Indoor / outdoor air quality relationship in urban commercial buildings: Dublin case studies

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Abstract
Legislative reductions in air pollutant limit values seek to better outdoor air quality, in turn reducing associated illnesses such as cardiopulmonary mortality, strokes and lung cancer. This study focuses on two major traffic related pollutants NO\(_x\) (NO\(_2\) + NO) and PM\(_{2.5}\) (particulate matter with aerodynamic diameter less than 2.5µm). Previous research suggests that people now spend up to 90% of their day indoors (Dimitroulopoulou et al., 2001) yet in Ireland no legislative indoor air pollutant limits exist.

This research aims to determine the relationship between exposure of staff to specific air pollutants in Irish working environments (e.g. shops, offices) and factors such as ventilation systems and door design. Simultaneously measurements of two traffic generated pollutants, NO\(_x\) and PM\(_{2.5}\), have been taken indoors and outdoors of the buildings under investigation. Outdoor concentrations were measured in two locations either directly outside the building at ground level or at the air intake of the buildings ventilation system.

To date seven work places located on busy street canyons of Dublin city centre have been monitored and clear relationships between indoor and outdoor concentrations have been observed at the sites. Results indicate that indoor concentrations can be significantly greater than outdoor concentrations, e.g. Indoor / Outdoor (I/O) ratios of up to 2.3 for NO\(_2\) and 2.13 for PM\(_{2.5}\). Clear differences in I/O (indoor to outdoor concentration ratio) for PM\(_{2.5}\) and NO\(_x\) were also observed for working and non-working hours. Daily diurnal patterns have been noted for both indoor and outdoor, with strong patterns for NO\(_2\).

1. INTRODUCTION
The United Nations urban environmental unit associates up to 1 million premature deaths annually to urban air pollution (United Nations Environment Program, 2010) and over 90% of the air pollution in developing cities has been linked with poor quality vehicles. Within the European Union alone roughly 5 million years of life are lost due to the traffic generated pollutant PM\(_{2.5}\) every year (European Environment Agency, 2010). Estimates of the European cost of health care due to air pollution derived illnesses range from €305 billion to €875 billion (United Nations Environment Program, 2010). Hence, improving air quality within Europe would prove financially beneficial to governments as well as the obvious benefits to population’s health.

This study compares the effect of outdoor pollutant concentrations on the quality of indoor air of inner city places of work. Simultaneously measurements of two traffic generated pollutants, NO\(_x\) and PM\(_{2.5}\) (particulate matter with aerodynamic diameter less than 2.5µm), have been taken indoors and outdoors of the buildings under investigation. Outdoor concentrations were measured in two locations either directly outside the building at ground level or at the air intake of the buildings ventilation system.
2. METHODOLOGY
The 7 Sites monitored to date are shown below in Fig. 1. The sites include a sports centre, a college canteen, two shops, two office buildings (one naturally ventilated one mechanically) and an office/gallery building all of which are located busy street canyons of the city centre in Dublin.

<table>
<thead>
<tr>
<th>Site</th>
<th>Vent type</th>
<th>Run 1</th>
<th>Run 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site 1</td>
<td>Natural</td>
<td>Ground</td>
<td>Ground</td>
</tr>
<tr>
<td>Site 2</td>
<td>Mechanical</td>
<td>Ground</td>
<td>Roof</td>
</tr>
<tr>
<td>Site 3</td>
<td>Mechanical</td>
<td>Roof</td>
<td>ground</td>
</tr>
<tr>
<td>Site 4</td>
<td>Mechanical</td>
<td>Ground</td>
<td>Roof/Ground</td>
</tr>
<tr>
<td>Site 5</td>
<td>Mechanical</td>
<td>Roof</td>
<td>N/A</td>
</tr>
<tr>
<td>Site 6</td>
<td>Natural</td>
<td>Ground</td>
<td>N/A</td>
</tr>
<tr>
<td>Site 7</td>
<td>Natural</td>
<td>Ground</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 1. Ventilation type

For all Sites the ratios of indoor to outdoor concentrations are calculated, which takes account of varying pollutant concentrations. If the ratio is below one, indoor concentrations are below outdoor and if the ratio is above 1 then indoor concentrations exceed outdoor ones. The Sites which were fitted with mechanical ventilation systems would be expected to have greater reductions due to their main air source being at roof level (Wu et al., 2002) rather than at street level where concentrations are higher. The mechanical ventilation systems are also fitted with a filter which removes a fraction of the PM$_{2.5}$ entering the building.

