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Monitoring and modelling carbon monoxide concentrations in a deep street canyon: application of a two-box model

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ABSTRACT

Carbon monoxide concentrations were monitored at 3, 10 and 30 meters in a deep street canyon with an aspect ratio of (*H*/*W*) ≈ 5.8 and were modelled using a two–box model developed in a previous CFD study. The monitoring campaign lasted 5 days, from 11th to 15th July, 2011. The turbulent kinetic energy at the rooftop level and traffic flow was also measured in the same period. Experimental data were used to evaluate parameters (mass transfer velocities and overall mass transfer velocity) of the box model. The daily pattern shows a significant increase of the overall mass transfer velocity from 9:00 to 11:00 and a decrease until 14:00. Turbulent kinetic energy measured at the rooftop level seems to play a major role with respect to wind velocity in determining the mass transfer between the canyon and the atmosphere above. The evaluation of the overall mass transfer velocity contributes to the use of operational street canyon dispersion models in the case of deep street canyons.

Keywords:
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1. Introduction

Modelling air pollution in large urban areas is a challenging task that is engaging researchers in finding an effective solution. Deterministic models such as Computational Fluid Dynamic (CFD) models can provide useful information if focused on the study of a single or a few streets (Sini et al., 1996), but their application over a whole urban area is not feasible due to the large extension and complexity of urban areas, thus incurring high calculation time and costs. Operational models are much less sophisticated, need fewer input parameters and the mathematics is often reduced to simple algebraic equations. For this reason, operational models seem to be more appropriate if a large–scale urban problem must be addressed. The most well–known operational models (e.g., STREET, OSPM, and ADMS) are frequently used at local (single or few streets) or urban scale and perform reasonably well but not always, and not under all operating conditions (Vardoulakis et al., 2007).

The mass transfer between the canyon and the atmospheric flow above is one of the key parameters in operational models. High concentrations of vehicular pollutants can occur in street canyons at pedestrian height in the case of high vehicular emissions and ineffective mass transfer due to the flow regimes established. Flow regimes are classified as isolated roughness flow, wake interference flow and skimming flow (Oke, 1987) depending on the aspect ratio (*H*/*W*). If (*H*/*W*) > 1.6–2, the street canyon is classified as deep (Vardoulakis et al., 2003), and two counter–rotating vortices may form (Sini et al., 1996), with the bottom vortex weaker than the upper.

Many papers have focused on mass transfer in street canyons (Bentham and Britter, 2003; Hamlyn and Britter, 2005; Salizzoni et al., 2009). Mass transfer inside the canyon and between the canyon and the atmosphere above is influenced by several parameters, and the conclusions of different papers do not always agree. The parameters investigated include the following: the external wind velocity (Murena et al., 2011), the turbulent structures in the outer flow and the structures in the shear–layer interface between the outer flow and the canyon (Salizzoni et al., 2011), the turbulence inside the shear layer that forms between the canyon and the atmosphere above (Caton et al., 2003), the aspect ratio (Solazzo and Britter, 2007); the frontal area density of buildings (Ratti et al., 2002), and the planar area density or packing density (Bentham and Britter, 2003; Hamlyn and Britter, 2005).

Once a certain understanding of the mass transfer phenomena inside the canyon and between the canyon and the atmosphere above is achieved, street scale operational models, also called mass balance or box models, can be developed (Salizzoni et al., 2009; Murena et al., 2011).

