Monitoring CO concentration at leeward and windward sides in a deep street canyon

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Abstract

Carbon monoxide concentration was measured on the two sides of a deep street canyon (aspect ratio = 5.7 and width = 5.8 m). One-minute average CO concentrations were obtained during a three-day monitoring campaign using an NDIR CO spectrophotometer. Traffic flow measurements were carried out in the same period and CO emission rates in the canyon were evaluated using the COPERT procedure. Data on wind direction and intensity measured at a meteorological station few hundred meters from the monitored street canyon are reported and analyzed together with experimental data. Results show that in the street canyon the difference between the two sides of the canyon is negligible regardless of wind direction. Experimental results are confirmed by CFD simulations. This result is in contrast with those reported for street canyons with AR > 1 where on the leeward and windward sides different pollutant concentrations are found when wind direction is mainly perpendicular to the street axis. Simulations carried out with a computer fluid dynamic software show that vehicle-induced turbulence plays a main role in reducing the difference of CO concentration in the two sides of the streets. Our results may be of interest for exposure studies and for developing dispersion models in deep street canyons.

1. Introduction

The spatial variability of air pollution in urban areas creates concern about the representativeness of measurements used in exposure studies (Scaperdas and Colvile, 1999; Vardoulakis et al., 2002). Moreover, it adds complexity to the development of useful air pollutant dispersion models. Air pollutant concentrations show spatial variability at different sites in the same urban area (e.g. background station measurements vis-à-vis those of air monitoring stations in busy streets). Berkowitz et al. (1996) showed that roadside measurements are site-dependent and not representative of the urban area. On a single-street scale, spatial variability has been observed both on a vertical (Vakeva et al., 1999; Chan and Kwok, 2000; Vardoulakis et al., 2002; Murena and Vorraro, 2003) and horizontal basis (Coppalle et al., 2001; Vardoulakis et al., 2002, 2005; Tsai and Chen, 2004). Horizontal variability has mainly been studied on the direction perpendicular to the street axis. Significant differences in concentrations on the two sides have been detected when wind direction is mainly perpendicular to the street axis (Vardoulakis et al., 2002, 2005; Tsai and Chen, 2004). Parametric models such as STREET (Johnson et al., 1973), CPBM (Yamartino and Wiegand, 1986) and OSPM (Berkowitz, 2000) take account of experimental evidence of different pollutant concentration levels on the leeward and windward sides through some empirical formulations. However, most of these studies are concerned with regular street canyons where the aspect ratio (ratio of the height of the surrounding buildings to the street width, H/W) is AR > 1. If AR > 1, and the wind direction is mainly...
perpendicular to the street axis, an induced vortex-like flow inside the canyon takes place (Sini et al., 1996). A single vortex occupies the entire canyon apart from possible smaller dead volumes near the walls (Sini et al., 1996). In this case wind direction at the bottom of the canyon (road level) is the opposite of that at roof top level. The consequence of this flow pattern is that exhausts from any traffic present in the canyon are transported by the vortex circulation towards the leeward side which is thus more polluted than the windward side, where “clean” air arrives from the roof top level (Kim and Baik, 2003). Indeed, a difference, at times significant, between leeward and windward pollutant concentrations, is reported by extensive experimental data (Vardoulakis et al., 2002, 2005; Tsai et al., 2003) and Chen, 2004).

In the case of AR > 1 the flow field inside the canyon changes significantly with respect to AR ≈ 1. If AR > 1.5–2 and the wind direction is mainly perpendicular to the street axis, more than one vortex could be formed, their number depending on the aspect ratio (Sini et al., 1996; Jeong and Andrews, 2002). The flow field in real deep street canyons could actually be even more complex than a multiple counter-rotating vortices flow. CFD simulations show that in real canyons (with cross intersections and wind direction not exactly perpendicular to the street axis) a helicoidal-like flow takes place instead of a pure vortex-like flow. In addition, the effect of vehicle-induced turbulence must be considered. This effect has been studied by several authors in computer simulations (Di Sabatino et al., 2003) and less frequently in wind tunnel studies (Kastner-Klein et al., 2003). Vehicle-induced turbulence can play a major role in determining the dispersion of vehicular pollutants in the bottom part of a street canyon. In a deep street canyon the area of influence of vehicle-induced turbulence can be as large as the whole street width and the stability of the bottom vortex is questionable due to its low velocity. Moreover, the presence of other effects generally not considered in models (e.g. thermal effects) can hinder the formation of the bottom vortex. Therefore, a vortex-like flow could not occur at the road level of a deep street canyon (AR > 1.5–2) and vehicle-induced turbulence would increase mixing in the bottom part of the canyon such that pollutant concentrations on the two sides of a deep street canyon may be assumed the same. In this paper this hypothesis is verified with a three-day monitoring campaign. Our results could be of interest for monitoring and exposure studies and for the development of specific models for deep street canyons.

