Proc. CIBSE A: Building Serv. Eng. Res. Technol. 19(2) 67–72 (1998) Printed in Great Britain B458

AIVC 11245

Summary In two separate experiments carbon monoxide (CO) concentrations were recorded at different locations in and around a naturally ventilated building in Nottingham, UK. This building is situated close to a busy road (A52). The results show that when the building was downwind of the traffic source the concentration of CO was on average four times higher in a ground-floor room than when the wind was from a large traffic-free area. The relationship between the indoor and outdoor CO concentrations was found to change during the day, as was the relationship between the concentration at ground and first-floor windows. Further measurements, based on these findings, are suggested to determine whether benefits to indoor air quality may be gained from use of intelligent ventilation strategies.

Traffic pollution in and around a naturally ventilated building

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Received 15 May 1997, in final form 21 July 1997

1 Introduction

In the United Kingdom the main source of carbon monoxide (CO) is road transport, with 89% of the nation's CO emissions caused by road vehicles(1). The effects of CO on health are well documented by organisations such as the World Health Organisation (WHO)(2) and the Expert Panel on Air Quality Standards (EPAQS)(3). These report that when inhaled, CO reacts 200 times more readily than oxygen with haemoglobin in the blood to form carboxyhaemoglobin (COHb). This diminishes the ability of the red blood cells to carry oxygen around the body. As the concentration of COHb in the blood increases the effects on human health become more severe. At blood COHb levels exceeding 50% unconsciousness and then death occur; lower levels may affect brain and heart function. The WHO and EPAQS have established a recommended safe threshold exposure level of an average 10 parts per million (ppm) over an eight-hour period. This is the equivalent of keeping blood COHb concentration below 2.5%.

The effects of exposure to high levels of CO are generally well known and reported, but it is the levels of CO that lead to behavioural changes and illness in micro-environments such as the motor car and the workplace which are attracting increasing interest. Recent research has indicated that exposure to CO may lead to changes in psychiatric behaviour(4). Work has also highlighted the adverse effect of long-term exposure to levels of CO indoors that would otherwise be considered harmless in the short term(5). In these situations inhabitants have complained of symptoms of dizziness and headaches. These have been reported as symptoms of the 'sick building syndrome'(6,7).

Research into CO in the urban environment as a result of motor vehicles has concentrated on CO levels at the roadside and in the moving vehicle. Less effort has been directed to examining the relationship between the levels of CO recorded at a building façade, inside a building and those recorded at the roadside. This is particularly true for naturally ventilated buildings.

Krüger(8) performed a study of pollutant levels at the façade of buildings in Gothenburg at different distances from the street, including a naturally ventilated building a short distance away from a main street in the city centre. At short distances, wind direction was found to be a more important factor than traffic density on the level of pollution recorded at the building. Kukadia and Palmer(9) examined the concentrations of various traffic-borne pollutants in a ground-floor, naturally ventilated office, with windows on the roadside face, situated next to an eight-lane major road. It was found that the building significantly attenuated the concentration of external pollutants; internal peaks were generally less than 50% of the external peak concentrations.

In order to develop sensible ventilation strategies — in the case of buildings in the urban environment situated near a busy road — it is important to gain an appreciation as to where and when pollution concentrations are highest. This paper describes a case study of the CO levels at different locations in a naturally ventilated building situated close to a busy ring road in Nottingham.

2 Experimental procedure

The experiment was run over two separate two-week periods. For clarity these periods are labelled here as Experiment One and Experiment Two. Experiment One was run from 27 January 1997 to 10 February 97 and Experiment Two was run from 4 March 1997 to 17 March 1997. In both experiments CO levels were measured in different locations in the vicinity of the main road (A52) which runs alongside the northerly perimeter of the campus of the University of Nottingham (Figure 1).