In a previous paper, Murena et al. (2011) proposed a box model to simulate mass transfer inside deep street canyons and between them and atmospheric flow above based on a CFD simulation study on ideal (2D) deep street canyons. An ideal street canyon is defined as a single road of infinite length delimited by buildings of the same constant height on both sides of the road and with wind direction perpendicular to the street axis. The box model proposed by Murena et al. (2011) assumes that a deep street canyon can be divided, in the vertical length, into two or three well–mixed volumes exchanging mass and with the upper volume exchanging mass with the atmosphere above. The mass exchange rates were evaluated through transient 2D–CFD simulations. Their values are reported as a function of the aspect ratio and characteristic wind velocity (Murena et al., 2011). Because the mass transfer process from the bottom level in the canyon to the atmosphere above is made up of a series of first–order processes, an overall mass transfer coefficient can be defined (Murena et al., 2011). Once the overall mass transfer coefficient is known, the pollutant concentration inside the street canyon at the pedestrian level can be easily calculated. Therefore, the overall mass transfer coefficient is a powerful parameter; unfortunately, it is not constant because it depends on geometrical parameters and meteorological conditions. In the STREET (Johnson et al., 1973) and OSPM (Hertel and Berkowicz, 1989) models, the mass transfer velocity is assumed proportional to a characteristic velocity in the atmospheric flow above. However, the dependence of the mass transfer velocity on the atmospheric flow is more complex, as reported by other authors (Hotchkiss and Harlow, 1973; Solazzo and Britter, 2007; Salizzoni et al., 2011).

In this paper, the results of a monitoring campaign of carbon monoxide measured at 3, 10 and 30 m in a deep street canyon in the urban area of Naples are interpreted with the box model previously proposed (Murena et al., 2011), and values of mass transfer velocities and the overall mass transfer coefficient are obtained.

2. Experimental Method and Analytical Apparatus

Carbon monoxide concentrations were measured at via Nardones, a deep street canyon in the urban area of Naples (Italy) with the following geometry: width $W \approx 6$ m, average building height $H \approx 35$ m $(H/W) \approx 5.8$ and length $L \approx 315$ m. Only one cross–road and a side road are present throughout its length. Via Nardones is a one–way uphill street with an average slope of approximately 5%. The 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).

CO was measured using a non–dispersive infrared photometer analyser (ML 9830B Monitor Europe Ltd. with a lower detectable limit LDL = 0.05 ppm). Calibration of the instruments was checked each day during the monitoring campaign, performing zero and span operations. One–minute average concentrations were stored by the ML 9830B analyser and downloaded on a laptop during the campaign. The sampling points were located at 3, 10 and 30 m from the road level and approximately 1 m from the building walls on the south side of the street. The sampling line was made of Teflon. Airflow was turned from one sampling point to another every 20 minutes operating on a valve system. The lag time for the most remote sampling point from the analyser was approximately 1 minute. Therefore, the first 2 minutes of each measurement were discarded to allow flushing of the sampling line. The 20–minute average concentrations were calculated and assumed to be hourly average concentrations for each sampling point.

Traffic flow was manually measured by counting 4–wheel, 2–wheel and low–duty vehicles. Two measurements of 5 minutes were performed each hour from 7:00 to 23:00. Some spot measurements were performed during night hours. Turbulent kinetic energy was measured at the rooftop level using an ultrasonic anemometer (Delta Ohm HD2003), which was placed on a pole (approximately 4 m height) above the roof of the same building where the sampling points were located on the south side of the canyon. The monitoring campaign lasted 5 days, from 11th to 15th July 2011.

3. The Models

In a previous study, Murena et al. (2011) performed 2D–CFD simulations of the mass transfer inside deep street canyons and between the canyons and the atmosphere above. Ideal street canyons with $(H/W) = 3$ and 5 were considered. The results of the CFD simulations showed (Murena et al., 2011) that in the case of a street canyon with $(H/W) = 3$, two counter rotating vortices formed, which is in accordance with results reported in the literature (e.g., Sini et al., 1996; Jeong and Andrews, 2002). For $(H/W) = 5$, the same paper (Murena et al., 2011) indicates the presence of three vortices. This finding is less documented in the literature because deep street canyons are rarely considered. Most papers study street canyons with an aspect ratio ≈ 1, for which a single vortex is formed. Jeong and Andrews (2002) and Sini et al. (1996), however, reported the presence of three vortices when $(H/W) > 3$. CFD simulations showed that CO concentrations can be assumed as uniform in each vortex (Murena et al., 2011). With this assumption, mass balance equations can be easily written. In the case of $(H/W) = 3$ (see Figure 1), the model is a two–box model and the mass balance equations are:

