam and the exhaust of the vehicle ahead added CO to the intake air such that c_a = 250 parts per million (285.7 mg/m^3).



(a) Location of Individuals

(b) Case 1

(c) Case 2

(d) Case 3

(e) Case 4

(f) Case 5

Figure 2 *Passenger smoking schedules*

For the 24 boxes in Figure 1, there were 24 coupled, ordinary differential equations. If the number of differential equations was smaller, Laplace transforms could be used (Rock *et al.* 1991; Yamamoto *et al.* 1989). If, however, the number is large or if the generation term $S_{i,j,k}$ or the volumetric flow rate or the ambient concentration c_a vary with time, Laplace transforms are of limited value and finite-difference techniques should be used. The equations were solved by a fourth-order Runge-Kutta technique that is a time-marching procedure in which the concentration in every box is computed after a time step (0.5 seconds).

Figures 3-7 show the smoke concentration in each passenger's breathing zone for each smoking sequence. Figure 8 shows the volume-weighted average smoke concentration in the compartment as a function of time. Figure 9 shows the carbon monoxide concentration in each passenger's breathing zone as a function of time.

Figures 3-9 show that steady-state conditions are reached approximately five minutes after the first person begins smoking. Figure 3 shows that smoker (B) receives the highest dose followed by passenger (E) directly to the rear of (B). Due to the strong air velocities of fresh air in the front seats, the driver receives the least dose. Figure 4 shows that smoker (B) receives a lower dose than smoker (C) since the transport of smoke to the rear is stronger than from the rear to the front. Figure 5 shows that as soon as smoker (B) stops smoking the concentration drops rapidly but rises shortly after due to the smoke transported from smoking passengers (D) and (E) in the rear seat forward to the front seat. Nonetheless, smokers (D) and (E) receive the largest dose. Figure 6 is not the anomaly it might first appear to be. During the first 10 minutes, smoking passenger (B) receives the largest dose and passenger (E) receives a lesser amount. From 10 to 20 minutes, smoker (E) receives an instantaneous dose in addition to the residual concentration from the previous 10 minutes with the result that the concentration rises very rapidly to a new steady-state value. The pattern is repeated for passenger (C), who smokes during 20 to 30 minutes. Throughout the entire period of 10 to 30 minutes, all the remaining nonsmoking passengers experience the same concentration. Figure 7 repeats the pattern seen in Figure 4, except the concentrations are nearly twice as large since there are now four rather than two smokers. Figure 9 shows a volume-weighted average concentration for the five smoking schedules.

Figure 9 shows that the CO concentrations approach their steady-state values in approximately 10 minutes. Considering the toxicity of CO, one would can expect to experience drowsiness and headache associated with the early stages of CO poisoning if one were stuck in a traffic queue for an hour.