Traffic flow statistics supplied by Nottinghamshire County Council for this part of the A52 show that rush-hour peak flows of 2500 vehicles per hour can be observed in either direction. The road is a single carriageway, although during peak periods drivers are observed to treat the link as a dual carriageway. The weekday morning rush-hour generally begins at 07:30 and lasts until 08:30. The evening rush 'hour' typically lasts from 16:30 until 18:00. During these peak periods traffic may be stationary for short periods, whereas at other times the traffic flows freely to a large extent. Total daily flows are in the region of 25 000 vehicles in either direction with noticeably smaller flows over the weekends. The traffic flows week-on-week were very similar, with only small differences in the peak, non-peak and total daily flows.

Four sampling points were selected altogether. In Experiment One samples of air were drawn simultaneously from the roadside, immediately adjacent to a ground floor window, and inside a ground floor room of a naturally venti-

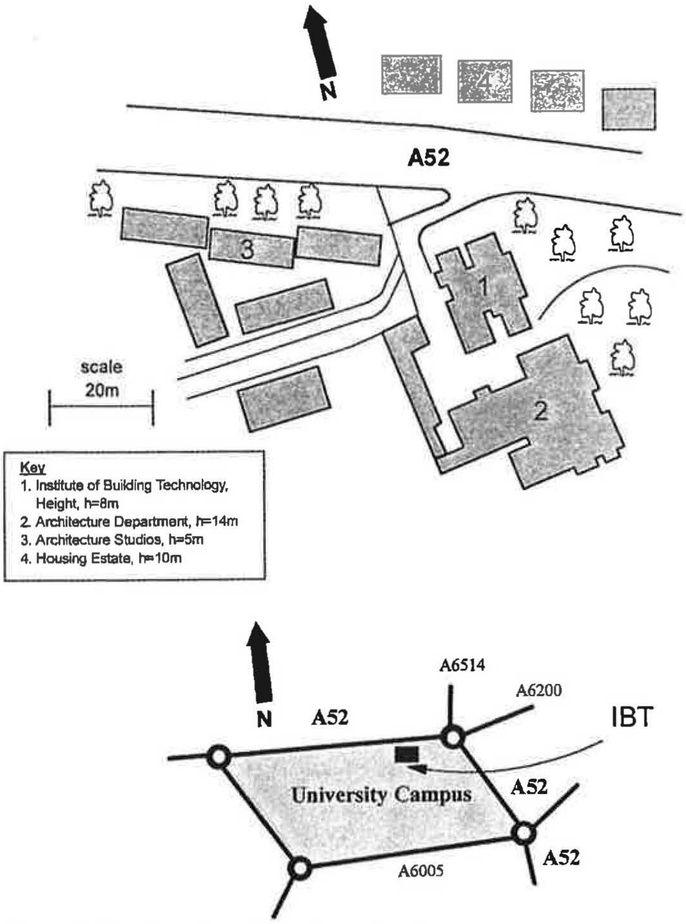

Figure 1 Location of sampling points and local road network

lated building. In the second experiment an extra sampling point at a first-floor window was added. The building used in the study was the Institute of Building Technology (IBT) and was selected because it is both naturally ventilated and in close proximity (10 m) to the A52. Figure 1 illustrates the position of the IBT with respect to the A52 and the local road network. The approximate heights of adjacent buildings are listed to provide further topographical detail. The ground floor room of this building where measurements were taken is used as a computer room; there are no other sources of CO in the building. The window in the ground floor room was opened and shut as and when the occupants felt necessary for their own comfort. However to a large extent the window remained closed, as would be expected during a winter month.

Samples of air were taken simultaneously from the each of the locations at 15 min intervals. A simple logging program driven by a personal computer (PC) controlled the operation of a small pump via a relay. The air sample was pumped from the sampling location via a plastic tube to a gas analyser (Crowcon RGD90 Toxic Gas Detector) which had previously been calibrated using a standard gas (subsequent calibrations of the sensor showed a drift of ±5%). The gas concentration in the sampled air was recorded as a voltage by a multimeter which was read and converted to a concentration in parts per million (ppm) by the PC. Data were then downloaded for analysis. The entire sample–measure–record cycle as described above is illustrated in Figure 2.