Due to restrictions with equipment, different runs at the Sites had to be carried out in order to gather data at both outdoor locations. During both runs one set of monitors was located outdoors and one set indoors. For one run (Site 4 Run 2) 3 sets of monitors were available which allowed data to be collected at ground level, roof level and indoors simultaneously. Fluctuations in pollutant concentrations were continuously monitored for 3-4 days durations. A specially fabricated steel container housed the outdoor equipment to protect and secure it from the public and weather. At each site wind speed/direction, temperature and humidity...
data were also collected noted as well as details on the building such as prevalence to open windows/doors or if any mechanical ventilation system was used.

3. RESULTS

3.1. INDOOR OUTDOOR RATIOS

3.1.1. PM$_{2.5}$

I/O ratios were highly varied for Site 2 Run 2 during the day with sharp peaks up to 7 regularly (Fig. 2). This pattern changed during non-working hours to settle just below 1. A similar pattern (to a lesser extent) can be seen in Sites 3, 5, 6 and 7. This may be caused by movement within the shops/offices keeping PM$_{2.5}$ suspended during working hours which settles out overnight reducing the I/O.

Sites 6, 7 and 3 are located near each other on the same street. When all indoor concentrations are graphed together, Site 6 and 7 showed higher peaks while Site 3 Run 2 (ground level outdoor monitors) shows low overall PM$_{2.5}$ concentrations compared to the others. Site 6 had an I/O ratio under 1, while both Sites 3 and 7 had working hours ratios of 1.2. The highest working hours I/O was for Site 1 Run 2 and 2 Run 2 at 2.1 and 1.7 respectively. Overnight, only two sites had higher indoor PM$_{2.5}$ concentrations compared to outdoors; these were sites Site 1 Run 2 and Site 3 Run 1 (outdoor monitors on roof level) with I/O of 1.25 and 1.13 respectively.

The lowest I/O for working hours was in Site 2 Run 1 (outdoor monitors on street level) where the ratio was 0.5. The reduction in the ratio (I/O Site 2 Run 2 (roof level outdoor monitors) was 1.7) indicates that the greatest reduction in PM$_{2.5}$ comes from the height between ground and roof level rather than the filtration system on the building. Interestingly Site 3, which had a much newer filtration, system showed lower I/O for roof level with indoor (I/O = 0.8) than for street level (I/O = 1.2).

![Fig. 2 I/O Site 2 Run 1 & 2 PM$_{2.5}$](image_url)

3.1.2. NO$_x$

When indoor and outdoor concentrations were graphed for Site 3 it became apparent that indoor NO$_x$ concentrations did not fall below 10 ppb even when outdoor concentrations fell to almost 0 ppb. This indicates a background indoor source or poor building ventilation which leaves a consistent background NO$_x$ concentration in the building. Within the office there was no clear reason for increased NO$_x$ levels (Fig. 3) although links between the background concentrations and possible sources throughout the building are being investigated. The potential health effects of such increased NO$_x$ levels may also be exaggerated due to the primary use of the building involved as it is a sports facility; i.e. people’s respiratory rates will
be higher through exercise, hence increasing their exposure to air pollutants. When this effect was investigated in other sites similar trends were observed. Increased I/O ratios overnight as the outdoor concentrations reduced the indoor concentrations did not fall proportionately. As the outdoor concentrations rose with morning rush hour and sunrise, the ratios reduced to closer to unity (Fig.4). Site 6 showed consistently low NO$_2$ average I/O of only 0.3 during working hours. I/O for NO was on average higher than for NO$_2$ with all the averages of at least 1 for all sites.