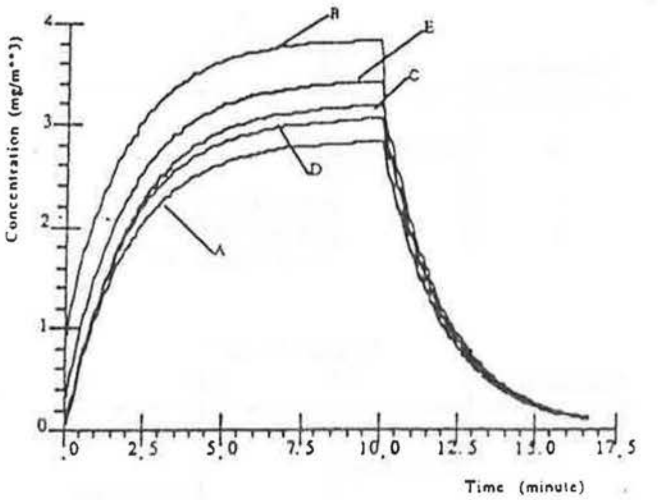


Figure 3 *Case 1, smoke concentration in passenger breathing zones versus time*

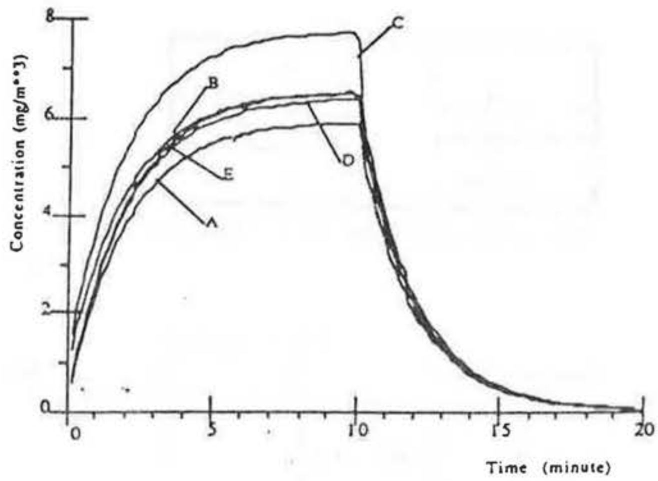


Figure 4 *Case 2, smoke concentration in passenger breathing zones versus time*

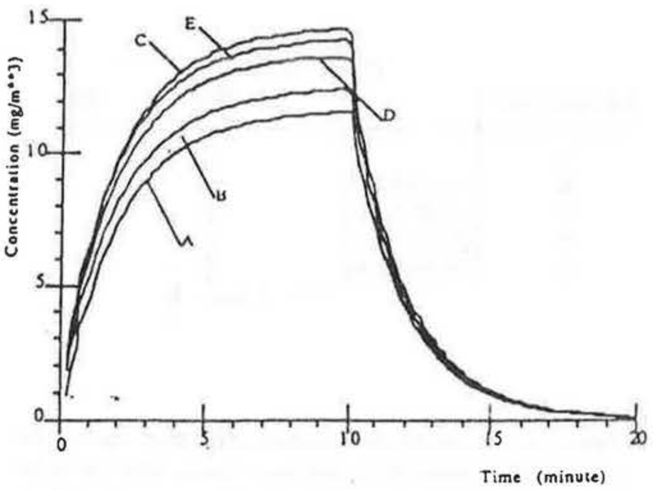


Figure 7 *Case 5, smoke concentration in passenger breathing zones versus time*

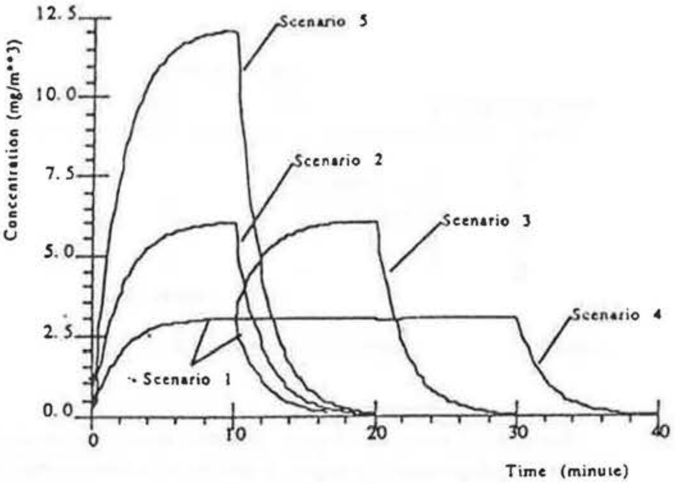


Figure 8 *Average smoke concentration in compartment versus time for 5 smoking schedules*

Opening the windows and improving the chance of receiving fresh air would certainly be a wise precaution.