In Experiment One local wind direction and speed were also measured by a wind vane mounted on the roof of the IBT at a height of approximately 10 m. Readings were taken every 10 seconds and logged as half-hourly means. Wind speeds were recorded to the nearest 1m s^{-1} and wind direction to the nearest whole degree. The whole process was driven by the PC.

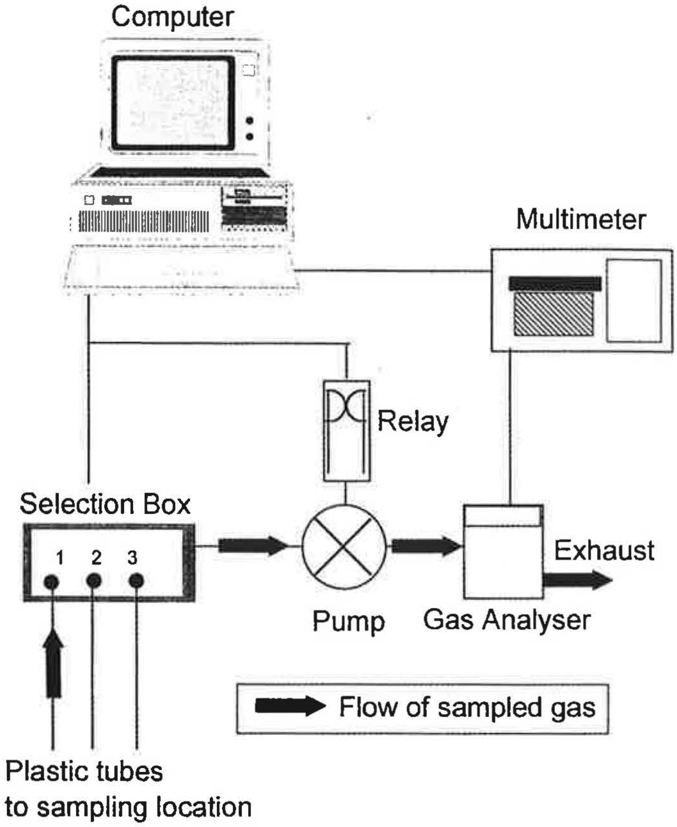

Figure 2 Equipment for sample–measure–record cycle

3 Results for Experiment One

Graphs were plotted to illustrate the CO levels recorded at the roadside, at the ground floor window and inside the ground floor room for each of the two weeks of Experiment One (Figures 3 and 4). CO levels were found to fluctuate in accordance with the observed peak traffic flow periods. Increases in the roadside CO concentrations were on average accompanied by increases in the concentrations at the window and inside the room.

To gain a clearer picture of the changes externally and internally Figure 5 shows the concentrations recorded in the fifth day of week two. This time period was chosen because there is a clearly defined peak in the roadside concentration during the evening rush. The expected buffering effect of room volume and ventilation rate can be seen in the comparison between window and room concentrations. Peaks in the window concentration are not accompanied by peaks in the room concentration, but they are often followed by periods where the room concentration exceeds that at the window. The time lag between the outdoor and indoor peak is a function of the air exchange rate in the room.

Table 1 summarises the key results. The average and maximum (98 percentile) CO levels in the three locations are expressed along with the ratio between the average indoor and outdoor concentration. Both the average and the maximum were noticeably higher in the first week than in the second week and this can be explained by the different wind conditions experienced. Figure 6 illustrates the frequency of the wind direction in each of the two weeks.

