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Summary This paper examines three different ventilation strategies aimed at reducing the indoor concentration of traffic pollutants by ventilation control. In the strategies the air change rate is adjusted in response to (*a*) the outdoor concentration of the pollutant (single-sensor strategy), (*b*) the outdoor and indoor concentration (double-sensor strategy) and (*c*) the time of the day (peak-period strategy). A double sensor was found to be twice as effective as the single sensor, reducing the mean indoor concentration of carbon monoxide by 34% over a 48-hour period. Reducing the ventilation rate during peak traffic periods gave only small benefits.

Ventilation control: Effect on indoor concentrations of traffic pollutants

N E Green MEng, **S B Riffat** MSc DPhil DSc CEng MIMechE MCIBSE MInstE and **D W Etheridge** PhD CEng
Institute of Building Technology, The School of the Built Environment, The University of Nottingham, Nottingham NG7 2RD, UK

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List of symbols

S_s Internal source strength (cm^{-3}s^{-1})
S_k Internal sink strength (cm^{-3}s^{-1})
Q Airflow rate (m^{3}s^{-1})
V Volume (m^3)
Δt Timestep (s)
t Time (s)
C_o Outdoor concentration (ppm)
C_i Indoor concentration (ppm)
C_i^n Indoor concentration at current timestep (ppm)
C_i^{n+1} Indoor concentration at next timestep (ppm)
C_s Supply air concentration (ppm)
C_E Exhaust air concentration (ppm)
(ppm: Volumetric parts per million)

1 Introduction

Occupants of buildings situated next to busy roads in the urban environment are exposed to a range of pollutants emitted by motor vehicles, such as oxides of nitrogen, volatile organic compounds and carbon monoxide. 89% of all the carbon monoxide (CO) in the urban air is due to the motor vehicle(1). The concentration of CO in the atmosphere has been shown to be good indicator of the concentrations of other traffic-related contaminants(2).

Ventilation of a building accommodates an exchange between outdoor and indoor air so that internally generated contaminants may be diluted with fresh air(3). However, in cases where the outdoor air is polluted, ventilation of a building may lead to unacceptable levels of externally generated pollutants(4). During the day the traffic density on a road is variable. This variability leads to peaks in the level of traffic pollution, and hence there is an opportunity to reduce internal pollution peaks through control of ventilation rates.

This paper examines the effectiveness of different theoretical control measures aimed at reducing the indoor concentration of an outdoor air pollutant, namely carbon monoxide (CO). These methods involve either changing the ventilation rate as a response to external and internal CO levels or changing the ventilation rate over a fixed period when external concentrations are normally high, such as during rush hours(5).

Kraenzmer(6) showed that reducing the flow of outdoor air into the building when contaminant concentrations were high resulted in a lower average indoor concentration of the contaminant. The results from this study are compared with those obtained by Kraenzmer and the differences discussed.

2 Study area

External CO concentrations used in the investigation were obtained in a previous study over a two-week period, inside and outside a naturally ventilated building situated close to a busy urban road (A52) in Nottingham(7). Elevated CO levels were recorded at the building façade due to the heavy traffic flows. These levels were judged to be reasonably representative of those expected around buildings in comparable urban areas. Figures supplied by Nottingham City Council indicate that the daily traffic flow is on average 50 000 vehicles. On average 5000 vehicles per hour use the road during peak periods.

In the field study four sampling points were selected, but for the purpose of this paper only the data from two are of interest: an outdoor concentration measured at a ground-floor window on the roadside façade, and an indoor concentration, measured in a ground-floor room facing the road. There were no other sources of CO in the building and for the purpose of this study any sink effects have been ignored. The position of the study building with respect to the A52 is illustrated in Figure 1.

Samples of air were taken simultaneously from the locations at 15 minute intervals. A simple logging program driven by a personal computer (PC) controlled the operation of a small pump which drew air from the sampling location via plastic tubing to a gas analyser (Crowcon RGD90 Toxic Gas Detector). This had previously been calibrated using a standard gas (subsequent calibrations indicated a drift of (±5%). The gas concentration in the sampled air was recorded in terms of a voltage by a multimeter. This was read and converted to ppm by the PC. Data were then downloaded for analysis. The whole sample–measure–record cycle is illustrated in Figure 2.

Figure 3 presents a 48-hour section from the recorded data and shows that the outdoor and indoor concentrations show similar variation according to periods of peak traffic flow. There is often a time lag between the external and internal peaks. This is presumably a result of the buffering effect of the room volume. The average measured outdoor and indoor concentrations over the 48 hours are 4.25 and 4.09 ppm respectively.