$$H_b \frac{dc_b}{dt} = -u_{bu}(c_b - c_u) + \frac{f_e Q_v}{W} \tag{1}$$

$$H_u \frac{dc_u}{dt} = u_{bu}(c_b - c_u) - u_{ua}(c_u - c_a) \tag{2}$$

where H_b and H_u are, respectively, the height of the bottom and upper boxes; c_b and c_u are the CO concentrations in the bottom and upper boxes; c_a is the air concentration above the roofs (out of the canyon); f_e is a weighted average CO emission factor (g km^{-1}); and Q_v is the number of vehicles per hour. Finally, u_{bu} (m s^{-1}) is the mass transfer velocity between the bottom and upper boxes, and u_{ua} (m s^{-1}) is the mass transfer velocity between the upper box and the atmosphere. The mass transfer velocity is a spatially averaged velocity that represents the net mass exchange between two volumes at uniform concentration; it is also called the exchange rate (Bentham and Britter, 2003) or exchange velocity (Hamlyn and Britter, 2005). The mass transfer velocity takes into account both instantaneous (turbulent) and mean (advective) contributions.

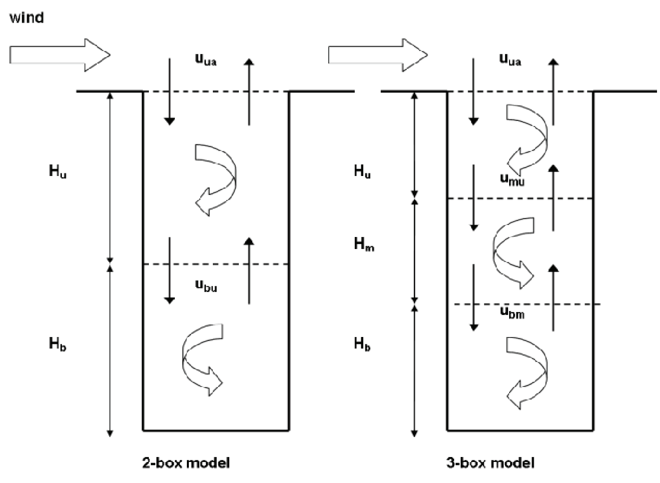

Figure 1. *Scheme of the box models.*

If $(H/W) = 5$, the model is a three–box model, and the equations are:

$$H_b \frac{dc_b}{dt} = -u_{bm}(c_b - c_m) + \frac{f_e Q_v}{W} \tag{3}$$

$$H_m \frac{dc_m}{dt} = u_{bm}(c_b - c_m) - u_{mu}(c_m - c_u) \tag{4}$$

$$H_u \frac{dc_u}{dt} = u_{mu}(c_m - c_u) - u_{ua}(c_u - c_a) \quad (5)$$

The notation is the same as in Equations (1) and (2). The subscript *m* corresponds to the middle box in the canyon.

Starting from the models above, it is possible to define an overall mass transfer velocity coefficient U_{ov} (Murena et al., 2011):

$$U_{ov} = \frac{1}{\frac{1}{u_{bu}} + \frac{1}{u_{ua}}} \quad (6)$$

in the case of the two–box model or, in case of the three–box model:

$$U_{ov} = \frac{1}{\frac{1}{u_{bm}} + \frac{1}{u_{mu}} + \frac{1}{u_{ua}}} \quad (7)$$

The overall mass transfer coefficient can be used to evaluate CO concentrations at the pedestrian level (Murena et al. 2011), assuming steady state conditions:

$$c_b = c_a + \frac{f_e Q_v}{W U_{ov}} \quad (8)$$

Equation (8) has practical applications other than the apparently strong steady–state assumption. In fact, if a time interval of one hour is considered, a steady state can be assumed, and hourly average values of c_b can be calculated by Equation (8). One hour is the minimum averaging time of all air quality legislations in the world. Therefore, hourly average concentrations of pollutants are of great practical interest. Equation (8) is similar to the solving equations of operational models such as OSPM. Considering the simple case when the vortex is completely immersed inside the canyon (according to assumptions made in the OSPM, this is the case when $(H/W) \geq 1$, the pollutant concentration can be written as follows (Berkowicz et al., 1997):

$$c = \frac{Q}{W \sigma_{wt}} \quad (9)$$

where Q is the CO emission rate in the street (g m^{-1} s^{-1}) [corresponding to $f_e Q_v$ in Equation (8)], W is the canyon width and σ_{wt} is the canyon ventilation velocity. If $(H/W) \geq 1$, then $\sigma_{wt} \approx 0.1\, u_t$ (Berkowicz et al. 1997), where u_t is wind speed at the top of the canyon. The overall mass transfer coefficient in Equations (6)–(8) is given as a function of aspect ratio and wind velocity (Murena et al., 2011).