2. Experimental apparatus

The monitoring campaign was carried out in via Nardones in the urban area of Naples (Fig. 1). The street has the following geometry: width \( W = 5.8 \) m, average building height \( H = 33 \) m (AR = 5.7) and length \( L = 315 \) m. Only one intersection and a side road are present throughout its length. It is a one-way uphill street with an average slope of about 5%. Orientation of the street axis and hence of the traffic flow is in the direction 70°–250° (i.e. from E–NE to W–SW).

The CO concentration was measured at 2.5 m height from the road pavement and 1.3 m from the wall, using a non-dispersive infrared photometer analyzer (ML 9830B Monitor Europe Ltd with lower detectable limit LDL = 0.05 ppm). Sampling started at 9.30 a.m and stopped at 8:30 p.m. The sampling point was shifted each hour from one side of the street to the other (Fig. 1). The operation was completed in a few seconds. The CO analyzer was placed in a storeroom located at the ground level of a building. The lag time due to the distance from the analyzer to the sampling points was less than 1 min.

During the monitoring campaign the traffic flow in Via Nardones was manually measured taking two 5-min measurements per hour. Vehicles were classified into three categories: cars, two-wheelers and “other vehicles” corresponding to light commercial vehicles. The “Computer Program to Calculate Emission from Road Transport” COPERT procedure (Ntziachristos and Samaras, 2000) was adopted to evaluate the average CO emission factors corresponding to each class of vehicle. Then the CO emission rate [g/h] in the street canyon was obtained.

More information on the street canyon geometry, the calibration procedure of the CO analyzer and use of the COPERT procedure are reported in Murena and Favale (2007).

3. Results

Via Nardones is a deep street canyon in the old centre of Naples. Benzene vertical gradients (Murena and Vorraro, 2003) and results of a CO continuous monitoring campaign (Murena and Favale, 2007) have been reported for the same street. Both papers show that due to poor ventilation and the relatively high traffic flow, Via Nardones is a hot spot for atmospheric pollution in the urban area of Naples. Following the traffic direction, it is essentially east–west oriented. Therefore, the two sides of the street are indicated, in this paper, as north and south (Fig. 1). To obtain hourly average CO concentrations at both sides of the street canyon, it was necessary to shift the sampling point each hour from one side to the other because our experimental apparatus did not give simultaneous measurements on both sides since only one analyzer was available. In Fig. 2 the 1-min average concentrations of CO measured on the north and south sides of Via Nardones from Monday 16th to Wednesday 18th April 2007 are reported. Since the shifting operation of the sampling point was completed in a few seconds and the lag time due to the length of the sampling

![Fig. 1. Map and cross-section of the street canyon with sampling points.](image-url)
Fig. 2. One-minute average CO concentrations.
Fig. 3. Hourly average CO concentrations in the street canyon.
tube (\(\equiv 30 \text{ m}\)) was less than 1 min, the concentrations reported in Fig. 2 can be considered as 1-min average concentrations in the street canyon at the corresponding sampling point. It can be observed that there are no steps, positive or negative, when the sampling point was shifted from one side to the other. The only exception is on the 17th at 17:30 when, on shifting the sampling point from the south to the north side, the concentration instantaneously increased from 1.5 to 2.0 mg/m\(^3\). The CO concentration levels measured during the monitoring campaign were generally low, but some spikes were detected. Major spikes occurred on the 16th at 16:15; on the 17th at 15:00 and on the 18th at 18:00. The decrease in concentration after the very rapid increase corresponding to the events reported above, generally took about 1 h. This time is consistent with the evaluation of average residence time of pollutants in a street canyon reported by Murena and Ricciardi (2005). During each hour the sampling point was positioned 30 min on one side and 30 min on the other (Fig. 1). On the basis of data reported in Fig. 2, 30-min average CO concentrations, on each side, were evaluated and assumed as hourly average values. Hourly average CO concentrations are reported as histograms in Fig. 3 where it may be observed that north and south side concentrations are very similar. When there is a significant difference it may be attributed to non-simultaneous measurements and not to an actual difference between the two sides (see, for example, the apparently high difference in hourly average values at 10:00–11:00 a.m. on the 16th in Fig. 3, actually due to the time concentration decrease as shown in Fig. 2). Therefore, both Figs. 2 and 3 constitute the first experimental evidence that north and south side concentrations are very similar at the same time. The same evidence emerges if CO daily averages measured on the south and north sides of the street canyon are considered (Table 1). On the whole the average during the three-day monitoring campaign was 2.26 mg/m\(^3\) on the south side and 2.18 mg/m\(^3\) on the north, which are very similar values again. For a better comparison of the CO concentrations measured on the two sides of the street canyon the ratio

