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Continuous monitoring of carbon monoxide in a deep street canyon

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Abstract

The results of a 1-week continuous monitoring campaign of carbon monoxide in a deep street canyon in the city of Naples are reported. CO was selected as a passive pollutant emitted by vehicle exhausts. The geometry of the canyon is: width $W = 5.8$ m and height $H = 33$ m (aspect ratio AR $= H/W = 5.7$). The monitoring campaign was carried out from 14 to 20 June 2006. CO concentration level was measured at pedestrian level ($h = 2.5$ m) and roof top level ($h = 25$ m). In the same period traffic flow in the street canyon was manually measured and the CO emission rate from vehicle exhausts was evaluated using the COPERT procedure. Meteorological conditions (wind velocity and direction) are also reported and their effect on CO concentration level in the canyon is discussed. Due to its geometry the street canyon monitored may be considered almost ideal. The results show that the deep street canyon is a "hot spot" compared with roads with high traffic flows in the urban area of Naples, and that significant differences exist between concentration levels at pedestrian and roof top level. Some insights into the effect and relative importance of meteorological parameters on the air quality in the canyon are also given. The monitoring data collected have been made available on the web and can be used by other researchers to test air dispersion models.

Keywords: Deep street canyon; CO; Continuous monitoring; Air quality; Modelling

1. Introduction

Urban air quality is a problem characterized by very different spatial scales (Soulhac et al., 2003), ranging from the regional scale (100 km) to local or street scale (100 m) (Vardoulakis et al., 2002a). Local scale modelling in urban areas uses the street canyon as standard reference. Many papers are involved with modelling or wind tunnel studies to give an insight into the fluid dynamics inside street canyons and on the mass exchange between canyons and the upper or surrounding atmosphere. The ideal street canyon is an infinite-length rectangular cavity, open in its upper part. Its geometry is characterized by the aspect ratio AR $= H/W$ (height/width). Depending on the AR values, different flow regimes have been identified. When the aspect ratio H/W is higher than 0.7 and L/H is >2, the flow regime is classified as skimming flow (Sini et al., 1996). In this flow regime the wind velocity component orthogonal to the street axis generates a large vortex inside the canyon. In very narrow street canyons ($H/W>1.7$ Sini et al., 1996) two ($H/W>2$) or more ($H/W>3$) vortices are formed. In our case it is $H/W = 5.7$. Therefore, more than two vortices

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would form. It must be remembered that this holds for an ideal street canyon where the wind direction is exactly orthogonal to the road axis. For oblique roof-level winds a spiral wind flow is induced inside the canyon. The flow along the street axis becomes the dominant pollutant transport mechanism for wind direction deviating by only 15° from the orthogonal direction (Savory et al., 2004). Other important feature is that in narrow street canyons a high reduction of mean horizontal velocity is observed (Sini et al., 1996). The simultaneous presence of multi-vortices and of low wind velocities inside a deep street canyon could cause a high concentration of vehicle pollutants at pedestrian level. Indeed, fairly high benzene concentration levels were measured in the street canyon in question in 2–6-day sampling using passive traps (Murena and Vorraro, 2003).

In the literature reference is generally made to street canyons with AR < 1.7 (Chan and Kwok, 2000; Baik and Kim, 2002; Vardoulakis et al., 2002b; Tsai and Chen, 2004). Data on air quality in deep street canyons are rarely reported since in many cases the streets are narrow and it is difficult to set up monitoring stations or analyzers. This is the case of many old urban historical centers: in such urban areas population density is often very high, with many commercial (shops, offices, artisanal workshops) or public (schools, public administration) attractors. As a consequence, traffic exhaust emissions could be significant and air quality rather low (Murena and Vorraro, 2003).

In this paper the results of a 1-week continuous monitoring campaign are reported. Carbon monoxide concentration levels at 2.5 and 25 m height from the road pavement were measured and reported together with vehicular emissions and meteorological parameters. This paper also aims to provide some insights into the effect of the main meteorological parameters on air quality in deep street canyons through the analysis of the monitoring data. Hourly average CO concentration levels and emission rate, together with meteorological parameters, are available at http://www.docenti.unina.it/docenti/web/index.php?id_prof=611 (download from "Area pubblica del docente") for researchers interested in testing air dispersion models in deep street canyons.

2. Experimental procedure and analytical technique

The monitoring campaign was carried out in via Nardones in the center of Naples a few hundred meters far from the coastline. 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 cross-road 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 two sampling points. One was located at 2.5 m height from the road pavement and 1.3 m from the south wall, representing the concentration at pedestrian level. The other was on the same side at 25 m height and represents roof top level concentration.