4. Results

Before discussing the results, the wind conditions during the monitoring campaign are described. The average hourly values of wind velocity and wind direction are reported in Figures 2 and 3. The average hourly values of wind direction were calculated by dividing the wind arising in 16 sectors and averaging the data of the sector with the highest frequency of observations. Meteorological measurements were obtained from the meteorological station of Naples Capodichino, located approximately 5 km NE of the monitoring site. The data were compared with spot measurements from the sonic anemometer, and they were in good agreement. The wind pattern, as expected, is that of a breeze regime. The wind velocity is low (~5 km h^{-1}) during the night and starts to increases at 10 a.m., reaching a plateau value (≈ 15 km h^{-1}) at noon and remaining constant until 7 p.m., after which it decreases. Additionally, the wind direction follows the breeze regime. During the day, starting from 9 a.m., the sea breeze brings the wind from the S–SW direction. During the night, the direction is more variable, but it comes most frequently from the northern sectors (NW–NE).

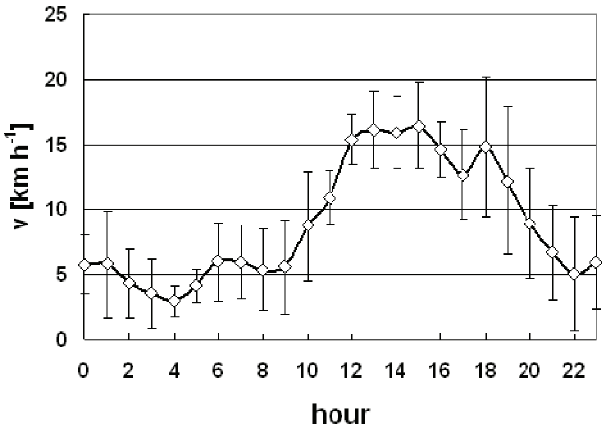

Figure 2. *Average hourly values of wind velocity.*

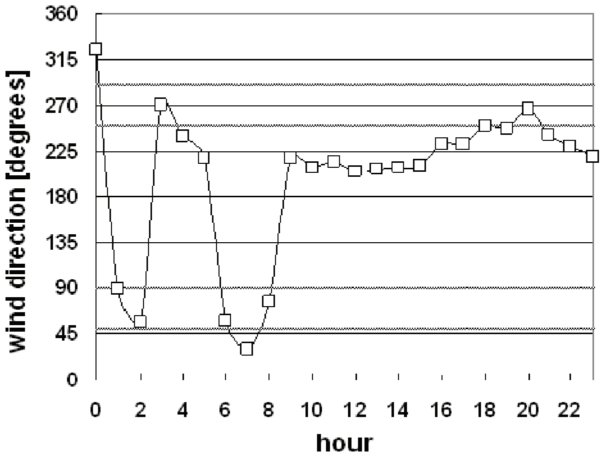

Figure 3. *Average hourly values of wind direction. Angles between the grey lines represent conditions of wind mainly parallel to the street axis (i.e., 50-90° and 250-290°).*

Considering that via Nardones is oriented in the direction 70–250°, during most of the monitoring campaign, the angle between the wind direction and the street axis was greater than 20° (Figure 3). Therefore, the wind component perpendicular to the street axis is significant, and the flow inside the canyon assumes a helicoidal pattern (Yamartino and Wiegand, 1986). Therefore, the monitoring campaign was performed in conditions approaching those of an ideal street canyon (wind perpendicular to the street axis and infinite street length).

