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Respirable Particulates and Oxides of Nitrogen Measured Inside a Building Alongside a Busy Road

Key Words
Respirable particles
Indoor/outdoor ratio
Traffic emissions
Diesel particulate

Abstract
Gravimetric determination and continuous monitoring of respirable dust in air has revealed that there are high levels of dust at some roadside and indoor locations in urban areas. Furthermore, where high dust levels are measured in roadside samples, high concentrations are also measured in adjacent buildings. The dust levels measured inside a building have been shown to be very closely correlated to ambient levels, and traffic emissions, particularly from diesel vehicles, are the principal source of respirable particulates. Other traffic-related air pollutants have also been measured in high concentrations inside a building alongside a busy road. A clear decline in respirable dust concentration with height above ground level has been observed inside a building, and this is proposed as good evidence that a ground level source such as diesel exhaust emissions is important.

Introduction

It is estimated that humans spend 75–85% of their time indoors. If that time is spent in an environment of poor air circulation, we should be concerned about the quality of the air and in particular the possible accumulation of pollutants. It has long been realised that air contaminants can build up to levels within buildings that the inhabitants find unacceptable.

The source of indoor pollutants can be outgassing from building materials, activities such as cooking or ingress of ambient pollutants. This last route obviously is dependent on the building's ventilation characteristics which can be an important pathway in some circumstances. Contaminants can enter the indoor environment with ambient air through windows, doors, ventilation shafts and adventitious leaks. Previous studies have shown the importance of this route for respirable particles which may not be filtered out by the building shell [1]. Air pollution that penetrates indoors can be related quantitatively to levels outside by an indoor/outdoor concentration ratio. Gases such as carbon monoxide (CO), which are unreactive and do not absorb strongly on to walls, have an indoor/outdoor ratio close to 1, whereas for reactive gases such as sulphur dioxide (SO_2), which is adsorbed onto surfaces, the ratio is less than 1. The ratio for solid particulates has been observed to vary considerably depending on the particle size. The average size of particulates that penetrate a building is less than for the average outside, as the building acts as a filter for the larger particles.

Traditionally, ambient particulates have been measured as total suspended particulates; however, in recent

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years, measurements have concentrated on the fine fraction of ambient particulate matter, as this material can readily enter the respiratory system and has been linked with respiratory illness in urban areas [2]. In the UK, the Quality of Urban Air Review Group [3] have stressed the importance of diesel motor vehicles as a source of fine particulates.

Whilst there is agreement in the UK that few central monitoring stations are likely to measure exceedences of proposed air quality standards, it is recognised that in urban areas there may be places with overly high particle concentrations due to traffic or industrial activity. In particular, areas with high traffic flows may possibly experience exceedences of the standards. Janssen and Vanmansom [4], working in the Netherlands, measured street level fine particulate concentrations ranging from 34 to 147 $\mu g \cdot m^{-3}$ in the city of Arnhem. There may be implications for residents in such areas, as it is possible for high concentrations of particles to enter buildings from the outdoor environment. Previous studies have shown that the indoor particulate concentration can be considerable. Li [5] reported that 20% of particulate measurements, measured as the PM_{10} standard, made inside domestic premises in Taiwan exceeded 50 $\mu g \cdot m^{-3}$. The UK Expert Panel on Air Quality Standards [6] have advised that a standard of 50 $\mu g \cdot m^{-3}$ as a 24-hour rolling average would have a dramatic effect on urban air quality, and this recommendation has been accepted as part of the UK National Air Quality Strategy [7].

The concentration of particles inside a building is dependent on climatic factors, proximity to sources and the behaviour of the occupants. For example, in a study of 24 homes in Vermont, USA [8], indoor fine particle concentrations ranging from 6 to 40 $\mu g \cdot m^{-3}$ were measured, whereas in Taiwan, Li [5] measured indoor fine particulate concentrations ranging from 20 to 300 $\mu g \cdot m^{-3}$. Taiwan lies astride the tropic of Cancer and presumably the direct transport of particulates through open windows and doors is significant there.

A building may act as a filter, so preventing the ingress of much of the airborne particulate material. Although the filtering action of the building shell will be greater for large particles, it is possible that some proportion of the finer fraction of particulate will also be removed in this way. Wallace [9] has calculated that, for a building with no indoor sources of particulate and a typical air exchange rate of 0.75 ach, the indoor fine particle concentration would be about 65% of the outdoor concentration. This clearly demonstrates the effectiveness of building shells in preventing the ingress of ambient particulates.