Two different CO analyzers were adopted. At $h = 2.5$ m the CO concentration levels were measured using a non-dispersive infrared photometer analyzer (ML 9830B Monitor Europe Ltd with lower detectable limit LDL = 0.05 ppm). Multi point calibration was carried out using a gas cylinder at 35.6 ppm_v of CO in nitrogen (SIAD SpA) and a 11-point gas divider (HORIBA) before starting the monitoring campaign. Linearity error was <1%. Calibration of the instruments was checked each day during the monitoring campaign, carrying out zero and span operations. The span operation was performed using the same gas cylinder. Zero and span adjustments during the monitoring campaign were very limited. One-minute average concentrations were stored by the ML 9830B analyzer and downloaded on a laptop during the campaign. At the higher sampling point ($h = 25$ m) a monitoring station (ETL 2000 UNITEC srl) using thick film sensors was adopted. Hourly average CO concentrations were evaluated by the ETL station and transmitted by a GSM modem to a remote PC installed at the Chemical Engineering Department. To calibrate the ETL station simultaneous measurements of CO at $h = 25$ m were carried out using both the analyzers. A plan view of via Nardones and a cross section of the street canyon are reported in Fig. 1.

During the monitoring campaign the traffic flow in via Nardones was manually measured from 8 am to 9 pm taking two 5 min measurements per hour. Vehicles were classified into three categories: cars, two-wheel vehicles and "other vehicles" corresponding to light commercial vehicles. On weekdays the total traffic volume from 8 am to 9 pm was on average 2943 cars, 2509 two-wheel vehicles and 141 light commercial vehicles. On Saturday total volume of traffic from 8 am to 9 pm was 1889; 1394

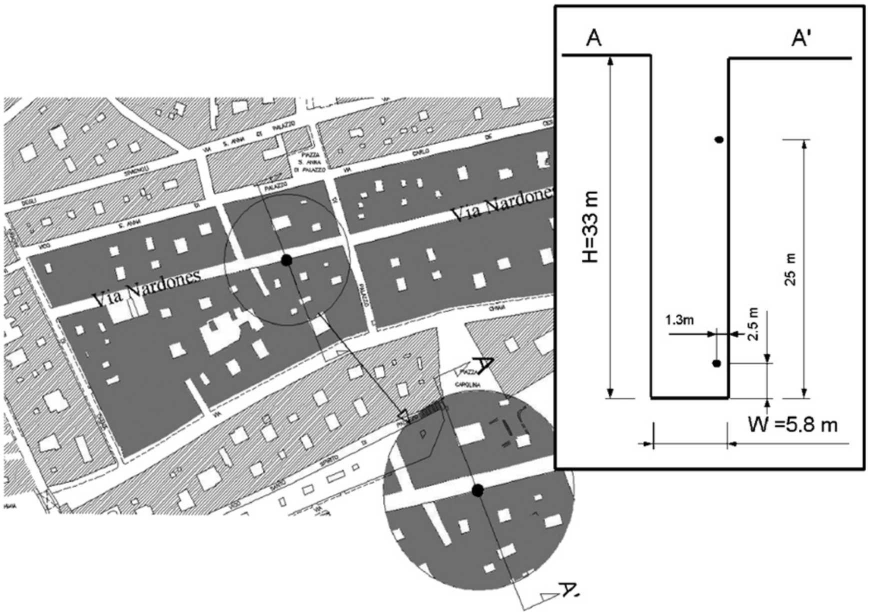

Fig. 1. Plan view of via Nardones and surrounding streets (left). Cross-section of the street canyon (right) with sampling points. Direction of slope and traffic flow is from right (east) to left (west).

and 72 respectively, while on Sunday it was 1266, 519 and 18. Saturday and Sunday data are estimates because not all hourly average data were available.

The COPERT procedure (Ntziachristos and Samaras, 2000) was adopted to evaluate the average CO emission factors corresponding to each class of vehicle and then the CO emission rate ($\mathrm{g\,h^{-1}}$) in the street canyon. The average time which vehicles took to travel the whole length of the street canyon was measured to evaluate the average vehicle speed. The values measured were in the range 20–30 $\mathrm{km\,h^{-1}}$. A value of 20 $\mathrm{kmh^{-1}}$ was assumed in COPERT procedure. Effects on the emission rate due to cold start, slope, congestion or queuing traffic were neglected. Congestion or queuing traffic occurred sometimes between 8 pm and 9 pm for a few minutes and rarely at other times. Using the 2004 fleet data, the following averaged emission factors were deduced: cars = 10.3 $\mathrm{g\,km^{-1}}$, two-wheel vehicles = 17.3 $\mathrm{g\,km^{-1}}$ and "other vehicles" = 5.3 $\mathrm{g\,km^{-1}}$. Hence the emission rate (E = $\mathrm{g\,h^{-1}}$) in the canyon was evaluated as

$$E = \sum_{i=1,3} (f_i \times N_i \times L), \qquad (1)$$

where f_i is the average emission factor of i-class of vehicles ($\mathrm{g\,km^{-1}}$), N_i is the number of vehicles per hour [$\mathrm{h^{-1}}$] belonging to the i-class, and L (km) is the street canyon length ($L = 315$ m). The index i ranges from 1 to 3 and represents the three defined classes of vehicles.