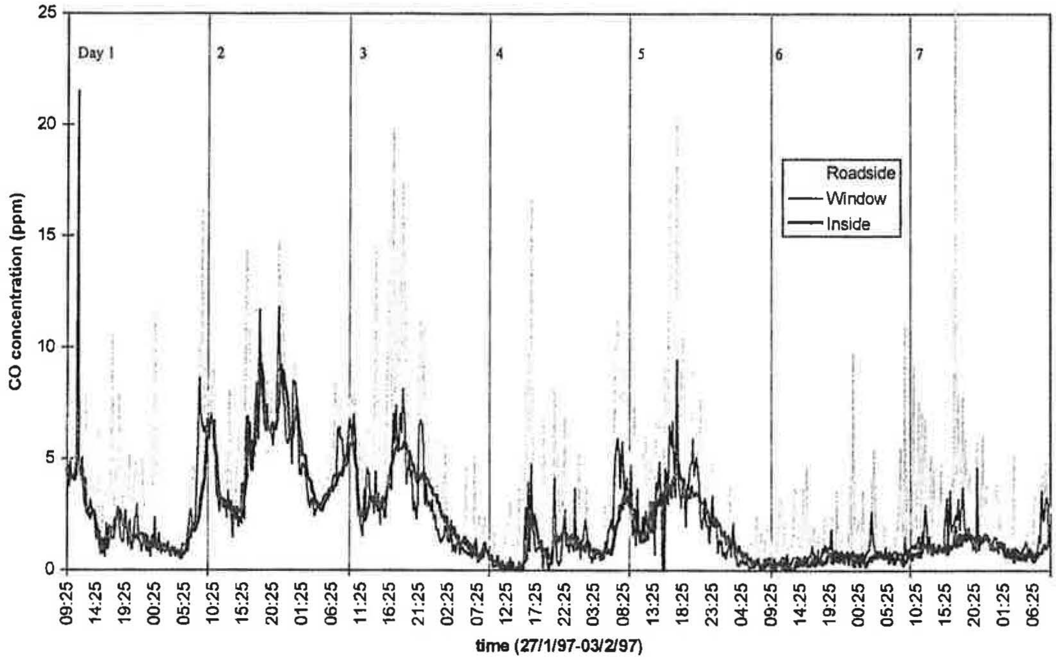

Figure 3 CO concentrations at roadside, by ground floor window and inside ground floor room in Experiment One: Week one

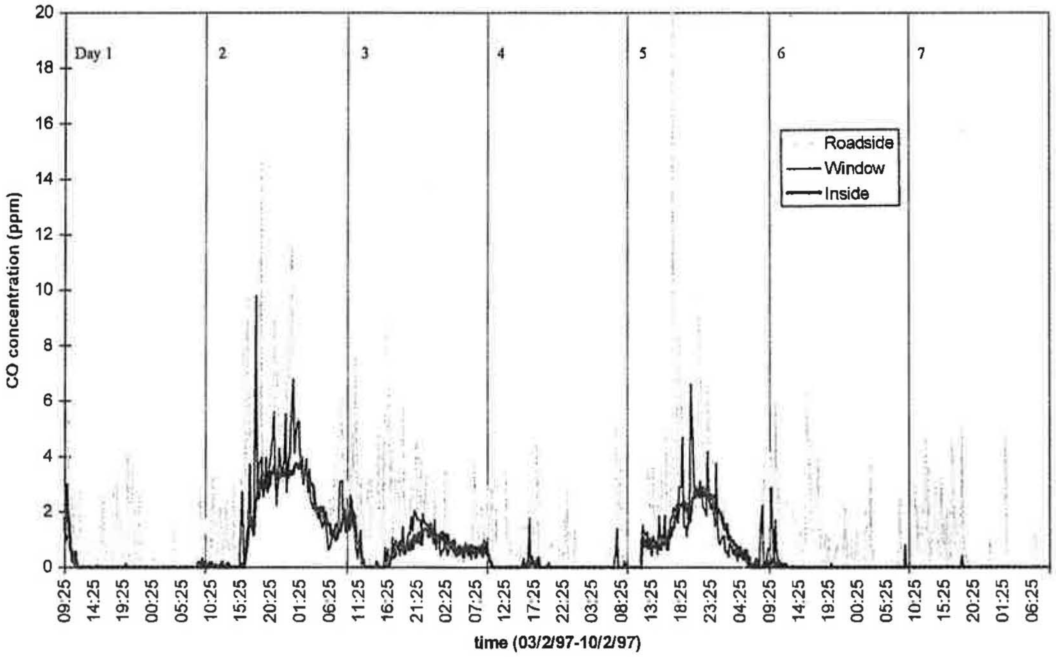

Figure 4 CO concentrations at roadside, by ground floor window and ground floor room in Experiment One: Week two