The hourly average CO concentrations measured at via Nardones are reported in Figures 4 and 5. The concentrations are in mg m^{-3} normalised at T = 20 °C and P = 1 atm. Both figures show that the CO concentration at the pedestrian level ($c_{H=3}$) is higher than the CO at 10 m ($c_{H=10}$) and 30 m ($c_{H=30}$). In fact, the concentration is $c_{H=3} > c_{H=10} \approx c_{H=30}$ and sometimes $c_{H=30} > c_{H=10}$. The average values during the whole monitoring campaign were 1.65 mg m^{-3} at H = 3 m, 0.89 mg m^{-3} at H = 10 m and 0.65 mg m^{-3} at H = 30 m. A hypothesis test shows that the difference in average values of CO concentration at H = 10 m and H = 30 m is not

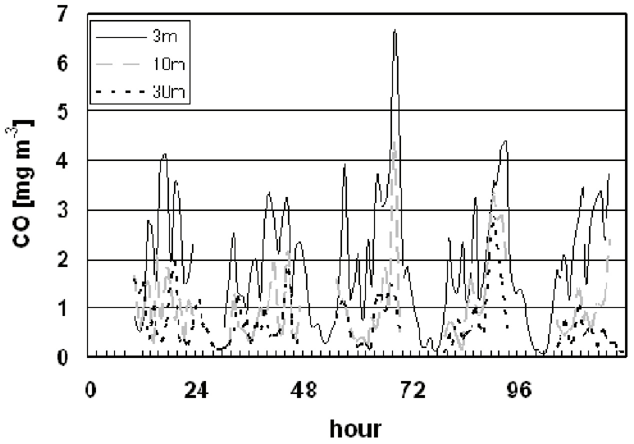

Figure 4. *Hourly average CO concentrations measured at H = 3, 10 and 30 m from 11th to 15th July 2011.*

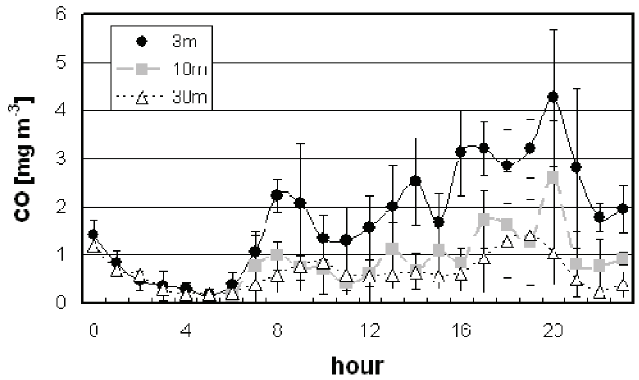

Figure 5. *Average hourly values of CO concentrations measured at H = 3, 10 and 30 m from 11th to 15th July 2011 at via Nardones.*

significant at a confidence interval CI = 95%. This observation leads to the conclusion that although the real canyon has an aspect ratio (H/W) > 5, it can be modelled by a two–box model. The discrepancy with the findings of the CFD simulations (Murena et al., 2011), that indicate the presence of three vortices and consequently the need of a three–box model when (H/W) > 5, may be due to the idealisation of the street canyon in the CFD simulations, where the effect of lateral streets was not considered nor was the roughness of the real canyon due to the presence of balconies. Both effects could modify the flow field inside the canyon, determining the fusion of the middle and upper vortices. Therefore, only the two–box model will be considered in the following, assuming that the heights H = 10 m and H = 30 m both belong to the upper volume and that height H = 3 m belongs to the bottom volume (see Figure 1).

Differential Equations (1) and (2) were than discretised assuming a time interval Δt of 1 hour and were rewritten as follows:

$$H_b \frac{\Delta c_b}{\Delta t} = -u_{bu}(c_b - c_u) + \frac{f_e Q_v}{W} \quad (10)$$

$$H_u \frac{\Delta c_u}{\Delta t} = u_{bu}(c_b - c_u) - u_{ua}(c_u - c_a) \quad (11)$$

where Δc_b and Δc_u are the differences of CO concentrations between the jth hour and the j–1th hour. All other variables in Equations (10) and (11) are constant (H_b, H_u, W), are assumed constant (f_e) or are hourly average values (c and u). The average weighted emission factor (f_e) was calculated through the formula, $f_e = \sum X_i f_i$ where the subscript refers to the class of vehicles measured (two–stroke; four–stroke and light–duty vehicles). X_i is the fraction of vehicles of class i passing in the canyon and $\overline{f_i}$ is the average emission factor of class I calculated by the COPERT procedure based on the composition of the vehicular fleet in Naples (Murena et al., 2011). X_i would change hourly as the traffic composition changes. However, because the traffic composition is constant during the day and only changes at night, its effect on the value of the average emission factor is minor and was neglected. Therefore, f_e is constant. If the CO concentrations are known from experimental data, then the only unknowns in Equations (10) and (11) are mass transfer velocities, and u_{bu} and u_{ua} and can be calculated through a regression procedure.