3. Results

Fig. 2 shows 1 min average CO concentrations vs time measured at $h = 2.5$ m from 14 to 20 June (concentrations are reported in $\mathrm{mg\,m^{-3}}$ under standard reference conditions of $T = 273.15$ K and $P = 100$ kPa). It can be observed that CO concentrations exceeding the limit value established by EC (limit value = 10 $\mathrm{mg\,m^{-3}}$ at standard temperature and pressure conditions $T = 273.15$ K and $P =$ 100 kPa as 8-h running average) were measured, albeit for a limited time interval. Concentrations of CO were greater than 10 $\mathrm{mg\,m^{-3}}$ in 265 min out of 9475 corresponding to the 97.2 percentile. Fig. 3 shows a comparison of diurnal average curves obtained with data of CO measured on weekdays from 14 to 20 June at via Nardones ($h = 2.5$ m) and at the permanent air quality monitoring stations in the urban area of Naples, indicated in figure as NA1, NA4 and NA7. NA1 is located in the center of Naples but in a relatively scarcely urbanized area far from roads with high traffic loads (background station), while the others (NA4 and NA7) are located in high traffic flow street canyons with AR$\cong$1. Sampling height of permanent stations is $h = 3$ m. It

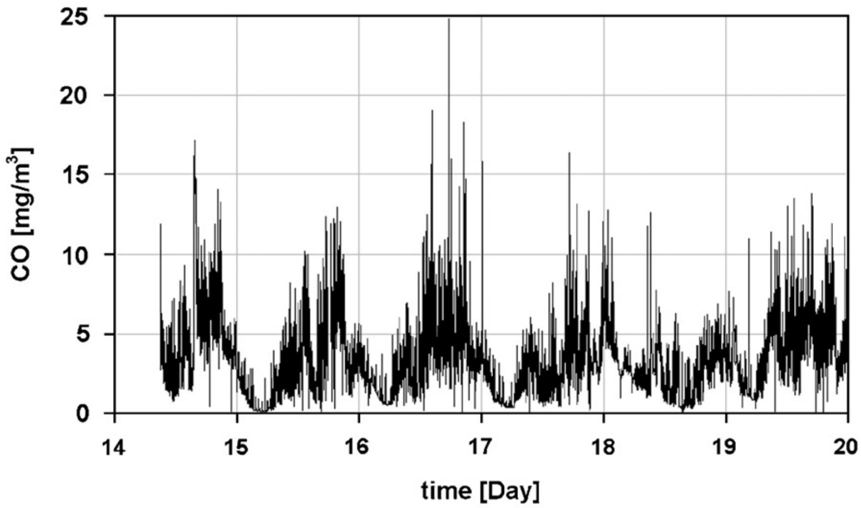

Fig. 2. Via Nardones: CO concentration levels (1-min averages) measured during the monitoring campaign (14–20 June) at $h = 2.5\,m$.

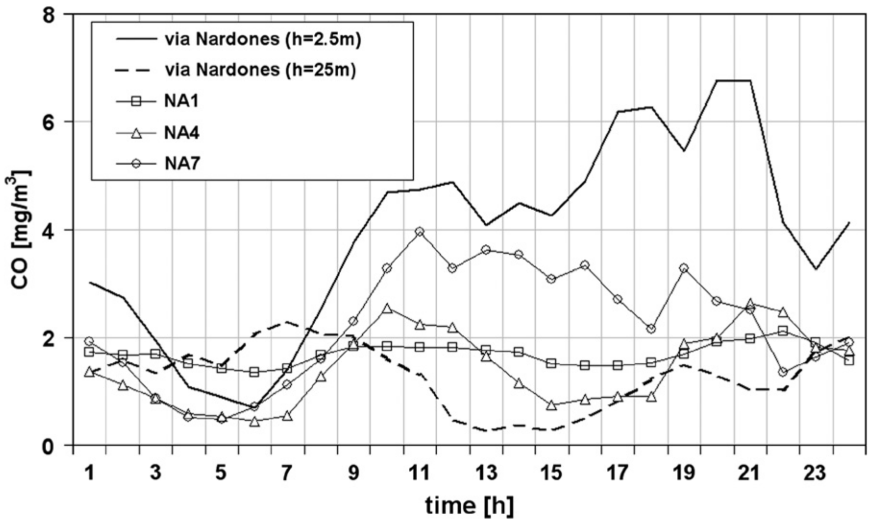

Fig. 3. Diurnal averages of CO concentrations measured in the deep street canyon (via Nardones $h = 2.5\,m$ and $h = 25\,m$) and at permanent air quality monitoring stations located in the urban area of Naples (NA1, NA4 and NA7). Data refer to week-days (Monday–Friday) from 14 to 20 June.

may be noted that CO concentration levels in the deep street canyon are higher than those measured by the permanent air quality monitoring stations located in the urban area of Naples. For a quantitative comparison of curves reported in Fig. 3 some statistical parameters were evaluated (Table 1).