In the first week the upwind direction falls between northerly and southerly such that for much of the time the building lies downwind of the A52. In contrast to this, in the second week the wind was predominately from the south-west. Wind from this direction passes over the university campus, which has insignificant traffic movement and large open areas. In addition to the different wind direction, the average wind speed in week one was lower than in week two; 0.4m s^{-1} in the first week compared to 1.5m s^{-1} in the second.

The diluting effects of the various wind directions on the average concentrations recorded are shown in Table 1. The average concentrations recorded in week one are expressed as a multiple of those recorded in week two. The reduction in the average concentration during week two is greatest inside the ground floor room and lowest by the roadside. This accords with expectation, since wind effects at the source are less significant.

For comparison, Krüger(8) recorded an average concentration of 1.02 ppm and a 98 percentile of 4.13 ppm at the roadside façade of the building in his study. These results are similar to those recorded in week two, but are almost half those recorded in week one (Table 1). The building in Krüger's study was situated by a main street with peak flows of 1540 vehicles per hour (VPH) and total daily flows of 17 300 vehicles, as compared with 2500 VPH and 50 000 vehicles per day in this study. This seems to reinforce the hypothesis that at short distances from the road, wind direction, rather than traffic density, is the major factor affecting the concentration of traffic pollution at the building façade. Over the duration of these experiments there was little change in the traffic flows.

Kukadia and Palmer(9) noted that peak internal concentrations of CO were generally 50% less than the peak external concentrations. This study shows similar attenuation of the 98 percentile concentration at the roadside and inside the room for the two weeks (Table 1).

The CO concentration at the window and inside the room was investigated further to determine whether there were any