The present study has investigated the efficiency of the building shell at reducing particulate levels inside rooms at the University of Wolverhampton. The buildings of the University of Wolverhampton are located in a busy town centre location. At the beginning of this study, ventilation air for the room under investigation was drawn directly from the street level, and concern had been expressed that vehicle-related air pollutants might be entering the building and affecting the health of researchers and students using the buildings.

Methods

On different sampling days, ten individual measurements of respirable dust were made in a selected study room whilst simultaneously ten measurements were made of ambient air immediately outside the study room. The study room was naturally ventilated with a window opening to the main road and a ventilation grill located approximately 0.75 m above the floor level. Throughout the study, the window remained closed although continuous ingress of outside air was possible through a vent. An internal door opened onto a corridor allowing air from within the building to enter the study room, although this door was only rarely opened as the study room was not heavily used during this investigation.

The study room chosen for this investigation was at ground level facing onto a road which led to the town's central bus station. It is common for buses to be held-up at a nearby traffic junction entering this road. Large amounts of visible diesel particulates are produced by the buses, particularly when their engines are idling as they pause at the junction. On either side of the road are large multi-storey buildings which may produce a canyon effect preventing the dispersion of vehicle emissions. This is clearly shown in figure 1, which is a view of the road looking towards the bus station. The traffic is typical for a usual working day. Initially, all samples were taken from a study room close to the main foyer area on the first floor of the building on the left hand side of the picture.

Monitoring of respirable dust was undertaken in the selected room and at the corresponding roadside location from 9.00 a.m. through to 5.00 p.m. on the day of study. This enabled an 8-hour time-weighted average to be calculated. The monitoring equipment used was a Casella high-volume 124 pump system which drew air through a metallic cyclone head at a rate of 1.9 $l \cdot min^{-1}$. Flow rates were set prior to each sample using a bulb flowmeter. The purpose of the cyclone head is to separate respirable dust from larger non-respirable particles, so reproducing the natural filtration of the bronchial system. Respirable particulates (here defined as those particles with an aerodynamic diameter of $<7\ \mu m$ as defined by the Johannesburg Convention) were retained on a Whatman cellulose nitrate filter paper (diameter 37 mm) which was held within the sampling head. Larger particulates were removed by deposition to a rubber grit pot attached to the sampling head. After being stored in a dessicator for 24 h to drive off adsorbed water vapour, the filter papers were weighed prior to and following the sampling period, allowing a gravimetric determination of the collected particulate mass to be made. The Casella instrumentation is one of several standard dust-monitoring devices which allow a satisfactory estimation

Fig. 1. The view along the study road on a typical working day. The study building is on the left hand side of the photograph.

of respirable particulate to be made in the indoor environment as described by Vincent [10].

At a later date, the building was revisited, and respirable dust concentrations were determined at ground level and on the next three floors upwards. Each floor was approximately 10 m above the previous floor. In this case, measurements were made using a portable forward light scattering monitor (Microdust 880 nm, Casella Instruments, UK) allowing a real-time respirable particulate concentration to be determined.

One further problem that is associated with dust penetration into buildings is the soiling effect of settled dust. Inside the building, this problem had been observed to be acute with dark/black soiling of many surfaces regularly occurring. To assess the significance of this deposit, gauges were placed inside the building, allowing dust to settle onto a pre-weighed glass microscope slide. These gauges were left in place for a period of 1 month, allowing a gravimetric estimation of the dust-settling rate on interior surfaces to be made.

Because of the dominance of diesel-fuelled buses using the road outside the study building, this work focused on fine particulate measurements. The diesel engine typically produces appreciably lower emissions of gaseous pollutants than a conventional four-stroke petrol engine [3]. Emissions of CO and hydrocarbons may therefore be less than from a petrol engine, although diesel vehicles emit more oxides of nitrogen (NO_x) due to high temperatures in the engine. On one occasion a chemiluminescent monitor (Horiba Instruments, Northampton, UK) was installed inside the foyer of the study building to allow a continuous measurement of NO_x over a 24-hour period. These data were then compared to the data collected at the Wolverhampton Central Air Quality Monitoring Station where the same technique is used to measure NO_x. Unfortunately, it was not possible to do the same for dust measurements, as dust is measured at the central station as PM_{10} and is not therefore directly comparable to respirable dust measurements.