At roof top level ($h = 25\,m$) lower CO concentration levels than at pedestrian height ($h = 2.5\,m$) are expected. Fig. 4 shows the comparison of hourly average values of CO concentrations measured at $h = 2.5\,m$ and 25 m. The concentration of CO at 2.5 m is generally greater than that at 25 m but during the night this is sometimes reversed. The ratios between the concentration at pedestrian level and roof top level (C_p/C_r) for different pollutants are reported in the literature: the C_p/C_r ratio depends on the aspect ratio, external conditions (meteorology), and the specific pollutant (the last only if reacting or secondary pollutants are considered). For two street canyons with AR$\cong$1 (heights in the range 17.2–20.2 m) the C_p/C_r ratio of average benzene concentration (2-day and 5-day averages) ranges between 1.5–1.9 ($h = 1.6\,m/h = 17.8\,m$) (Vardoulakis et al., 2002b). For the same street canyon as this paper a C_p/C_r ratio

Table 1
Statistical parameters of data in Fig. 3

	Via Nardones $h = 2.5$ m	Via Nardones $h = 25$ m	NA1	NA4	NA7
Average in the period 14–20 June	3.7	1.4	1.7	1.4	2.1
Max hourly averages	9.4	3.6	2.8	4.1	6.8
Max 8 h running averages	6.5	3.2	2.2	2.7	4.7

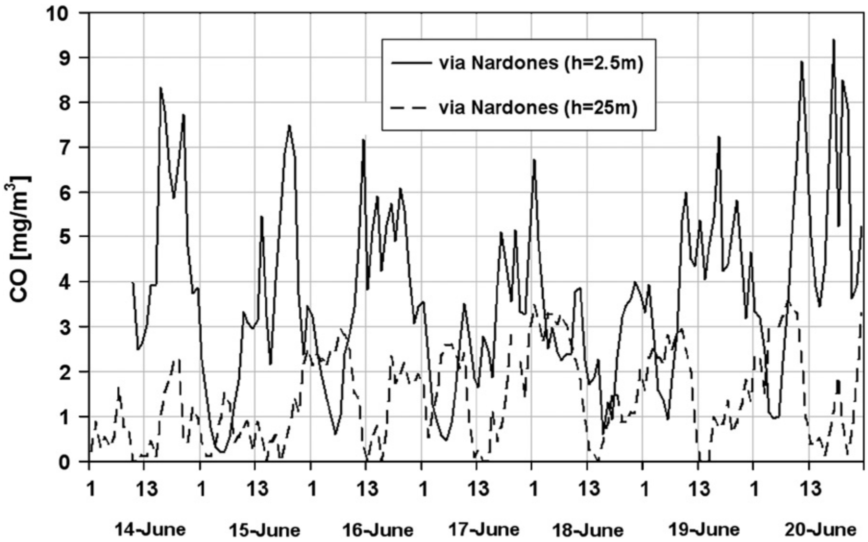

Fig. 4. Via Nardones: hourly average values of CO concentrations measured at $h = 2.5$ m (solid line) and $h = 25$ m (dashed line).

of average concentrations for benzene of 3.1 is reported (Murena and Vorraro, 2003). From data measured during the present monitoring campaign the C_p/C_r ratio of concentration levels averaged on the period of the monitoring campaign ($\sum_{i=1...n} C_{p,i}/C_{r,i}$), where n is the number of hourly data, is 2.6 (3.1 if only week-days are considered). If night hours, where it is sometimes $C_r > C_p$, are excluded and only the data from 7 am to 9 pm are considered then the ratio is 3.5 (4.2 on week-days). Besides evaluating C_p/C_r as the ratio of average concentration levels it could be more appropriate to determine average hourly C_p/C_r ratios $\left(\sum_{i=1...n}(C_{p,i}/C_{r,i})/n\right)$. In this case, the average hourly ratio is 5.0 (which is 6.8 if only data from 7 am to 9 pm are considered). Finally, if only weekdays are considered the ratios are, respectively, 5.9 and 8.0. In Table 2 the different C_p/C_r ratios are summarized.

Fig. 5 shows the relationship between the CO emission rate produced by vehicles in the street canyon (evaluated with the COPERT procedure) and the CO concentration measured at $h = 2.5$ m. As expected, a relationship exists but only to a partial extent.