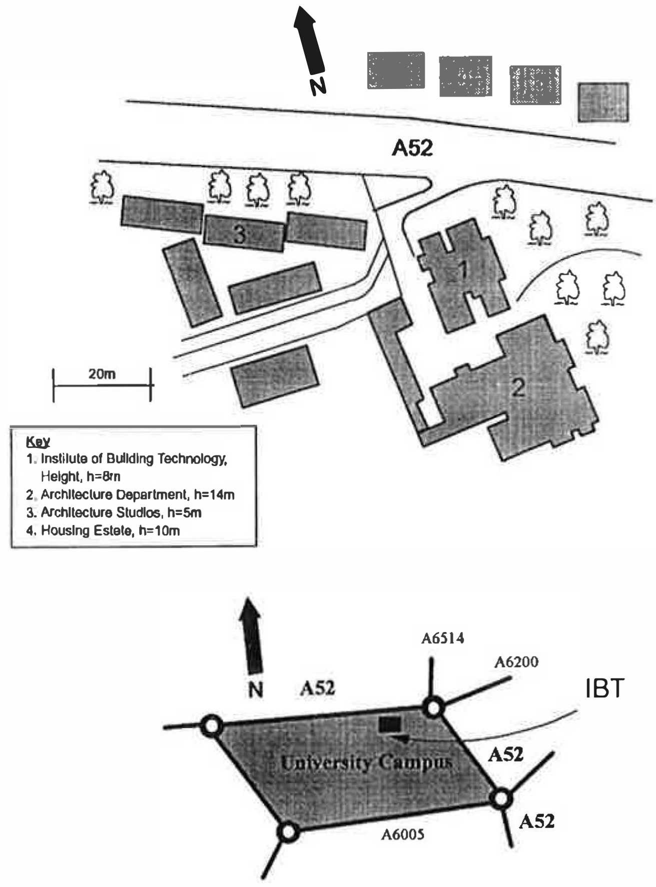

Figure 1 Location of study building with respect to main road (A52)

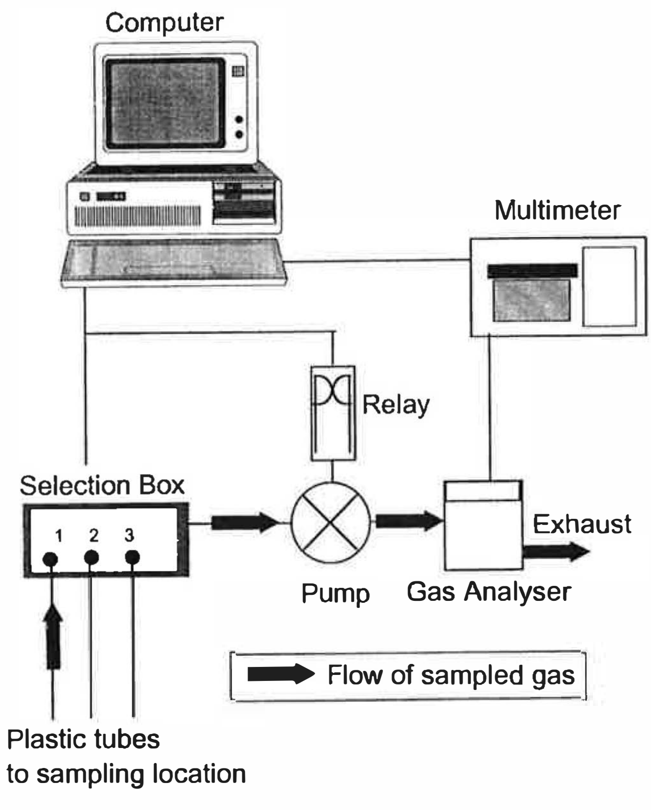

Figure 2 Equipment used in sample–measure–record cycle

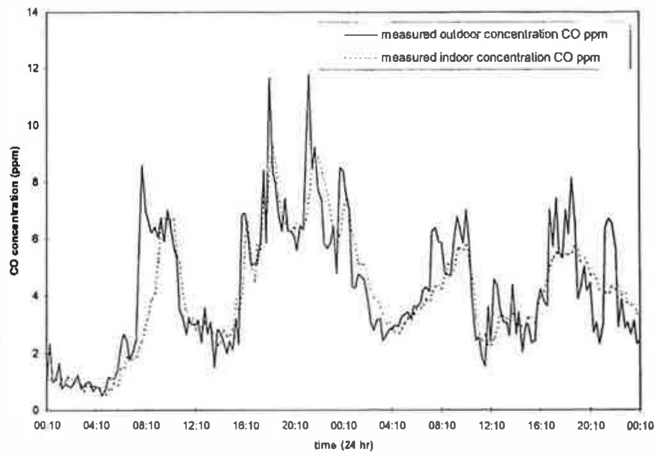

Figure 3 CO concentrations measured indoors and outdoors during a 48-hour period of the field study