\[
R = \frac{C_{\text{high}}}{C_{\text{low}}} \tag{1}
\]

between the two sides was determined. In Eq. (1) \(C_{\text{high}}\) and \(C_{\text{low}}\) are, respectively, the higher and lower CO values measured on the south and north sides of the street canyon at the same hour (it is always \(R \geq 1\)). Table 1 shows the daily average and the hourly maximum values of the ratio \(R\). Daily averages of \(R\) are in the range 1.08–1.14, while if the entire three-day monitoring campaign is considered the ratio is 1.04. In data reported in Table 1 values measured at 9:00–10:00 on the 16th and 16:00–17:00 on the 18th were not considered because they would give an erroneous evaluation of \(R\). Also maximum hourly values of \(R\) (Table 1) are not very high (1.52–1.95) and would probably be lower if sampling was instantaneous on both sides. In a street canyon where AR \(\equiv 1\), \(R\) ratios are generally much higher than those reported in Table 1. In a one-week monitoring campaign in Paris a ratio of 2.6 at \(h = 1.5 \text{ m}\) and 2.2 at 2.6 m is reported for benzene (Vardoulakis et al., 2005). For the same pollutant ratios of 1.8 at 4.2 m (AR = 0.8) and 1.6 at 1.6 m (AR = 1.1) are reported for a five-day (weekday) monitoring campaign (Vardoulakis et al., 2002). Importantly, such data refer to observations averaged over a longer time (one week or five days). If a shorter averaging time was considered (three days, as in this paper) still higher values of the ratios would be expected.

In Fig. 4 diurnal averages of CO concentrations measured on both sides and CO emission rates in the street canyon are reported. The correlation coefficient between vehicle exhaust emissions and CO concentration is very low (\(R^2 = 0.076\)). The highest CO concentrations are reached in the early morning or in the evening while the lowest are measured in the early afternoon in agreement with previous findings (Murena and Favale, 2007). The minimum CO concentration in the early afternoon does not correspond to the minimum CO emission rate (Fig. 4). The low correlation coefficient reported in Fig. 4 is an indication that meteorological parameters play a dominant role in determining CO concentrations even in a deep street canyon.

In Fig. 5 a wind rose graph with data measured during the three-day monitoring campaign is reported. Data were measured at a meteorological station a few hundred metres from the street canyon. For a better understanding of the correlation between wind direction and values of \(R\), hourly average angles of incidence (\(\alpha\)) of the wind with respect to the street axis (70–250°) were determined. For wind perpendicular to the street axis \(\alpha = 90°\), while for wind parallel to the street axis \(\alpha = 0°\). In Fig. 6 hourly \(R\) ratios are reported against the angle of incidence of wind direction \(\alpha\).

### Table 1

<table>
<thead>
<tr>
<th>Day</th>
<th>CO daily average South [mg/m(^3)]</th>
<th>CO daily average North [mg/m(^3)]</th>
<th>(R) Daily av. values</th>
<th>Maximum hourly values</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1.35</td>
<td>1.25</td>
<td>1.08</td>
<td>1.52</td>
</tr>
<tr>
<td>17</td>
<td>2.35</td>
<td>2.59</td>
<td>1.10</td>
<td>1.95</td>
</tr>
<tr>
<td>18</td>
<td>3.09</td>
<td>2.71</td>
<td>1.14</td>
<td>1.59</td>
</tr>
<tr>
<td>16–18</td>
<td>2.26</td>
<td>2.18</td>
<td>1.04</td>
<td>1.95</td>
</tr>
</tbody>
</table>

![Fig. 4](image-url) Diurnal averages of CO and emission rates during the three-day monitoring campaign.
\( \alpha \) ranges between 10° (wind direction mainly parallel to the street axis) and 80° (wind direction mainly perpendicular to the street axis). There is no correlation between the angle of incidence and the ratio \( R \), and even though the wind direction is mainly perpendicular (\( \alpha > 60° \)) the value of \( R \) is \( \approx 1 \). Fig. 6 shows clearly that in our deep street canyon leeward and windward sides do not actually exist. As a consequence, parametric models developed and tested for street canyons with AR \( \approx 1 \) that assume the existence of a leeward and windward side would give inconsistent results if adopted for a deep street canyon. Indeed, poor agreement between CO concentrations measured in our street and those modelled with OSPM was obtained (Favale et al., 2007). The CO concentrations measured were significantly higher than those modelled. It was necessary to apply a reduction of the street level wind speed calculated by OSPM by an empirical factor of 10, so that OSPM results could be appreciably improved. Significant differences in CO concentration at the pedestrian level on the north and south sides as result of CFD simulations are reported (Favale et al., 2007). This is in contrast with experimental results shown herein which demonstrate that CO concentration is the same on both sides of the street whatever the angle of incidence. Importantly, the CFD simulations reported by Favale et al. (2007) did not consider the effect of vehicle-induced turbulence.