On the basis of the collected data diurnal averages in weekdays (Monday–Friday) of the emission rate, CO concentration at $h = 2.5$ and 25 m are obtained and reported in Fig. 6. The bars on both the CO concentration curves correspond to the confidence interval CI = 90% referred to the range of data within the average. Averaging the data over the 5 week-days shows a clearer relationship between CO concentration level at $h = 2.5$ m and CO emission rate in the street canyon. But some discrepancies still remain: (i) reduction in the CO concentration level (from 12 noon to 2 pm) in correspondence to an increase in the CO emission rate; (ii) the higher concentrations in the evening (from 5 pm to 7 pm) compared with values measured in the morning (from 12 noon to 1 pm) in correspondence to similar CO emission rate. To clarify this point a specific experiment was carried out measuring for half an hour the vehicle flow minute by minute and obtaining 1 min average CO emission rates. The comparison between 1 min average CO concentrations at $h = 2.5$ and CO emission rates in a half hour period is reported in Fig. 7. No relationship

Table 2
Via Nardones C_p/C_r: ratios of CO concentration at pedestrian level ($h = 2.5$ m) to roof top level ($h = 25$ m)

C_p/C_r	Week-days and week end		Week-days	
	0:00–24:00	7:00–21:00	0:00–24:00	7:00–21:00
Ratio of average hourly concentration	2.6	3.5	3.1	4.2
Average of hourly ratios	5.0	6.8	5.9	8.0

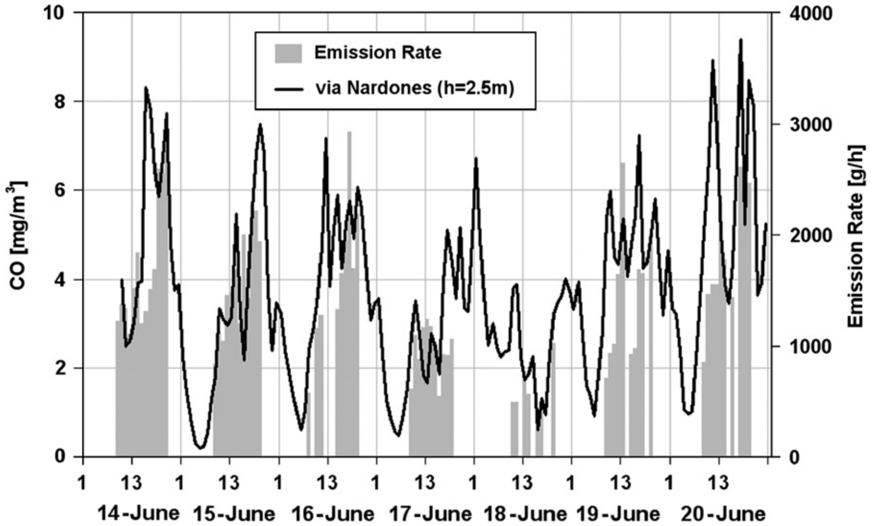

Fig. 5. Via Nardones: hourly average CO concentration level at $h = 2.5$ m and CO emission rate evaluated with COPERT procedure.

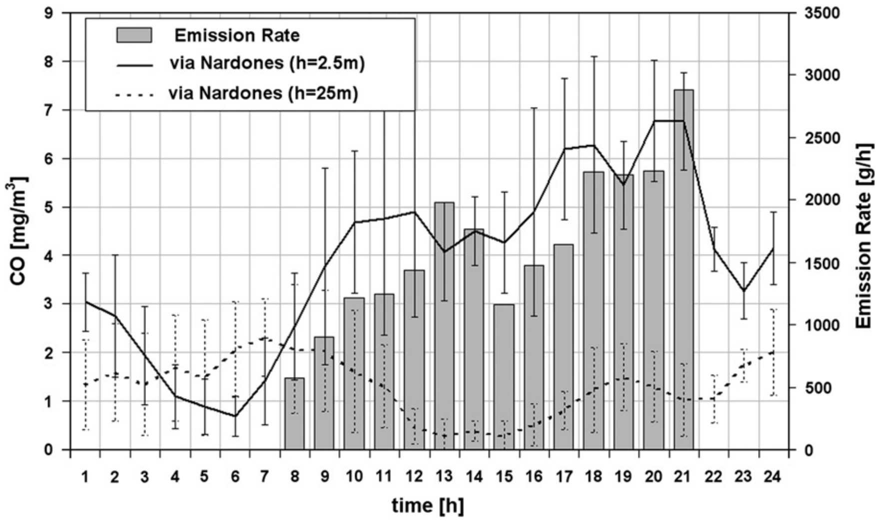

Fig. 6. Via Nardones: diurnal averages on weekdays (Monday–Friday) of CO concentration measured at $h = 2.5$ m, $h = 25$ m and emission rate.

seems to exist between the two patterns. The comparison of CO concentrations at pedestrian height ($h = 2.5$) and emission rate evaluated by manual measurements and application of the COPERT procedure requires analysis in a greater depth. Fig. 5 and, to a greater extent, Fig. 7 show a low correlation, while Fig. 6 shows a better correlation. It must be remembered that the CO