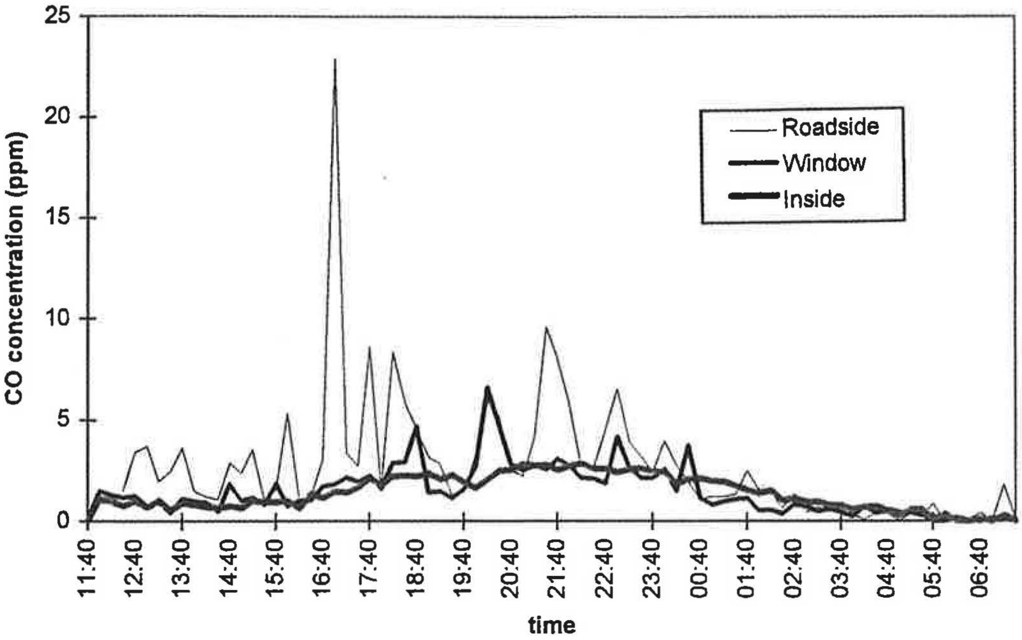

Figure 5 CO concentrations recorded on day 5 of Week two

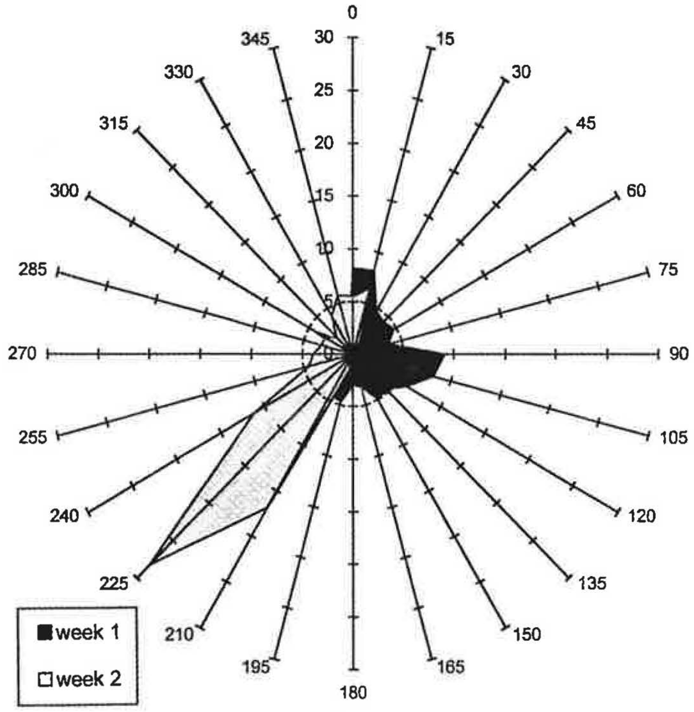

Figure 6 Wind rose illustrating frequency of occurrence (%) for 15° sectors

differences in the relationship between these levels at different times of the day. For each of the two weeks in Experiment One scatter diagrams were drawn for data collected in four different periods of the day. These periods were based on the observed times of peak and non-peak traffic flows.

Table 2 shows the equation of the best fit linear function to the data and the correlation coefficient r^2 for the different time periods. In all cases a linear function appears a sensible fit to the data, with r^2 ranging from 0.53 to 0.85. Neglecting the intercept, which can be considered negligible, the linear function has different gradients during the day, suggesting different relationships between indoor and outdoor air quality over the course of 24 hours. For all time periods the gradient of the linear function is greatest in week one when the upwind direction was from the traffic source.

Table 2 CO concentration in the ground floor room as a linear function of CO concentration at the ground floor window (x is concentration at window (ppm); $f(x)$ is concentration in room (ppm))

Time period	Linear function and r^2 value			
	Week one		Week two	
	$f(x)$	r^2	$f(x)$	r^2
07:00–09:00	$0.54x + 0.29$	0.69	$0.51x + 0.03$	0.58
09:00–16:00	$0.89x + 0.14$	0.85	$0.66x + 0.07$	0.74
16:00–18:00	$0.73x + 0.54$	0.72	$0.62x + 0.05$	0.53
18:00–07:00	$0.86x + 0.29$	0.83	$0.77x + 0.14$	0.85
All data	$0.80x + 0.29$	0.79	$0.77x + 0.08$	0.81

Considering all the data from each week, i.e. making no distinction between the different periods of the day, the functions are very similar, with a gradient of 0.8 in the first week and 0.77 in the second. This suggests that the prime factor driving the ventilation of the building was the stack effect. Air is drawn in at lower levels, so that irrespective of the wind direction, the CO concentration in the room will always be dependent on the CO levels at the window on the roadside façade. If the building were ventilated purely by wind pres-