VELOCITY FIELD

The velocity field in the vehicle compartment was predicted using a commercial Navier Stokes solver (Creare 1987). Exfiltration was neglected and the ventilation fan run at two settings, "low" (71.87 ft³/min, 2.04 m³/min) and "high" (268.75 ft³/min, 7.62 m³/min). Air entered the compartment through the four inlets at either 199.8 ft/min (61.2 m/min), "low" or 600.0 ft/min (183.0 m/min), "high." The computer program was limited to two dimensions, and the passenger compartment was assumed to be symmetrical about a vertical midplane. The program computed the air velocity at 9,408 nodes in the half-section of the compartment and displayed the output as velocity vectors on horizontal or vertical planes selected by the user. Figures 10-12 show predicted velocities for a low fan setting (71.87 ft³/min) on three vertical planes:

- Figure 10—plane between the driver and door,
- Figure 11—plane bisecting the driver,
- Figure 12—midplane through the compartment.

An identical flow field consisting of higher velocities was computed for a "high" fan setting (268.75 ft³/min).

Figure 10 shows that air leaving the fresh air register passes between the driver and door, creating an upward, low-velocity streaming flow in the rear seat that ultimately convects air forward along the roof. Figure 11 shows that an upward eddy exists directly in front of the driver, while a larger but lower velocity eddy exists in front of the passenger in the rear seat. Figure 12 shows that fresh air leaving the dashboard register travels directly between the seats to the rear, where it induces an upward eddy that forces air to join