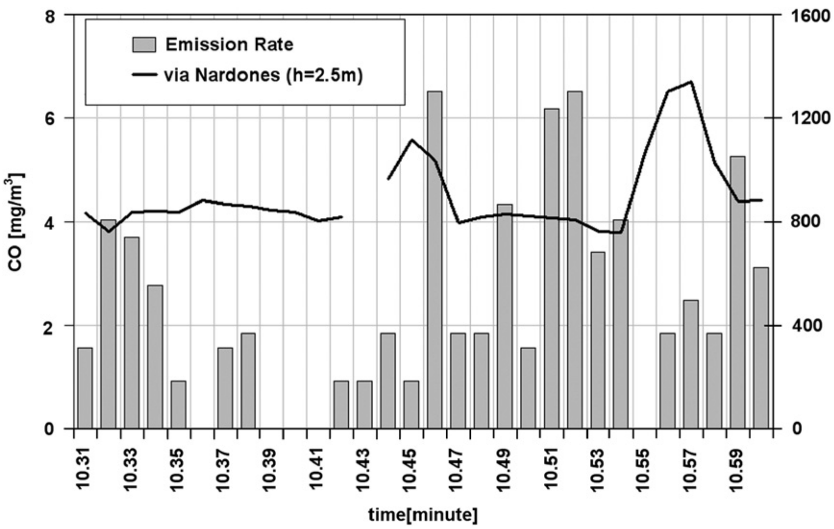

Fig. 7. One-minute average CO concentration at $h = 2.5\,m$ and CO emission rate.

emission rate was obtained by determining an average emission factor for each of the three vehicle classes considered (see the previous paragraph). In the case of cars, for example, the CO emission factors, as reported in the COPERT database, range from about 1 to $40\,g\,km^{-1}$ depending mainly on the fuel and the year of construction. Therefore, the procedure adopted, based on average values of emission factors, is a rough evaluation of actual emission rates. It is reliable when applied on a large number of vehicles. This is rather the case of data in Fig. 6 where diurnal average is considered and the emission rates are evaluated on the number of vehicles measured in the same time slice on five different days. In Fig. 5 emissions are evaluated on the number of vehicles measured in a single hour and in Fig. 7 in a single minute. Therefore, results in Figs. 5 and 7 are much more dependent on the specific vehicle running in the street canyon, which might explain the low correlation between CO concentration levels and emission rates in Figs. 5 and 7.

For a better understanding of the results of CO monitoring in the street canyon hourly average wind speed and wind direction measured by a permanent station sited at roof top level in the centre of Naples not far from via Nardones are reported in Fig. 8. The wind direction is where the wind is blowing from. The rose wind graph in Fig. 9 shows that during the monitoring campaign the wind direction was generally from E–SE. In Fig. 10 the diurnal averages of wind velocity and direction over the whole seven-day monitoring campaign are reported. Wind directions reported in Fig. 10 were obtained as the most frequent direction per hour considering sectors of 22.5 degrees.

Figs. 8 and 10 show that during the monitoring campaign wind velocity (WV) reached a maximum from noon to 4:00 pm ($WV \cong 3\,m\,s^{-1}$). At night-time wind velocity was at a minimum ($WV \cong 0.5\,m\,s^{-1}$). Wind direction was E–SE during the day, and N in the night. This is typical of the breeze wind regime characterizing the urban area of Naples.

In Fig. 11 diurnal CO averages over the five weekdays at $h = 2.5$ and $25\,m$ together with the CO emission rate in the street canyon, wind velocity and wind direction are reported. Fig. 11 shows that the main effect which could explain the reduction of the CO concentration from 12 noon to 2 pm and the high concentration levels observed in the evening (from 5 to 7 pm) is the pattern of CO concentrations at roof top level ($h = 25\,m$) which decreases significantly in the afternoon and increases at night. Several meteorological parameters could play a role in determining the patterns reported in Fig. 11. We guess that the most important are: the breeze regime, wind intensity and mixing height. The urban area of Naples and its surroundings are located mainly from NE to NW of via Nardones while the sea (Bay of Naples) from SE to SW. Therefore, when the wind direction was from E–SE it came mainly from the sea and contributed to a reduction in CO at $h = 25\,m$. In contrast, when the wind was from the north it collected all the emissions of the urbanized area north of via Nardones and CO at $h = 25\,m$ reached maximum