3 Calculation of indoor concentration

The indoor concentration of a pollutant can be calculated if the outdoor concentration and air change rate, or time constant, of the building are known[8]. Thus if we assume that the air in the room is well mixed and that all the air entering the space has the same pollutant concentration, the conservation equation for the pollutant in the room gives

$$QC_o + S_r = QC_i + S_k + V\mathrm{d}C_i/\mathrm{d}t \quad (1)$$

where, in general, all quantities except V are functions of time. When the outdoor concentration, airflow, source strength and sink strength are all constant, an analytical solution to equation 1 can be obtained as

$$C_i(t) = C_o + (S_r - S_k/Q) + [C_i(0) - (S_r - S_k)/Q - C_o]\exp(-Qt/V) \quad (2)$$

where $C_i(0)$ denotes the internal concentration at time $t = 0$. When the outdoor concentration and other parameters are not constant, a numerical solution to equation 2 is appropriate. Equation 3 is a finite-difference form of equation 1 and allows for a variation of the parameters provided the time-step Δt is sufficiently small to ensure stability:

$$C_i^{n+1} = [S_r - S_k + Q(C_0^{\,n} - C_i^{\,n})]\Delta t/V + C_i^{\,n} \quad (3)$$

4 Verification of modelling strategy

Air change rates and external pollutant concentrations were input into the simple mathematical model to obtain an indoor concentration of CO. Using equation 3 with source and sink strengths set to zero, measured outdoor CO concentrations as inputs for C_o, and Δt set as 0.25 hours, the indoor concentration of CO ($C_i^{\,n}$) was calculated for different air change rates in the building. The initial value of C_i was set to the actual measured indoor concentration at the first timestep. Table 1 shows the linear correlation r^2 between the modelled internal CO concentration and the actual concentration recorded in the building during the field study for a range of constant air change rates. There is a good degree of correlation between the field and model results for an air change rate of 1 ac h^{-1}. In this case the average modelled indoor concentration over the study period was 4.260 ppm. Figure 4 compares the measured and calculated indoor concentrations for an air change rate of 1 ac h^{-1}, and it can be seen that the modelled concentration follows closely the measured concentration. Results from subsequent models were then

Table 1 Effect of different air change rates on modelled average indoor concentration and linear regression coefficient (r^2) between measured and modelled indoor concentrations with a constant timestep Δt = 0.25 h

Air change rate (h^{-1})	Average internal CO concentration (ppm)	Correlation coefficent r^2
0.1	3.60	0.317
0.5	4.16	0.763
0.9	4.22	0.864
1.0	4.22	0.872
1.5	4.24	0.880
2	4.25	0.870
4	4.26	0.780

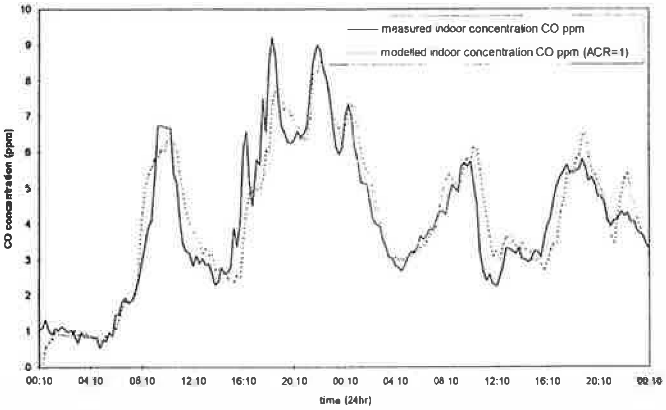

Figure 4 Indoor concentrations of CO: Measured and calculated values. The calculated value uses an air change rate of 1 ac h^{-1} and timestep Δt = 0.25 h.

compared to the indoor concentrations obtained using an air change rate of 1 ac h^{-1}.