Results

Figure 2 shows both the indoor and outdoor dust levels. Although occupational exposure standards were not exceeded on any sample day, indoor dust samples were relatively high. Outdoor respirable dust concentrations were always higher than corresponding indoor values; however, it is clear that the indoor concentration closely mirrors the outdoor concentration. The indoor and outdoor concentrations are strongly correlated ($R^2 = 0.8541$, $p < 0.001$) as shown in figure 3.

Figure 4 clearly shows the decline in both indoor and outdoor respirable particulate concentration with height. This can be seen as good evidence of a ground level source, presumably diesel-powered buses. It is noticeable that the indoor concentration falls more sharply than the outdoor concentration. On the day of the measurements, the indoor/outdoor ratio at ground level was 0.24, falling to 0.07 at 30 m above ground level. The large majority of University activity in the building occurs on the first two floors with mainly staff offices and storerooms on the upper floors. There are fewer open windows and doors on the upper floors to allow entry to ambient respirable particulates.

Monitoring of nitrogen dioxide over a 24-hour period shows a similar pattern as shown in figure 5. Levels measured inside the building were compared to those recorded at Wolverhampton Central Monitoring Station which

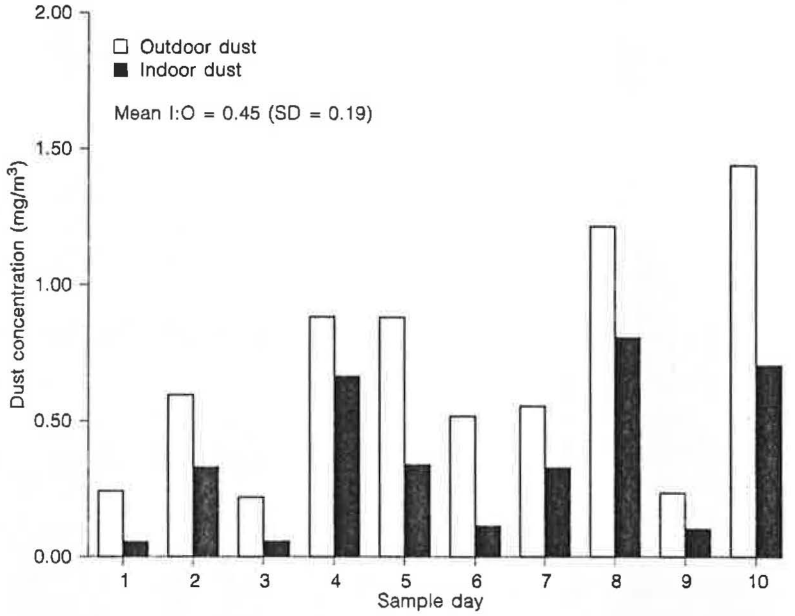

Fig. 2. Levels of respirable dust inside university buildings. I:O = indoor/outdoor concentration ratio.

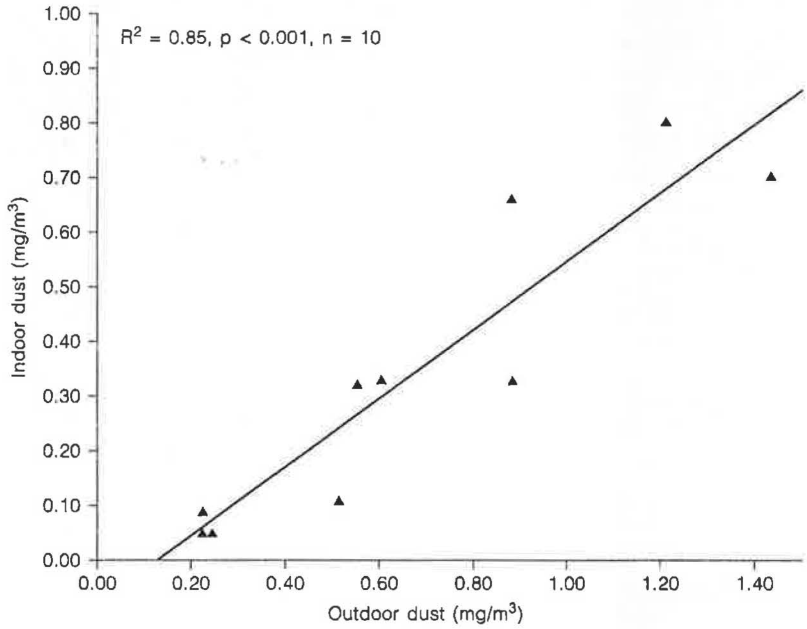

Fig. 3. Correlation between indoor and outdoor dust levels.

is located approximately 0.5 km from the study building and is described as an urban background site (i.e. >30 m from a road). The indoor measurements quoted here were taken in the foyer of the building just 3 m from the road and are significantly higher than those recorded at the central site (t test: $p = 0.001$). The presence of a morning and evening rush hour peak in both data sets is good evidence that traffic emissions are the prime source of this material.