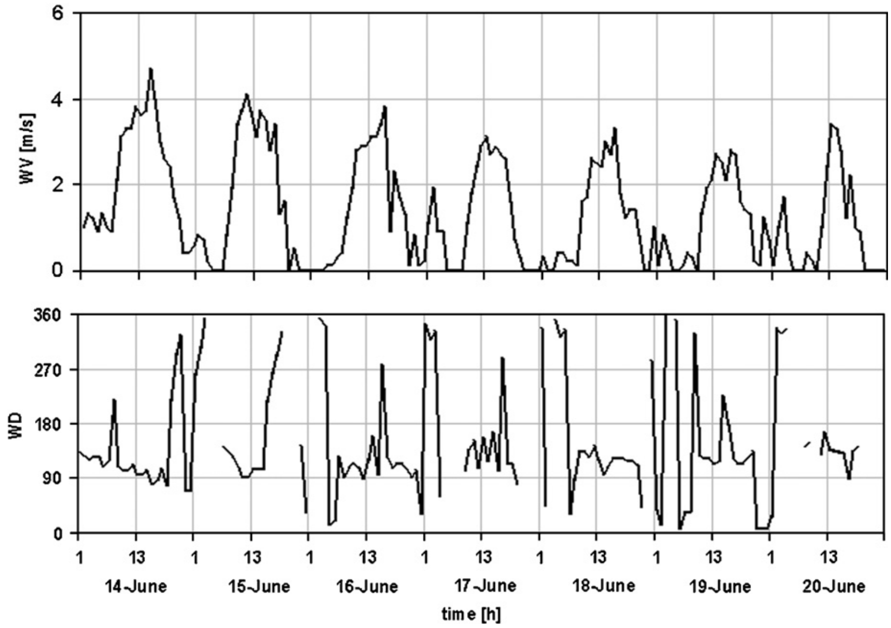

Fig. 8. Hourly average wind velocity WV (above) and wind direction WD (below) at roof top level.

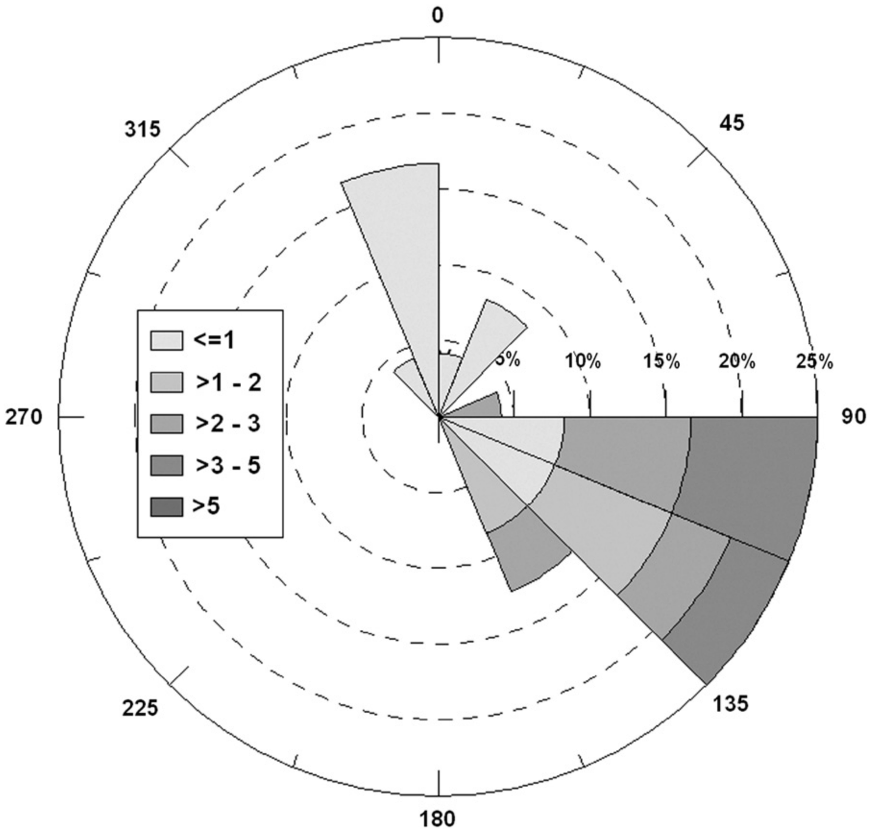

Fig. 9. Rose wind graph. The numbered scale is wind velocity [$m\,s^{-1}$].

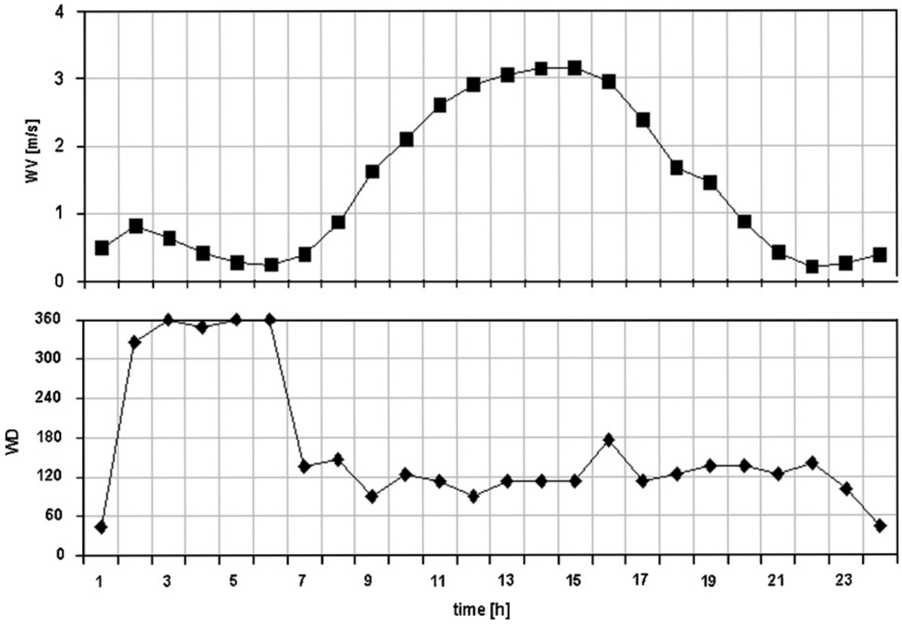

Fig. 10. Diurnal averages of wind velocity WV (above) and wind direction WD (below) measured by a permanent meteorological station in the urban area of Naples at roof top level over the whole seven-day monitoring campaign.