The chosen timestep Δt = 0.25 hours was consistent with the interval between successive measurements during the field study. Table 2 shows that there is little effect on the correlation between the modelled and measured concentrations if a timestep is selected within the range of 0.1–0.5 h.

5 Varying air change rate to reduce indoor concentrations

Using equation 3, three different airflow rate control strategies were tested and their effectiveness in reducing indoor concentrations determined. The three strategies were:

(*a*) *Single-sensor strategy*
The air change rate was reduced from (i) 1 ac h^{-1} to 0.1 ac h^{-1} and (ii) 1 ac h^{-1} to 0.5 ac h^{-1} when the external CO level exceeded a specified limit.

Table 2 Effect of timestep Δt on linear regression coefficient r^2 between measured and modelled indoor concentration with constant air change rate 1 ac h^{-1}

Δt (h)	Average internal CO concentration (ppm)	Correlation coefficient r^2
0.05	3.950	0.514
0.10	4.125	0.713
0.20	4.210	0.851
0.25	4.220	0.872
0.30	4.233	0.883
0.40	4.244	0.882
0.50	4.250	0.870
1.0	4.260	0.780

(*b*) *Double-sensor strategy*
The air change rate was reduced from (i) 1 ac h^{-1} to 0.1 ac h^{-1} and (ii) 1 ac h^{-1} to 0.5 ac h^{-1} depending on the concentration outdoors and indoors.

(*c*) *Peak period strategy*
The air change rate was reduced from 1 ac h^{-1} to 0.1 ac h^{-1} during periods of peak traffic flow.

5.1 *Single-sensor strategy*

This strategy changes the air change rate in response to the outdoor CO level. When the outdoor concentration exceeds a specified limit the air change rate is reduced from 1 to 0.1 ac h^{-1}. Figure 5 shows the calculated indoor concentrations when the outdoor CO limit is set at 5 and 1 ppm, and for a constant air change rate of 1 ac h^{-1}. Table 3 shows the average CO concentration over the 48 hour period for the different limits. It is seen from the table that increasing the limit at which the lower air change rate was initiated resulted in a trend towards lower average indoor concentrations.

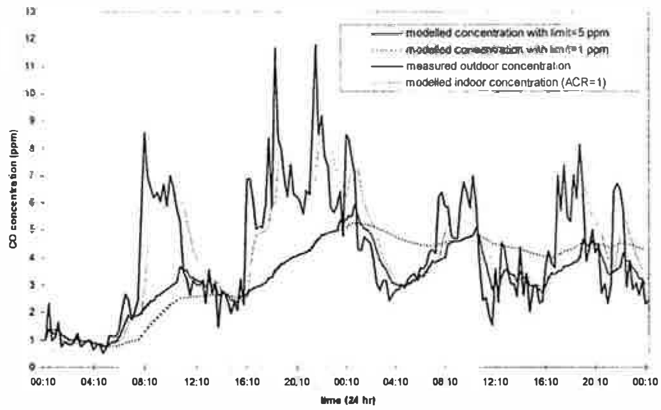

Figure 5 Single-sensor model: Changing the air change rate in response to the external CO concentrations (limits). Results are compared with the concentration obtained using a constant air change rate of 1 ac h^{-1}.

Table 3 Average indoor CO concentrations calculated using the singe-sensor model. The decrease in CO concentration refers to the average concentration compared with that calculated using a constant air change rate of 1 ac h^{-1}. Values in brackets refer to Kraenzmer's model.

Limit CO concentration (ppm)	Average internal CO concentration (ppm)		Decrease in average internal CO concentration (%)	
	Air change rate (ac h^{-1})		Air change rate (ac h^{-1})	
	1–0.1	1–0.5	1–0.1	1–0.5
1	3.55 (1.04)	4.16	16 (38)	6
1.5	3.60 (1.12)	4.16	14 (34)	2
2	3.48 (1.17)	4.13	17 (31)	2
2.5	3.39 (1.22)	4.10	19 (28)	3
3	3.20 (1.24)	4.04	24 (27)	5
4	3.21	3.97	24	6
5	3.29	3.95	22	1

5.2 *Double-sensor strategy*

The rapidly fluctuating nature of the external pollutant concentration can result in situations where the indoor concentration is greater than that outdoors, even when the level outdoors exceeds the limiting value. In this situation there is no advantage in reducing air change rates (as in §5.1) since this merely increases the time for indoor concentrations to decay. A more efficient means of reducing the average concentration indoors is to compare indoor and outdoor concentrations and