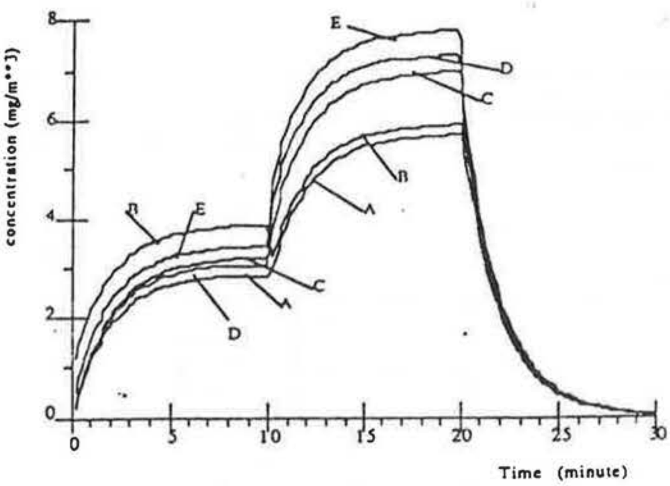


Figure 5 *Case 3, smoke concentration in passenger breathing zones versus time*

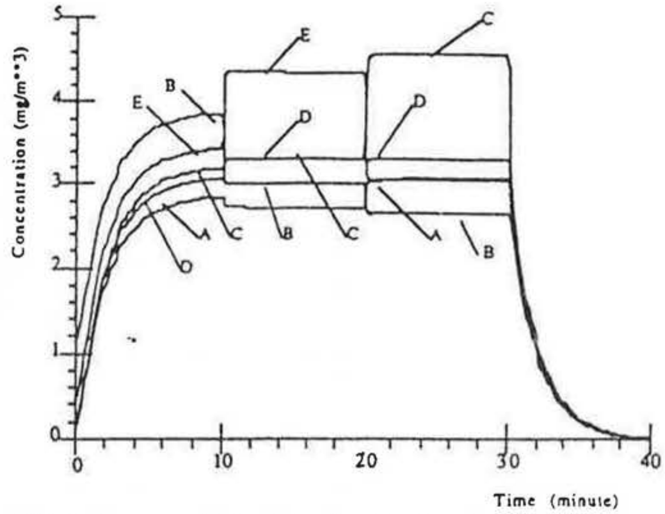


Figure 6 *Case 4, smoke concentration in passenger breathing zones versus time*

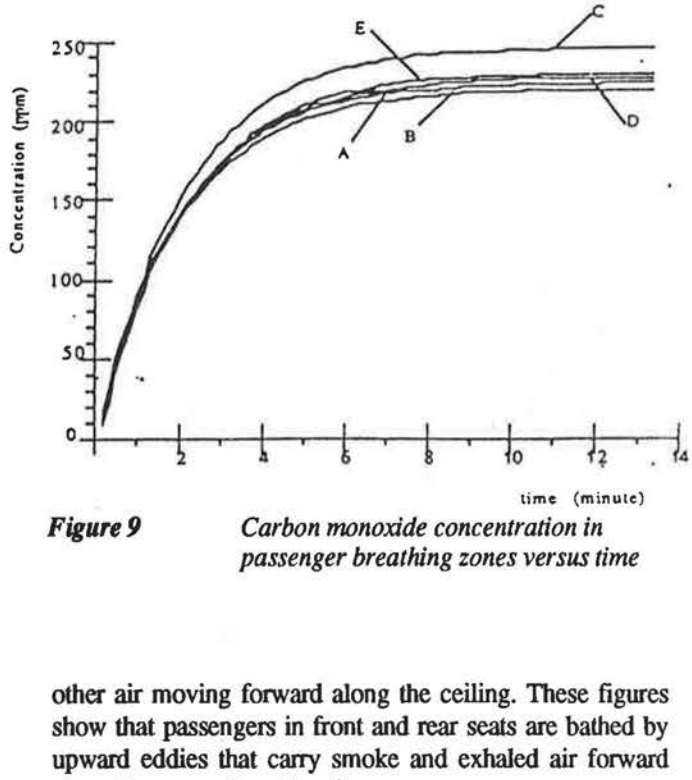


Figure 9 *Carbon monoxide concentration in passenger breathing zones versus time*

other air moving forward along the ceiling. These figures show that passengers in front and rear seats are bathed by upward eddies that carry smoke and exhaled air forward along the compartment roof.

Table 3 is a comparison of the assigned exchange coefficients and those computed from Equations 13, and 14 using the predicted velocity field on the common face separating two pair of selected boxes.

DISCUSSION

When fully occupied, the ventilation volumetric flow rates are 14.4 ft^3/min per person and 53.8 ft^3/min per person and within ASHRAE (1989, 1999) guidelines. In terms of air changes, these values correspond to 1.1 and 4.0 air changes per minute. With such ventilation, one might assume that one could always use a single, well-mixed box model to predict c(x,y,z,t). The results of this analysis suggest that this should only be done for certain types of contaminant generation. The reason is obvious when one reviews the velocity profiles, Figures 10-12. The pronounced recirculation eddies in front of the passengers and dead air space adjacent to the registers withdrawing compartment air for recirculation lead one to conclude the air is not thoroughly mixed within the occupied compartment. It is important to know when the compartment can be modeled as a single, well-mixed box and when it cannot. When cigarette smoke is generated in various boxes at specific times and transported to other locations, it is wise not to model the compartment as a single, well-mixed box, whereas when CO is injected steadily in the intake air, the single, well-mixed model is adequate.

Smoking Passengers

A review of data generated by the SBM shows that at any instant, the concentrations were not uniform within the compartment and that the lowest values are in boxes (111), (112), and (113), where compartment air is withdrawn for recirculation. If the entire compartment is assumed to be a single, well-mixed region, the steady-state smoke concentrations (c_{ss}) can be found by setting the left-hand side of Equation 8 equal to zero:

$$c_{ss} = (S/Q)/[1 - f(1-E)]. \tag{15}$$

The results are shown in Table 4. The value of c_{ss} in Figures 3,4,and 7 are higher than steady-state c_{ss} in Table 4 because the smoke concentration in the recirculated air is less than it is for the single, well-mixed box model; thus a larger amount accumulates than is predicted by the single well-mixed box model. The same arguments pertain to Cases 3 and 4 but because smoking is staggered, the comparison is more difficult to make.