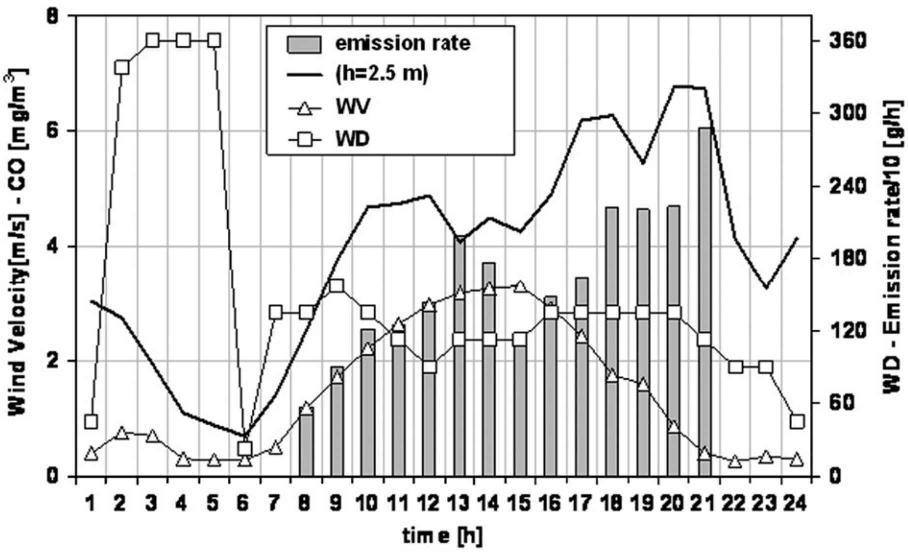

Fig. 11. Via Nardones: diurnal averages on weekdays (Monday–Friday) of hourly average CO concentrations at $h = 2.5$, 25 m, wind velocity (WV), wind direction (WD) and emission rates.

values. At same time it would be considered that wind velocity drops to a minimum from 9 pm to 7 am, while mixing height is at a maximum in the early afternoon. All these parameters lend an important contribution to the patterns during the day of both CO concentrations at roof top level and the C_p/C_r ratio. Another parameter to be considered but that cannot be assessed from our data is the thermal effect inside the canyon due to the road heating resulting from solar irradiance.

The experimental findings of CO at $h = 25\,m > CO$ at $h = 2.5\,m$ in the night hours from 3 to 7 may depend on a complex combination of emission rates and meteorological conditions. At night time emissions in the canyon are at a minimum and hence concentrations in the street canyon decrease significantly; low wind velocity and high atmospheric stability could contribute to reduce the mass exchange between the canyon and the upper atmosphere. In this case the CO level at $h = 25\,\mathrm{m}$ could depend more on CO transported by the wind from the northern part of the town (the wind blows from the north in night hours) than on the CO emitted in the canyon itself. Indeed, this phenomenon was much more limited in the night between Saturday (17 June) and Sunday (18 June) (see Fig. 4) when emissions are high also at night time. Fig. 3 shows a similar phenomenon comparing the patterns of permanent monitoring stations NA1, NA4 and NA7. At night-time from 3 to 7 am the CO concentration at NA1 (background station located inside the urban area but not in a street canyon) is higher of both NA4 and NA7 (street canyons with $AR \cong 1$).

4. Conclusions

In deep street canyon high levels of vehicle pollutants may be reached. Indeed, CO at pedestrian level in the street canyon studied in this paper was on the average higher than CO levels measured by permanent monitoring stations located in the urban area of Naples by a factor ranging from 1.7 to 2.6 (from 1.8 to 2.8 in week-days). From hours 7 am to 9 pm the average value of hourly ratios (CO at pedestrian level/CO at roof top level) is 8.0 if only week-days are considered. These results show that the deep street canyon is a "hot spot" in the urban area. Therefore, in developing air quality models for urban areas the local scale (100 m) cannot be neglected: an approach using nested models covering different scales from the regional (100 km) or urban (10 km) to the local one (100 m) is mandatory. Concentrations at roof top level may be evaluated by urban air quality models on an urban scale and used as input for local scale (street canyon) models.

Concentrations in the deep street canyon at pedestrian height are dependent on vehicle emission rates in the canyon. However, our results show that meteorological conditions play a major role, having a significant effect on air quality in the canyon. Meteorological conditions also have a major effect on roof-top CO concentrations, which affects the mass exchange rate of CO and hence the CO concentration at pedestrian height.

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