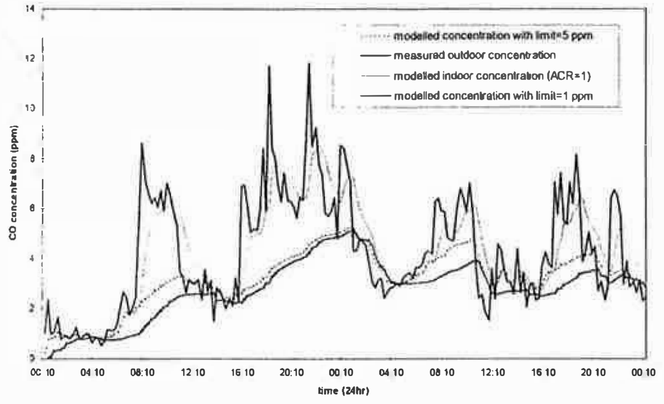

Figure 6 Double-sensor model: Changing the air change rates in response to internal and external CO levels. Results are compared with the concentration obtained using a constant air change rate of 1 ac h^{-1}.

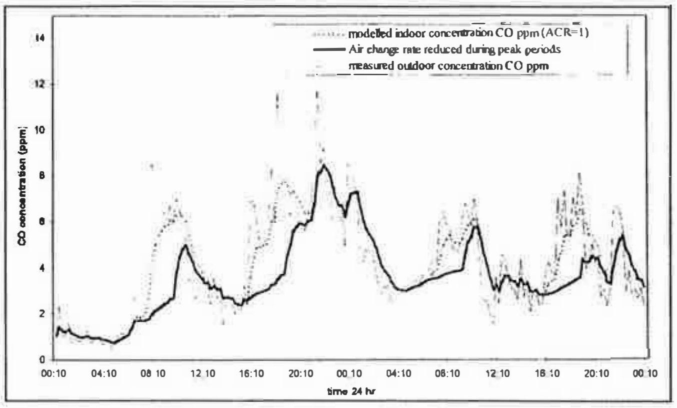

Figure 7 Peak period model: Reducing the air change rate from 1 to 0.1 ac h^{-1} during the morning (07:00 to 10:00 h) and evening (16:00 to 19:00 h) rush hours. Results are compared with the concentration obtained using a constant air change rate of 1 ac h^{-1}.

to reduce the air change rate only when the outdoor level is greater than the indoor level and the outdoor level exceeds some specified value. There are four possible indoor-outdoor situations:

(*a*) $C_i < C_o$ AND C_o < limit

(*b*) $C_i < C_o$ AND C_o > limit

(*c*) $C_i > C_o$ AND C_o < limit

(*d*) $C_i > C_o$ AND C_o > limit

For cases (*a*), (*c*) and (*d*) an air change rate of 1 ac h^{-1} is used. For case (*b*) the air change rate is reduced to 0.1 ac h^{-1}.

The indoor CO concentration was calculated using equation 3 with the air change rate set according to (*a*) to (*d*). Figure 6 shows the indoor CO concentrations as a result of air change control when the limit was set at 5 and 1 ppm, and with a constant air change rate of 1 ac h^{-1}. The average indoor CO concentration in each case is shown in Table 4. The double sensor is most effective when low limits are set, with greater decreases in the average indoor concentration occurring for lower limits.

Table 4 Average indoor CO concentrations calculated using the double-sensor model. The decrease in CO concentration refers to the average concentration compared with that calculated using a constant air change rate of 1 ac h^{-1} (4.22 ppm). Values in brackets refer to Kraenzmer's model.

Limit CO concentration (ppm)	Average internal CO concentration (ppm)		Decrease in average internal CO concentration (%)	
	Air change rate (ac h^{-1})		Air change rate (ac h^{-1})	
	1–0.1	1–0.5	1–0.1	1–0.5
1	2.78 (1.01)	3.80	34 (40)	10
1.5	2.84 (1.12)	3.82	33 (34)	9
2	2.85 (1.17)	3.82	32 (31)	9
2.5	2.93	3.84	31	9
3	2.96	3.85	30	8
4	3.10	3.87	26	8
5	3.2	3.90	24	7