Carbon Monoxide in the Makeup Air

The compartment behaves more like a single, well-mixed box model when CO enters the air intake. Since the source of

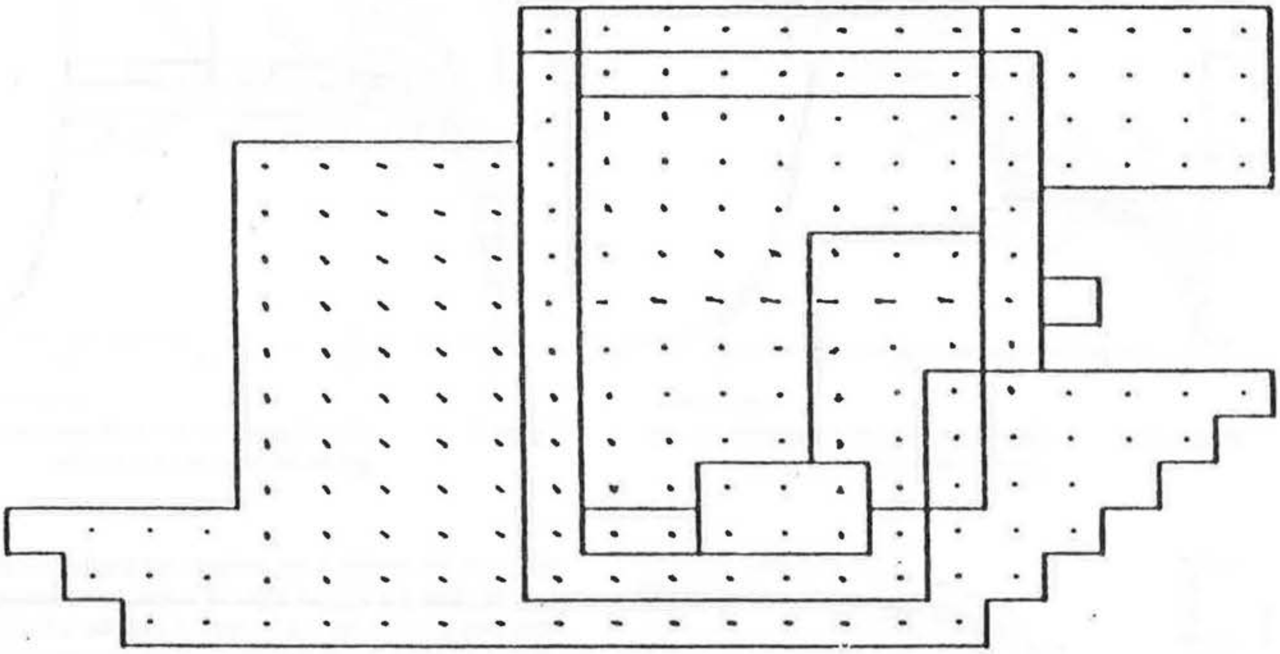


Figure 10 *Velocity profile in vertical plane between driver and door, "low" setting, Q = 71.87 ACFM, maximum velocity vector = 120.0 FPM (36.6 m/min)*

contaminant enters the compartment uniformly, internal mixing mechanisms distribute it quickly and rather uniformly. Within approximately two minutes, the concentration has risen to values similar to what would be predicted if the entire compartment was assumed to be a single, well-mixed box model.

Estimated and Computed Exchange Coefficients

The four exchange coefficients chosen for comparison are those related to the passenger breathing zones. The disparity in value is such that a completely new set of coefficients should be selected. Since the velocity field was computed at a later date than the SBM studies, this was not possible. It is clear that mixing in the compartment is not as vigorous as anticipated when the values in Table 1 were selected. Reviewing the velocity field (Figures 10-12) will enable users to select wiser exchange coefficients. The computer program that generated the velocity field (Figures 10-12) can be used to compute a full set of exchange coefficients in Table 1. The influence of the reduced exchange coefficients is easy to forecast. Since small values of the exchange coefficients signify a small exchange of material between boxes, users can expect that steady state will be achieved more slowly and that concentrations within the breathing zones will be more disparate.

CONCLUSIONS

The SBM is a conceptually easy and mathematically straightforward method to estimate the time-varying concentration at arbitrary points in a ventilated enclosure such as an automobile compartment. This paper is an attempt to expand existing SBMs to a three-dimensional array of boxes of arbitrary shape. It is believed that the results are more accurate than what can be obtained from assuming a single, well-mixed box model. The critical step in the SBM is selecting a set of exchange coefficients to reflect the actual transport of air. Users can select values most intelligently by using hand-held velocity meters to measure velocities on the surfaces separating the boxes. Greater accuracy can be obtained by computing the exchange coefficients using Navier Stokes solvers.