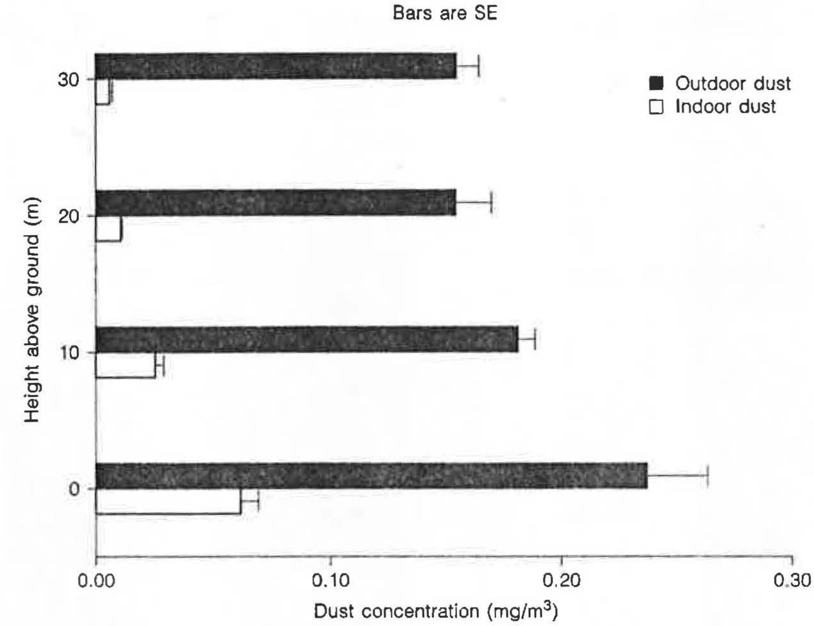

Fig. 4. Variation of respirable dust concentration with height above ground.

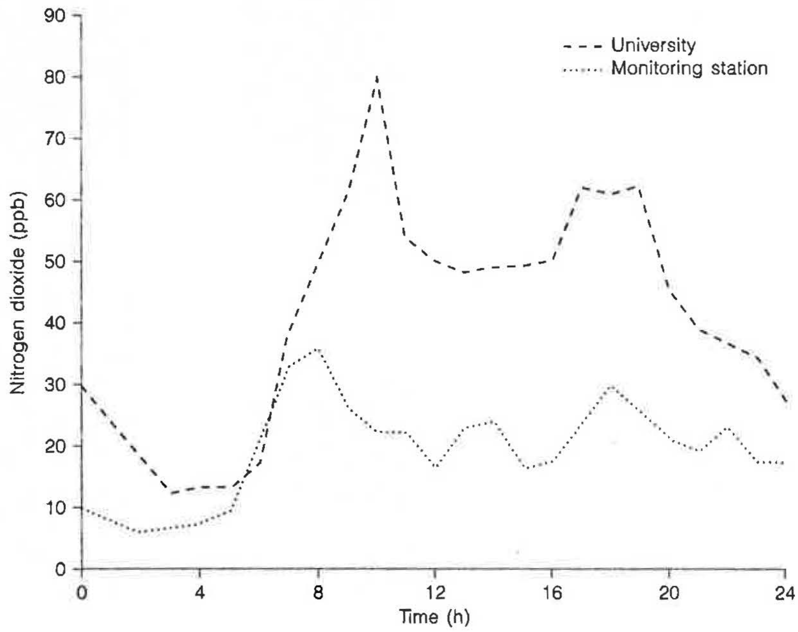

Fig. 5. A comparison of nitrogen dioxide levels in university buildings and at the Wolverhampton Central Monitoring Station.

Another feature of diesel fuel dust is that it is very carbonaceous, consisting largely of unburnt fuel and oil. This gives the dust a dark/black colour. Apart from the health implications of indoor particulates there may also be a nuisance effect in soiling interior surfaces of buildings. This was certainly true from visual observations of the affected rooms. The soiling rates measured in the foyer and two office rooms are given in table 1.