In order to investigate on the influence of the wind direction and intensity and vehicle-induced turbulence on the CO concentration at the south and north sides of the street canyon "computer fluid dynamic" (CFD) simulations were carried out using the software FLUENT. Six wind directions were selected on the basis of the more frequent directions as reported in wind rose graph of Fig. 5. Wind direction was assumed in all the case as 2 m/s at the reference height of 50 m from the ground level. In order to consider the not uniform wind characteristics, caused by the friction with the urban ground, we used the functions in Eqs. (2)-(4) so as to take into account the wind velocity and turbulence change with the height:

\[
v = v_t \left( \frac{z}{z_t} \right)^m
\]

\[
k = \beta v^2
\]

\[
\epsilon = C_k \frac{z^3}{k} \left( \frac{k}{\nu z} \right)^{3/2}
\]

where \( m = 0.28; \beta = 3 \times 10^{-2}; C_k = 9 \times 10^{-2} \) and \( k \) is the Von Karman constant = 0.41. \( v_t \) and \( z_t \) in Eq. (2) are, respectively, a reference velocity and a reference height. The geometric domain representing the street canyon was created using the software GAMBIT. The domain was meshed with two different approaches; the volume inside the canyon was subdivided with a uniform method by bricks with edges 1 m large, while volumes outside the canyon were meshed with a not uniform tetrahedral method in order to limit the computational effort. Simulations were carried out using a steady RANS model with a \( k-\epsilon \) RNG turbulent closure method. In order to take into account the effects of mechanical turbulence generated by the traffic within the canyon a Turbulence Kinetic Energy production in the bottom part of via Nardones was introduced using the function in Eq. (5)

\[
P_T = \frac{\rho C_{D_T} A_T n_T v^3}{B H}
\]

where \( \rho \) is the air density, \( C_{D_T} \) is the drag coefficient, \( A_T \) the vehicle frontal area, \( v \) the average velocity of the vehicles, \( n_T \) the number of vehicles per unit length, \( B \) the canyon width and \( H \) a characteristic height. Fig. 7 reports the values of ratio \( R \) (Eq. (1)) calculated by FLUENT in correspondence of the sampling points (Fig. 1). Fig. 7 shows that if vehicle-induced turbulence is not introduced in computer simulations, CO concentration ratio (\( R \)) at two sides of the street canyon may assume high values depending on the wind direction. If vehicle-induced turbulence is considered, the value of \( R \) is always about one as observed during the monitoring campaign. Therefore, vehicle-induced turbulence plays a determinant role in making CO concentration at the two sides of the street very similar.

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**Fig. 5.** Wind direction and intensity during the monitoring campaign.

**Fig. 6.** Scatter plot of the ratio \( R \) of CO concentration on the two sides of the street canyon and the wind direction as angle of incidence.

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\( R \) is the value of the ratio of CO concentration on the two sides of the street very similar.
4. Conclusions

In a deep street canyon with AR = 5.7, CO concentrations on the two sides of the canyon at pedestrian level are very similar. This was proved in a three-day monitoring campaign with wind direction varying from 10° to 80° as angle of incidence with the street axis. The average ratio between south side/north side CO concentrations throughout the monitoring campaign was 1.04. This result shows how deep street canyons behave differently with respect to street canyons where AR ≈ 1. This appears to be a consequence of two different effects: (i) the flow field inside the canyon is much more complex than the simple vortex-like flow generated in a street canyon with AR = 1. Therefore, a single vortex-like flow does not form, and the leeward and windward side with respect to the vehicle exhaust line source cannot be defined; (ii) vehicle-induced turbulence due to the limited width of the street (W = 5.8 m) plays a determining role in mixing the pollutants and making the pollutant concentrations quite uniform as shown by CFD simulations. This experimental result is of interest in the development of both exposure studies and dispersion models. Results of parametric dispersion models developed for street canyons with AR ≈ 1 are not reliable if applied to deep street canyons. Deep street canyons require the development of specific parametric dispersion models.

References