Table 1 Average and 98 percentile CO levels recorded in Experiment One

Week no.	Average CO concentration (ppm)				98 percentile concentration (ppm)		
	Roadside	Window	Inside	Ratio Inside/Window	Roadside	Window	Inside
One	3.91	2.32	2.14	0.92	14	8	—
Two	1.61	0.64	0.53	0.82	8	4.5	3.5
Ratio One/Two	2.4	3.6	4.0	—	—	—	—

sure fluctuations then a smaller value for the gradient would be expected in week two. In this case, the indoor air concentration would depend on the external concentration on the other side of the building, and since this side of the building is further away from the raod and the upwind direction is from a traffic-free area, the external concentration might reasonably be expected to be lower. This theory is reinforced by the average values in Table 1, where the change in wind direction from week one to week two has a large influence on the absolute values, but not on the ratio between room and window concentrations.

4 Results for Experiment Two

As noted earlier, in this experiment measurements of CO concentrations were simultaneously taken at the roadside, at a ground floor window and at a first floor window, with no attempt to measure local wind speed and direction. Figure 7 illustrates the concentrations recorded at these locations for a typical period of the experiment. Roadside levels were generally lower than in Experiment One, with the average CO concentration over the two-week period equal to 1.19 ppm. From Figure 7 it can be seen that the CO concentrations at the ground floor and first floor window varied in line with the roadside levels, with peaks at all locations occurring during peak flow traffic times. During these times the concentration at the first floor window was found to be lower on average than at the ground floor.

Scatter diagrams were plotted to determine the relationship between the concentrations at the two different heights for different times of day. The linear functions and r^2 values from this analysis are shown in Table 3. Neglecting the intercept value, which again is negligible, it can be seen that the relationship between the concentrations at the two levels changes during the day. The linear functions indicate that concentrations are lower at the first floor window than at the ground floor for all periods, but that at some times, such as the peak morning period, there is almost no difference between the concentrations. The r^2 values for all the periods indicate a high degree of correlation, with values ranging from 0.77 to 0.95.

Table 3 Linear relationship between CO concentration at the ground floor window and the concentration at the first floor window (x is concentration at ground floor window (ppm); $f(x)$ is concentration at first floor window (ppm))

Time period	Linear function and r^2 value	
	$f(x)$	r^2
07:00–09:00	$0.95x - 0.01$	0.95
09:00–16:00	$0.82x + 0.03$	0.81
16:00–18:00	$0.73x + 0.11$	0.77
18:00–07:00	$0.91x + 0.02$	0.90
All data	$0.86x + 0.03$	0.86

5 Discussion

The simple experiments described here illustrate several points. In the first experiment a decrease in pollution levels at the sampling points occurred when the upwind direction was away from the A52. In this case the distance to the nearest significant traffic source is approximately 1 km, with the relatively traffic-free campus forming the separation belt. In the urban environment separation belts of such size would, of course, be impractical and uneconomic, since land space is at a premium. However the results do illustrate the influence of wind direction on external and internal pollutant levels.

The relationship between the internal and external CO concentrations was seen to differ during course of the day, and there was a reasonable correlation in the data. The external pollution level varies during the day, with maximum concentrations found at peak traffic periods. There is a potential here to vary ventilation rates through intelligent control as a response to the outdoor levels, or by simply reducing the ventilation rate at specific times when external pollution levels are known to be high, such as the rush hour. In order to investigate further the daily variations in pollution levels it would be of interest to take more readings so that correlations can be made for more discrete periods of the day. At present, due to the stack effect, changes in wind direction do not change significantly the indoor–outdoor CO concentration relationship for this building.