The hourly average values of u_{bu} and u_{ua} were then evaluated by Equations (10) and (11) assuming as hourly average values of c_b and c_u the experimental values at H = 3 m and the mean of values at H = 10 m and H = 30 m, respectively. For the CO concentration in the atmosphere above the rooftop level, c_a = 0 was assumed.

The other input parameters are H_b = 3 m, H_u = 32 m and f_e = 0.05 g km^{-1}, as reported in Murena et al. (2011). With these values, it was observed that mass transfer velocities (u_{bu} and u_{ua}) were in many cases negative; in fact, they must be positive by definition [Equations (1) and (2)]. It was immediately clear that the reason for this result was the low value that the generation term $\left(\frac{f_e Q_v}{W}\right)$ in Equation 10 assumes with the input parameters adopted. In fact, the generation term was generally lower and often negligible with respect to the accumulation term $\left(H_b \frac{\Delta c_b}{\Delta t}\right)$. Consequently, every time the accumulation term was positive (c_b at hour j > c_b at hour j–1), as it is always (see Figure 1) $c_b > c_u$, then u_{bu} must be negative [see Equation (10)].

The generation term cannot be negligible with respect to the accumulation term because we experimentally observed (Figures 4 and 5) that it is $c_{H=3m} > c_{H=10m} \approx c_{H=30m}$ then $c_b > c_u$. We must conclude that the generation term is underestimated. In the generation term, the only parameter that could be affected by a significant error in the evaluation is the average weighted emission factor f_e. In the calculation of f_e (Murena et al., 2011), the effect of cold starts and pendency were neglected because they were not of real interest in that case. Tsang et al. (2011) analysed the on–road emissions of a Euro–4 petrol car driven on four urban routes in Hong Kong. They observed that when the engine is in fuel–rich operation with an air/fuel ratio less than 14.7, which usually occurs when a vehicle is accelerating or when the vehicle starts to drive uphill, the CO emissions are drastically higher. With road grades of 10.5%, 7.0% and 0%, the emission factors of CO were estimated as 20.5 g km^{-1}, 2.05 g km^{-1} and 0.43 g km^{-1}, respectively. Therefore, it seems evident that, neglecting the effect of road pendency, f_e = 0.05 g km^{-1} is an underestimation of the actual value of the average weighted emission factor. Assuming as a weighted average emission factor that f_e = 0.5 g km^{-1} (ten times higher than that initially assumed), the generation term was generally higher than the accumulation term, and the u_{bu} values calculated by Equation (10) were positive. Once u_{bu} was obtained by Equation (10), u_{ua} was calculated by Equation (11). The average hourly values of mass transfer velocities u_{bu} and u_{ua} calculated by Equations (10) and (11) are reported in Figure 6.

A comparison of mass transfer velocities obtained by CFD simulations (Murena et al., 2011) with those obtained through modelling (Figure 6) is reported in Table 1. It is evident that the mass transfer velocities calculated in the CFD simulations (Murena et al., 2011) are higher than those obtained in the present paper.