The method is particularly useful when any or all of the following input parameters vary with time and/or location: contaminant generation rate $S(x,y,z,t)$, volumetric flow rate $Q(x,y,z,t)$, and inlet contaminant concentration $c_a(x,y,z,t)$. Under these circumstances, the single, well-mixed box model is of no value. A Runge Kutta method is recommended as the way to solve the set of coupled, ordinary differential equations, since Laplace transform techniques can only cope with analytical expressions for the S, Q, and c_a terms.

For vehicle compartments, the analysis shows that the interior is not well mixed, since recirculation eddies exist in passenger breathing zones and a dead air space exists in the region where air is withdrawn for recirculation. As a consequence, the concentration of cigarette smoke shows variations not revealed by the single well-mixed box model.

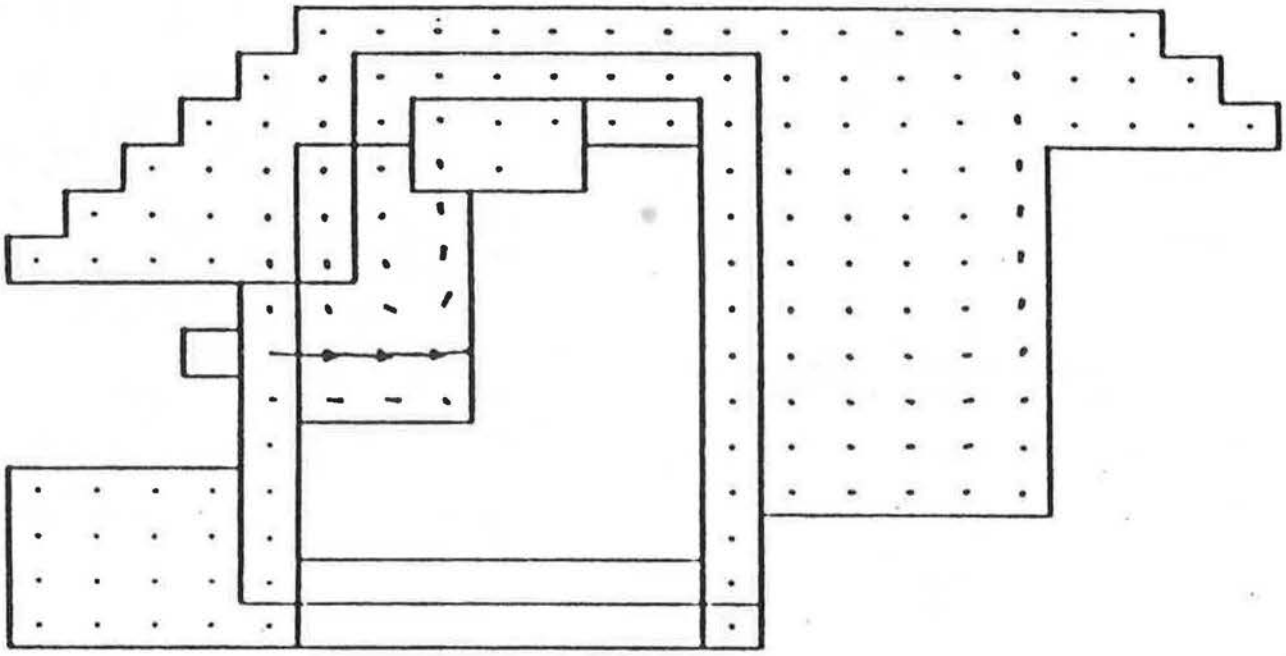


Figure 11 *Velocity profile passing through driver, "low" setting, Q = 71.87 ACFM, maximum velocity vector = 359.7 FPM (110.0 m/min)*