5.3 Reducing the air change rate during peak traffic hours

Peak traffic periods are normally found at the beginning and the end of the working day. On a day-to-day basis these times will be fairly constant. Peak traffic flows were observed in the morning between 07:30 and 09:30, and in the evening between 16:30 and 18:30. At these times traffic was often slow-moving or stationary. During these peaks ventilation rates could be reduced. Figure 7 shows the effect of reducing the air change rate from 1 ac h^{-1} to 0.1 ac h^{-1} during the morning (07:30–09:30) and evening (16:30–18:30) peaks. The average CO concentration when the air change rate is reduced from 1 ac h^{-1} to 0.1 ac h^{-1} is 3.79 ppm. This is 10% lower than the average concentration achieved by keeping the air change rate constant at 1 ac h^{-1}. If we extend the periods when the air change rates are reduced to between 07:00 and 10:00 (morning) and 16:00 and 19:00 (evening), the average CO concentration is 3.59 ppm (i.e. a reduction of 15%).

6 Discussion and conclusions

The most effective method for reducing the average CO concentration indoors is the double sensor. This is consistent with Kraenzmer's findings and is illustrated in Tables 1 and 2. Decreases in the average CO concentration of up to 34% were found when the CO limit was set at 1 ppm. Increasing the limit was found to decrease the effectiveness of the double sensor in reducing average concentrations. In both the single and double sensors, a switch from 1 to 0.1 air changes per hour was more effective in reducing indoor concentrations than a switch from 1 to 0.5.

Kraenzmer found that a double sensor was more effective when low limits were set, although the differences between the single and double sensor in his study were quite small as shown in Tables 2 and 3. In the current study, it can be seen that the double sensor performed almost twice as effectively as the single-sensor when the limit was set between 1 and 2.5 ppm and the air change rate switched between 1 and 0.1 ac h^{-1}.

When a single sensor was modelled there were again interesting differences in the results compared to those reported by Kraenzmer's. Increasing the limit did not increase the average CO concentration, instead the average concentration tended to fall as the limit was increased. This difference is most likely explained by the differences in the outdoor concentration data collected. The average concentration recorded at the site in Kraenzmer's study was 1.68 ppm and the maximum time when the outdoor concentration exceed 1 ppm was approximately four hours. In the current study the average outdoor concentration was found to be 4.09 ppm and the maximum period when the concentration exceeded 4 ppm was approximately eight hours.

The effect of the differences in the outdoor concentrations is to alter the number of occasions when the lower air change rate is set. In our strategies, with low limits, there were long periods when the outdoor concentration exceeded the limit value and hence the strategy set the lower air change rate. However, when the concentration subsequently fell, it did not always fall below the limit — and therefore the strategy did not switch the air change rate. Increasing the limit in this case would have the effect of increasing the number of occasions in which the higher ventilation rate was set, causing average levels to fall. In Kraenzmer's case, with significantly lower average outdoor readings, increasing the limit value would have resulted in fewer occasions when the lower air change rate was set; thus average levels would be observed to increase.

The differences in results indicate that choosing a limit value should be done on an individual site basis. It may be necessary to take measurements of pollutant concentration at the façade of the building over a sufficiently long period to enable sensible limits to be applied to any intended ventilation control. Of particular importance in the case of a single sensor is the length of time that the outdoor pollution level exceeds the limit value.

Control of ventilation rates over a fixed time period when traffic volume is expected to be high yields the smallest improvements in the average indoor concentration; although it is effective in reducing the internal peaks associated with the rush-hour periods. Increasing the length of time for which air change rates are a minimum results in small decreases in the average indoor CO concentration.

The strategies investigated did not take into account any other human comfort criteria. Altering air change rates in response to one pollutant may result in adverse levels of another. The levels of internally generated pollutants such as carbon dioxide (CO_2) from human activity or the off-gassing of volatile compounds from building materials should also be considered. This fact is addressed by Kraenzmer, who showed that low limits resulted in long periods when a lower air change rate was set and internally generated CO_2 rose to unacceptable levels. It may therefore be necessary to assess the impact on health of the internally and externally generated pollutants when devising the control strategy.

A final consideration must be given to the nature of the ventilation control described in this study. The form of control that has been investigated is more suited to a mechanical ventilation system, since control of air change rates in naturally ventilated buildings could not be achieved to this precision. The results presented here show how control of the ventilation rates can give noticeable improvements in the indoor concentrations of traffic pollutants. This may perhaps best be considered as just one part of an overall strategy in reducing indoor concentrations, alongside such measures as appropriate siting of air intakes and increased separation belts between roads and buildings.

Acknowledgements

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