Discussion

Some of the individual respirable dust concentrations measured here are relatively high for a study room with no obvious indoor source of particulates. The highest value of 0.8 $mg \cdot m^{-3}$ is more than twice the maximum value recorded by Li [11], where windows and doors remained open during measurements. Results of a paired t test demonstrated that the indoor and outdoor concentrations were significantly different ($p = 0.001$) with the outdoor concentrations being consistently higher than concentrations measured indoors. It could be postulated that the building shell is clearly acting to prevent ingress of much of the particulate material. It should also be noted that there are other mechanisms which may reduce the levels of respirable dust within the study room. Particles may settle on indoor surfaces, effectively reducing the indoor concentration, and the resuspension of this deposited material could further complicate the situation. Also, as the study room has an internal door, which was used occasionally in this study, air may have entered the study room from elsewhere in the building. This air may well be cleaner than the air from the outside, diluting the respirable dust concentration in the study room.

It is possible that the ingress of particulates from ambient to indoor air may be driven by local meteorological factors or the ventilation regime of the building as the indoor/outdoor ratio varied considerably from day to day (mean = 0.45; SD = 0.19). This is in line with some previous studies, where indoor/outdoor dust ratios have been reported to vary widely between samples. For example, Li [11] reports fine particulate indoor/outdoor ratios ranging from 0.10 to 2.30 in Taiwan. Here, the frequent opening of doors and windows in a subtropical climate had a major effect on the indoor/outdoor ratio. It is likely that in a temperate climate such as the UK, the variable meteorological conditions may lead to frequent closing and opening of windows and doors which clearly can have a dramatic effect on the indoor/outdoor ratio. Although meteorological data were not collected during this study, the work was undertaken in the spring, when ambient conditions may vary quite widely on a day-to-day basis.

From observations made in the building, there appears to be a problem of soiling due to the dark/black colour of settled diesel particulate. There is a major limitation in assessing dust soiling rates in that there are no well-defined criteria against which to assess any findings. Bate and Coppin [12] suggested a level of 200 $mg \cdot m^{-2} \cdot day^{-1}$ as a threshold for serious nuisance, but other literature sources have proposed values ranging from 133 to 350 $mg \cdot m^{-2} \cdot day^{-1}$. The exact nature of the dust will also play a crucial role in determining its nuisance effects. For example, studies undertaken on coal dust have used a threshold value of 80 $mg \cdot m^{-2} \cdot day^{-1}$ due to the dark/black colour of the dust, and this value is possibly the most applicable in these measurements, as diesel dust also has a similar dark colour.

Table 1. Dust soiling rates inside a university building

Location	Soiling rate, $mg \cdot m^{-2} \cdot day^{-1}$
Foyer	155
Office A	5
Office B	27

The results of these measurements indicate that as expected the foyer area is the worst affected with a level almost double the threshold value of 80 $mg \cdot m^{-2} \cdot day^{-1}$. In the other offices, a fairly low soiling rate was recorded, but this may not be representative of the problem, as these slides were placed on desk tops and bench spaces. It would appear that the worst affected areas are computer screens and plastic notices placed on the walls. Most atmospheric dusts carry a small electric charge, and the electrostatic charges associated with these surfaces are likely to enhance particle deposition onto these surfaces. These surfaces will require regular cleaning at the current dust loading, although, if the concentration of dust in the air could be lowered, the severity of the problem might also be reduced.

Conclusions

Although central air quality monitoring stations indicate that there are likely to be few exceedences of particulate air quality standards, it is clear from the measurements made here that in some areas there may be localised problems. Such problems are typically associated with vehicle emissions, particularly diesel fumes. Furthermore, high ambient particle concentrations create the potential for ingress into buildings. The results of this study have shown evidence for indoor particle concentrations to be controlled by ingress from outdoor sources. Vehicle sources of respirable particles appear to be important, since the highest indoor concentrations were measured on the ground floor, although resuspension of settled dust due to high levels of staff activity here could also increase airborne respirable dust concentrations. Finally, although occupational exposure standards were not exceeded, for staff working in the building, the dark colour of the dust creates a nuisance when deposited on surfaces.

Acknowledgment

Some of the nitrogen dioxide concentrations quoted here were recorded at Wolverhampton Central Monitoring Station which is operated on behalf of the Department of the Environment, Transport and the Regions (DETR) by Wolverhampton Metropolitan Borough Council. Monitoring results are published on the DETR Internet home page.

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