CO levels at the first floor window were only slightly lower than those recorded at the ground floor. This was perhaps to be expected due to the relatively short distance between the

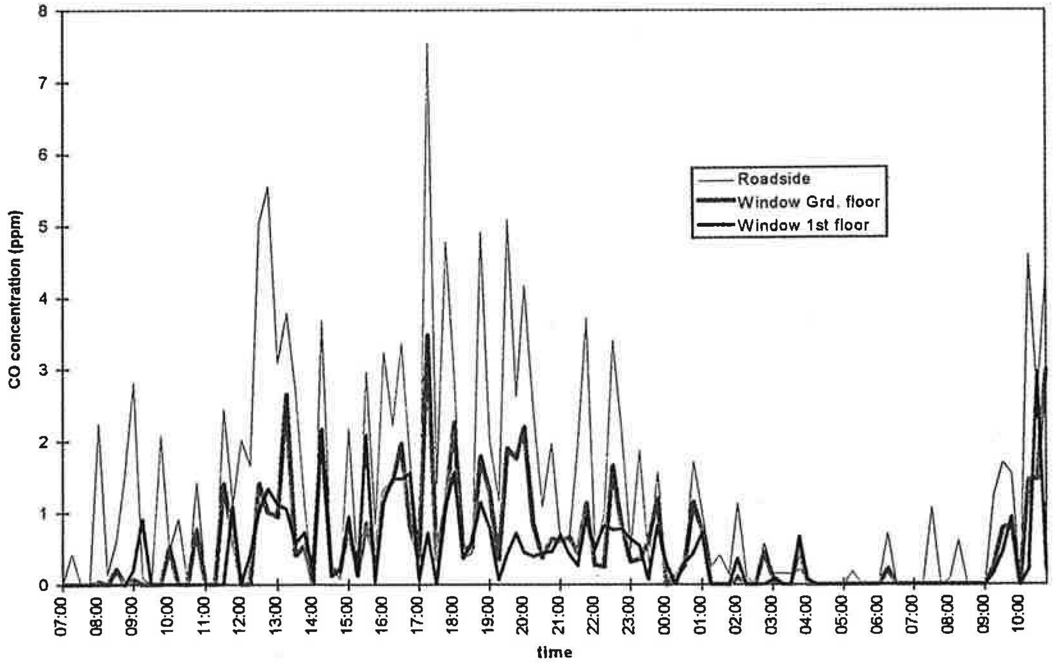

Figure 7 Typical variation in CO concentrations at roadside, ground floor window and first-floor window in Experiment Two

sampling points, which at 2 m is 20% of the separation between the road and the building distance. However, analysis of the data indicates periods of the day when it would be advantageous to draw air in at higher openings, since CO concentrations are of the order of 25% lower. Again, a form of ventilation control may be used to optimise the indoor air quality. Since no measurements were taken at the other side of the building, no conclusions can be drawn as to the advantages to be gained by locating air inlets there. It would be reasonable to expect a further decrease in external CO concentrations with the increase in distance from the traffic source, but further measurements are needed to quantify this.

No attempt was made to control the opening or shutting of the window on the roadside façade, and therefore it is not possible to quantify the influence this has on the indoor levels. This study has shown the indoor levels occurring under conditions of normal use for the room during a winter month.

6 Conclusions

Concentrations of carbon monoxide recorded around the building in this study were found to vary in line with the peak and non-peak traffic flows on the adjacent road. On average, with the daily traffic characteristics constant, the wind direction was found to be of major influence on the concentrations of CO recorded. The indoor air quality was seen to vary throughout the day. This study has shown that a slight benefit may be gained from situating vents at higher locations on the building façade, and that varying ventilation rates may also yield gains. Further readings are required over a longer period of time to quantify these benefits. At present the data collected support the supposition that the building is ventilated principally by stack effects, so that efforts to control pollution intake would have to be aimed at reducing the air entry through some of the low-level openings.

7 Further work

The experiments described above are a part of a continuing project which aims to quantify vehicle emissions and dispersions in the urban environment, and in particular around naturally-ventilated buildings. As the project progresses it is hoped to develop ventilation strategies that optimise indoor air quality. Wind tunnel studies are currently in progress to compare field with model results and to develop ventilation strategies under different traffic scenarios.

Acknowledgements

The authors express their gratitude to the UK Engineering and Physical Science Research Council for their support in this project.

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