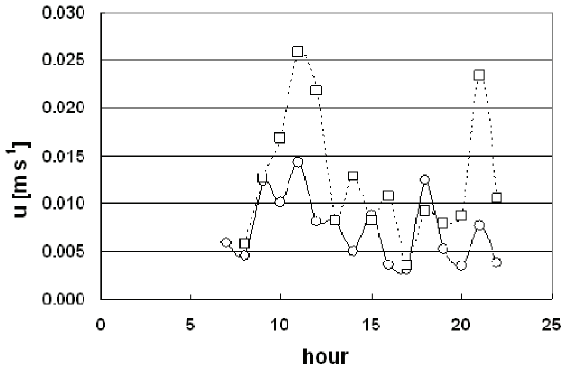

Figure 6. *Average hourly values of u_{bu} (circle and solid line) and u_{ua} (box and dashed line).*

Table1. *Comparison of mass transfer velocities obtained by CFD simulations (Murena et al., 2011) and in present paper*

	CFD simulation		Modelling	
Wind velocity (km h^{-1})	u_{bu} (m s^{-1})	u_{ua} (m s^{-1})	u_{bu} (m s^{-1})	u_{ua} (m s^{-1})
5	0.06	0.025	0.005	0.005
15	0.15	0.06	0.01	0.01-0.025

If the mass transfer velocities u_{bu} and u_{ua} are known, then the overall mass transfer coefficient U_{ov} can be calculated from Equation (6). The average hourly value–day values of U_{ov} are reported in Figure 7 as box symbols. A maximum of U_{ov} occurs at 11 a.m. An increase of U_{ov} is correlated with a similar increase of turbulent kinetic energy (*TKE*) measured with an ultrasonic anemometer at the rooftop level during the monitoring campaign. In fact, an increase in *TKE* is observed (Spano, 2011) starting from 9:00 a.m. (Figure 7), then a plateau is reached at noon. The *TKE* is then constant until 3:00 p.m. The TKE measurements in Figure 7 are the average values obtained during the monitoring campaign. The increase of *TKE* can be explained both with the increase of wind velocity and the heating caused by solar irradiation that increases the atmospheric turbulence and makes the mass transfer more efficient. The pattern of U_{ov} in the afternoon is less clear, as shown in Figure 7, although a decrease from the maximum value at 11:00 a.m. is evident. From the data reported in Figure 7, the U_{ov} average hourly values have been modelled assuming a minimum constant value plus a Gaussian function to describe the more efficient mass transfer in the morning from 9 a.m. to 13 a.m.

The model function is then:

$$U_{ov} = a + b\exp\left[-\left(\frac{h-11}{\sigma}\right)^2\right] \quad (12)$$

where h is the current hour (from 0 to 23). Parameters a, b and σ will be determined through a best–fitting procedure.

Defining the daily pattern of overall mass transfer velocity through Equation (12), the CO concentration at the pedestrian level can be calculated by Equation (8), even though it is derived in steady state conditions. The real conditions are only slightly unsteady; in fact, the generation term prevails over the accumulation term, which is minor. The other input parameters in Equation (8) are the emission factor (f_e = 0.5 g km^{-1}) and the average hourly values of traffic flow Q_v, which were measured during the campaign (Spano, 2011). U_{ov} was calculated from Equation (12) with following parameters: a = 0.0025 m s^{-1}, b = 0.006 m s^{-1} and σ = 1.5 h. A comparison of c_b from the model [Equation (8)] with real data is reported in Figures 8 and 9. The correlation with the hourly average values (Figure 8) is R^2 = 0.64. The average hourly values (Figure 9) are adequately modelled.

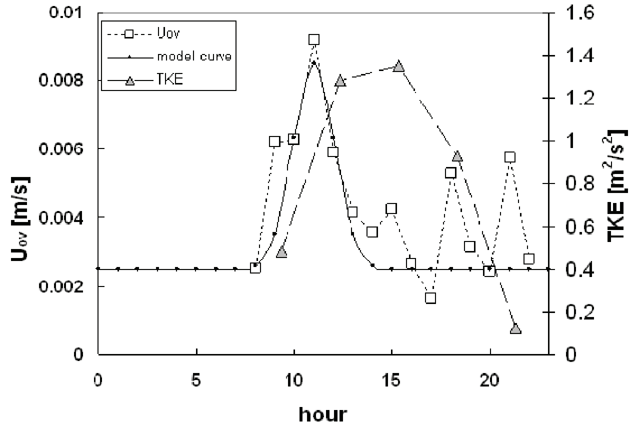

Figure 7. *Average hourly values of overall mass transfer velocity obtained by Equation 6 (boxes) and of turbulent kinetic energy (triangle) measured at the roof-top level at via Nardones. The solid line is a model curve (Equation 12). The TKE values are on the right scale.*