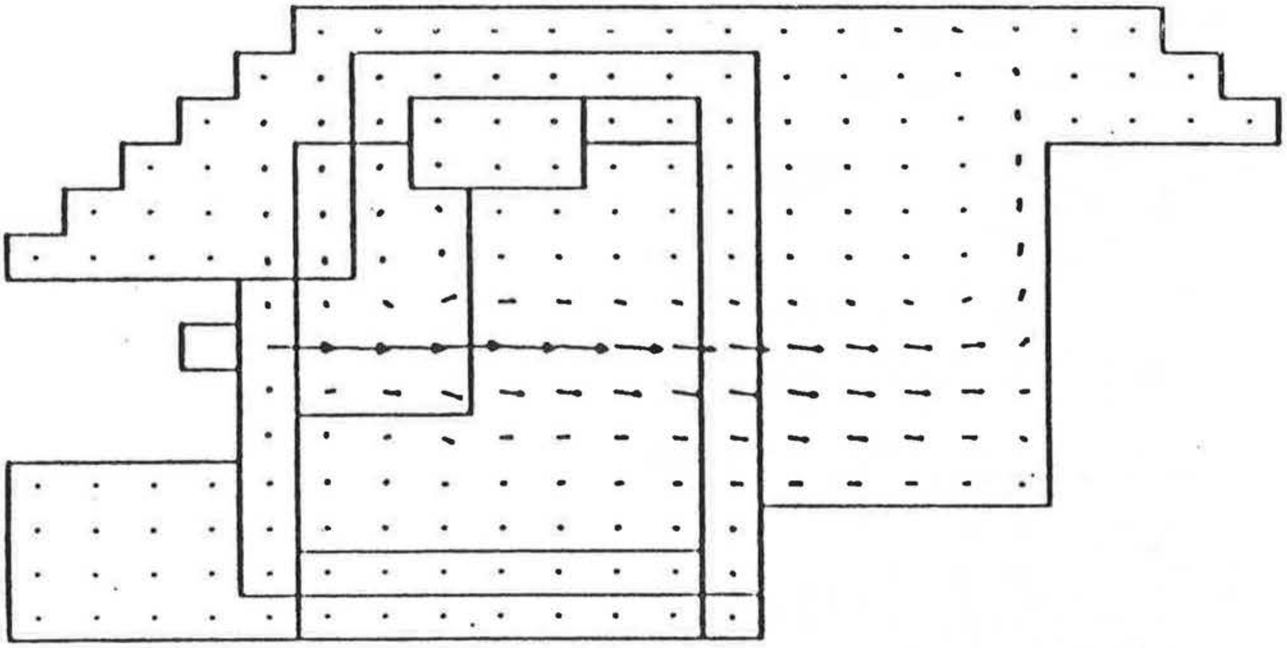


Figure 12 *Velocity profile in plane passing between driver and passenger (B), "low" setting, Q = 71.87 ACFM maximum velocity vector = 360.4 FPM (109.9 m/min)*

While the SBM has some compelling features, it also has its drawbacks. Users need refined physical intuition to select exchange coefficients. In addition, users need skill to write the SBM computer code. An alternative to SBM are numerous CFD programs available commercially in the US, Europe and Asia. These programs are more accurate but nonetheless require computer skills and physical intuition no less proficient than for multi-box methods.

Table 3
Assigned and computed exchange coefficients

Boxes	Exchange Coef.	Assigned	Computed
212 & 122	F_{212122}	0.6	0.278
212 & 122	F'_{212122}	0.4	0.009
222 & 322	F_{22322}	0.6	0.240
222 & 322	F'_{22322}	0.4	0

Table 4
Steady-state concentrations, assuming a single well-mixed box model, Q = 63.57 ACFM

Case Number	Time (min)	c_{ss} (mg/m^3)
1	$0 << t < 10$	.78
2	$0 << t < 10$	3.58
3	$10 << t < 20$	3.58
4	$20 << t < 30$	1.78
5	$0 << t < 1$	7.12

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