![Fig.3. Indoor & Outdoor concentrations NO$_2$ Site 3 Run 1 & 2](image)

![Fig.4. Comparison of I/O NO$_2$ in Sites 1, 2, 3, 4, 6 & 7](image)

### 3.2. SEASONAL AND DAILY OUTDOOR PATTERNS

Daily diurnal patterns were clear for both NO$_2$ (Fig 6) and PM$_{2.5}$. For NO$_2$, sharp peaks can be see in the morning where the combination of sunrise and morning rush hour push concentrations upwards. Concentrations slowly decreased in the evening to create overnight troughs in the data. Smaller peaks can be seen throughout the day representing evening and lunch time increases in traffic concentrations.

Artinano (2004) noted up to 70% decreases in NO$_x$ concentrations between winter and summer due to changes in photochemical interactions with UV light and ozone. Sites 3 and 4 outdoor monitoring was located at the same point and when compared for December and July 2010 agreement with Artinano’s (2004) findings (Fig. 5). As well as less sunlight in winter, higher concentrations of NO$_x$ are emitted due to greater traffic volumes and colder...
conditions which lead to greater emissions from vehicles. The change in the diurnal pattern that can be seen is the morning peaks beginning later during the winter due to the later sunrises.

![Graph](image)

**Fig. 5 Comparison of outdoor ground level summer/winter NO\textsubscript{2}**

![Graph](image)

**Fig. 6 Comparison of outdoor street level NO\textsubscript{2}**

4. **CONCLUSIONS**

The Indoor / Outdoor air pollutant ratios of PM\textsubscript{2.5} and NO\textsubscript{x} have the opposite relationships during the day and night. During the day PM\textsubscript{2.5} peaked with the re-suspension of dust in the air, this reduces significantly at night. However, the opposite effect was observed with respect to NO\textsubscript{x}, with I/O increasing at night in many buildings. This ratio increase can be put down to reducing outdoor concentrations in conjunction with fewer air exchanges at night when the offices are better sealed (mechanical ventilation off and windows/doors shut). The lack of air changes keeps the higher day time concentrations indoors overnight while the outdoor concentrations reduce. For naturally ventilated office buildings air exchange rates are estimated to reduce from 1.6 ach\textsuperscript{-1} to 0.8 ach\textsuperscript{-1} and mechanically ventilated buildings are estimated to reduce from 1.2 ach\textsuperscript{-1} during working hours to 0.4 ach\textsuperscript{-1} during non working hours (Dimitroulopoulou et al., 2001).

Site 2 showed a significant drop in the PM\textsubscript{2.5} I/O between the two runs, the I/O dropped from 1.7 to 0.5 when the outdoor monitor was moved from the roof (at the air inlet intake) to the
street level. As the mechanical ventilation system was the main source for air within the building this indicates an indoor source increasing PM$_{2.5}$ concentrations or that the entrance to the building was allowing air with higher concentrations of pollutants to enter. As the indoor monitoring was carried out in an area close to a canteen where cooking was taking place this may be the major source of PM$_{2.5}$.

Daily diurnal patterns can be seen for NO$_{x}$ and PM$_{2.5}$. Patterns are particularly clear for NO$_{x}$ with concentrations reducing at night and increasing significantly for morning rush hour / sunrise. The concentrations then tend to slowly reduce during the day although a lower peak for the evening rush hour can be seen. The lowest concentration occurs about 3am. Much more noise in the PM$_{2.5}$ data was seen making patterns harder to discern although in general the I/O were lower than for NO$_{x}$ during working hours. During working hours the I/O ratios showed that ventilation systems provided cleaner indoor air with respect to PM$_{2.5}$ although the same was not always true for NO$_{x}$ (Which varied from site to site with little influence from ventilation systems).

The compliance of Ireland and many other European countries to air quality limit values is based on outdoor air quality; these results show that outdoor monitoring alone may not be enough to quantify true exposures of those working in urban areas.

REFERENCES