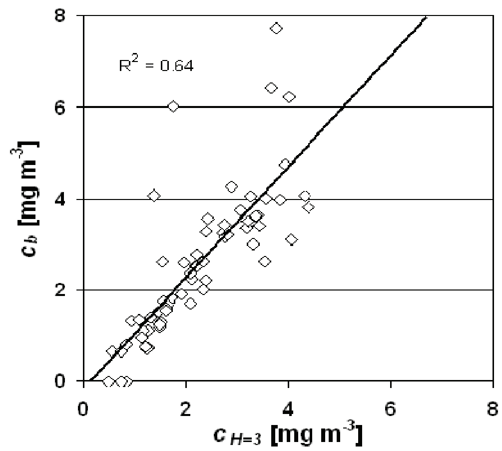

Figure 8. *Correlation of measured and modelled average hourly values of CO concentrations at H = 3.*

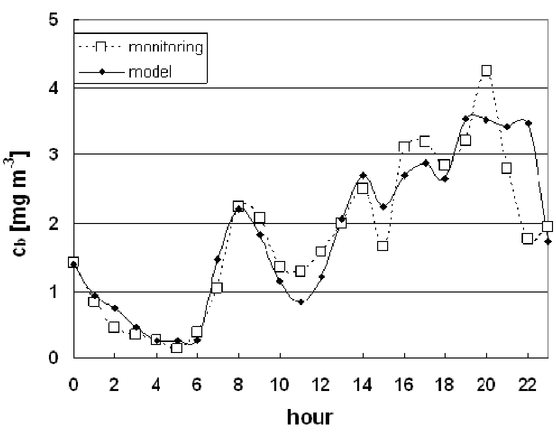

Figure 9. *Average hourly values of CO concentrations at H=3 measured (box) and modelled (solid line).*

A sensitivity test was performed on the effect of the dimension of the two volumes in which the street has been divided (H_b and H_u). H_b could assume values in the range $3 \le H_b < 10$ because, as shown in Figures 4 and 5, the bottom box must include the 3 m height and exclude the 10 m height. Correspondingly, $H_u = H - H_b$. The variation of H_b in the range $3 \le H_b < 10$ m did not have a significant effect on the results of the model.

5. Conclusions

This paper shows that the carbon monoxide concentrations in a deep street canyon can be effectively modelled by assuming a two-box model (Murena et al., 2011). The two-box model defines an overall mass transfer coefficient that, once known and with a few other input parameters, allows the evaluation of the concentration at the pedestrian level, which is of particular interest for environmental and health impact assessment studies. The overall mass transfer coefficient depends on many variables, both geometrical (street geometry) and meteorological (wind speed, wind direction, atmospheric turbulence, temperature). The results of the present paper show that, at least in meteorological conditions occurring during the monitoring campaign (11^{th}-15^{th} July, 2011) in Naples characterised by a breeze regime, the overall mass transfer coefficient is quite constant during the 24-h period apart from a significant increase in the morning from 9:00 to 11:00 followed by a decrease until 14:00. A good correlation of real and modelled data was obtained by modelling the U_{ov} daily pattern as a constant plus a Gaussian function.

During the monitoring campaign, the wind direction was rarely parallel to the street axis, so the results of this paper are related to a wind direction mainly perpendicular to the street axis. In these conditions, the results seem to indicate that wind velocity is not a significant parameter, while the turbulent kinetic energy measured at the roof level seems to play a more relevant role in determining the mass transfer rate. These findings have been evidenced by a simulation study (Salizzoni et al., 2011).

The results of this paper are of practical interest because they can be used to improve the performance of operational models, especially if applied at deep street canyons, for which few data are reported in literature. Additionally, the results of the most popular operational models, such as OSPM and ASDM, are unreliable because they were developed and validated for street canyons with an aspect ratio ~1.

Future research will aim at a validation of the model through a more prolonged monitoring campaign performed in different seasons and in street canyons with different aspect ratios. The correct evaluation of the CO emission rate due to vehicles passing in the street canyon will be a critical issue in the validation procedure.

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