Carbon monoxide concentrations evaluated by traffic noise data in urban areas

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Summary. — It is shown that variations in carbon monoxide concentrations can be evaluated by measuring environmental noise, wind velocity and vertical thermal stability. The results can be justified on the basis of the theory of the street canyon effect. The methodology proposed was verified in two Italian cities with different characteristics: Milan and Ravenna.

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1. – Introduction

Processes of urbanisation produce drastic modifications in the atmosphere and terrain, bringing about the transformation of radiative and thermal properties and in the features of aerodynamics and humidity. For example, building materials increase the thermal capacity of the system and cause the surface to become more impermeable. The geometry of buildings produce multireflectivity which leads to an entrapment of solar radiation. The heat and water generated by human activity combine with natural sources of heat and water of the urban system, with the result that, during daytime, the urban area absorbs more heat than the surrounding area and therefore, at night, especially in conditions of weak wind, the city air is warmer than that in the surrounding rural suburbs.

The physical structure of the city also exerts a strong influence on the wind field whose speed is generally reduced due to the friction with the surfaces (urban buildings oppose a greater resistance to the wind flux compared to those in rural areas), while the street system forces its direction.

Up to now, considerable difficulties have been encountered in describing pollutant dispersion in urban atmospheres by means of mathematical models. The basic reason lies in the complexity of topography in the urban environment, comprising streets lined with buildings, squares where several streets meet, green areas, large-scale trunk roads and areas of dense traffic. To this, we must add any natural complexities in cases where towns are located in the hills, mountains or along the coast.

Numerous studies have been performed on the phenomenology of diffusion in urban areas, many of which have highlighted certain regularities in the interaction between the undisturbed wind field and microtopography; such regularities have therefore been schematised in semi-empirical operative models, defined with phenomenological parameters dependent on the specific situation under study [1-4].

Air quality standards are important tools for legislators and local authorities in the control of air pollution. In order to verify respect of air quality standards a combination of measurements and models are required. Measurements generally yield concentrations for a particular location, and it is usually not easy to transfer the results to other locations. This is particularly true for air pollution in streets. In fact the complexity of the turbulent flow and the strong spatial concentration gradients render it very difficult to predict the levels of pollution in streets or to extrapolate concentrations measured at one location to others. In Italy, a further impediment to the application of models derives from the fact that the traffic fluxes are often unknown.

To obviate this problem and to make the best use of the available data, also bearing in mind that environmental management is generally based on mean monthly, seasonal and/or annual values in the development of new traffic circulation plans, we advance a method with which to evaluate CO concentrations from traffic noise measurements. The advantage of the proposed approach lies in the fact that it allows the evaluation of CO on the basis of noise measurements alone, with no need for traffic flux data.

2. – Traffic noise data and CO concentrations

Mathematical models which describe the field of concentrations in an urban area of pollutants emitted by automobile traffic, such as carbon monoxide, express the concentration in terms of the "street canyon effect", where the concentration in the street is calculated as the sum of two contributions: the mean concentration present in the air entering the street and the contributions of local sources situated in the street itself. In the case of wind normal to the street (more precisely, in the quadrant bisected by the perpendicular to the street), such contribution turns out to be different on the two sides of the street. The downwind side presents a higher concentration due to the vortex-type circulation forming within the street [1, 2]. The ground concentration is calculated using the formula of Ludwig and Dabbert [5]:

$$C = \frac{0.1 KNS^{-0.75}}{(u+0.5)[(x^2+z^2)^{1/2}+2]} \tag{1}$$

on the downwind side, and

$$C = \frac{0.1 KNS^{-0.75}}{W(u+0.5)}\ , \tag{2}$$

on the upwind side. C (ppm) is the pollutant concentration, K is an empirical constant, N is the number of vehicles per hour, S (mph) is the mean speed of the vehicles, u (m/s) is the wind speed at roof level, W (m) is the width of the street, x (m) is the horizontal distance of the traffic line-flow from the calculus point and z (m) is the height of the calculus point. In cases where the wind direction is parallel to the street (more precisely, in the quadrant not bisected by the perpendicular to the street), the concentration is uniformly calculated along the street as the mean value of the two equations reported above.

More recently, Eerens *et al.* [3] and Boeft *et al.* [4] have found a similar relation for the evaluation of CO in urban streets by wind tunnel experiments and field dispersion measurements.

In view of the above considerations, there is experimental evidence that the air concentrations of pollutants emitted by automobiles are closely correlated to the traffic flow, automobile speed, as well as to the wind speed and the atmospheric turbulent intensity at the height of the buildings lining the streets.

Considering that traffic noise can be related to traffic intensity [1], in this paper we attempted to establish whether carbon monoxide concentrations in the air can be evaluated on the basis of traffic noise measurements, insofar as they are indicators of traffic intensity and, as such, of CO emissions. The estimate of the flow of the vehicles per hour (F), was compared to the statistical value of $L50$ noise (the noise level measured in dBA was passed during 50% of the observation time). $L50$ may be considered a significant parameter in the case of moving traffic of a homogeneous character; it represents a function of the flow and type of traffic, vehicle speed and characteristics of the street. The bibliography contains several empirical formulas which link these variables, most of which take the form of straight lines of multiple linear regression [1]. We have chosen a logarithmic relation to the vehicle flow by means of the following expression:

$$L50 = a \log(F) + b \,, \tag{3}$$

where a and b are empirical constants related to the characteristics of the street.

We verified whether the CO concentrations (C) could be evaluated by means of the following formula:

$$C = A(\overline{U}/\overline{F})\, FI/U \,,$$

where A is an empirical constant, F the hourly flux estimated from $L50$ (eq. (3)), I varies from 1 to 7 as a function of the atmospheric stability class (with 1 representing the most unstable class) and the bar denotes the mean value over the measuring period.

TABLE I. – *Sampling periods, mean values for noise and* CO *in Ravenna.*

Site	First day	Last day	$L50$ (dB)	CO (mg/m^3)
Via Cesarea	28/12/90	13/01/91	67.1	2.1
Via Zalamella	19/01/91	05/02/91	71.7	2.7
P.zza Resistenza	06/02/91	15/03/91	67.6	2.5
Via Venezia	16/03/91	28/03/91	67.3	4.6
Via S. Alberto	12/04/91	18/06/91	71.9	1.6
Via Alberoni	17/05/91	03/06/91	56.0	1.1
Via Maggiore	25/07/91	02/08/91	69.4	1.0
Via Bellucci	23/08/91	17/09/91	65.2	2.2
Via S. Gaetanino	23/09/91	08/10/91	70.0	1.8
Via Missiroli	09/10/91	08/11/91	66.6	2.3
Via P. Costa	24/12/91	03/02/92	61.6	1.0
Via Darsena	06/02/91	13/03/92	73.4	2.9

TABLE II. – *Values of coefficients a and b.*

Site	a	b
All Ravenna streets	11.9	31.4
Via Statuto (Milan)	9.7	30.6
Via Senato (Milan)	11.6	32.4

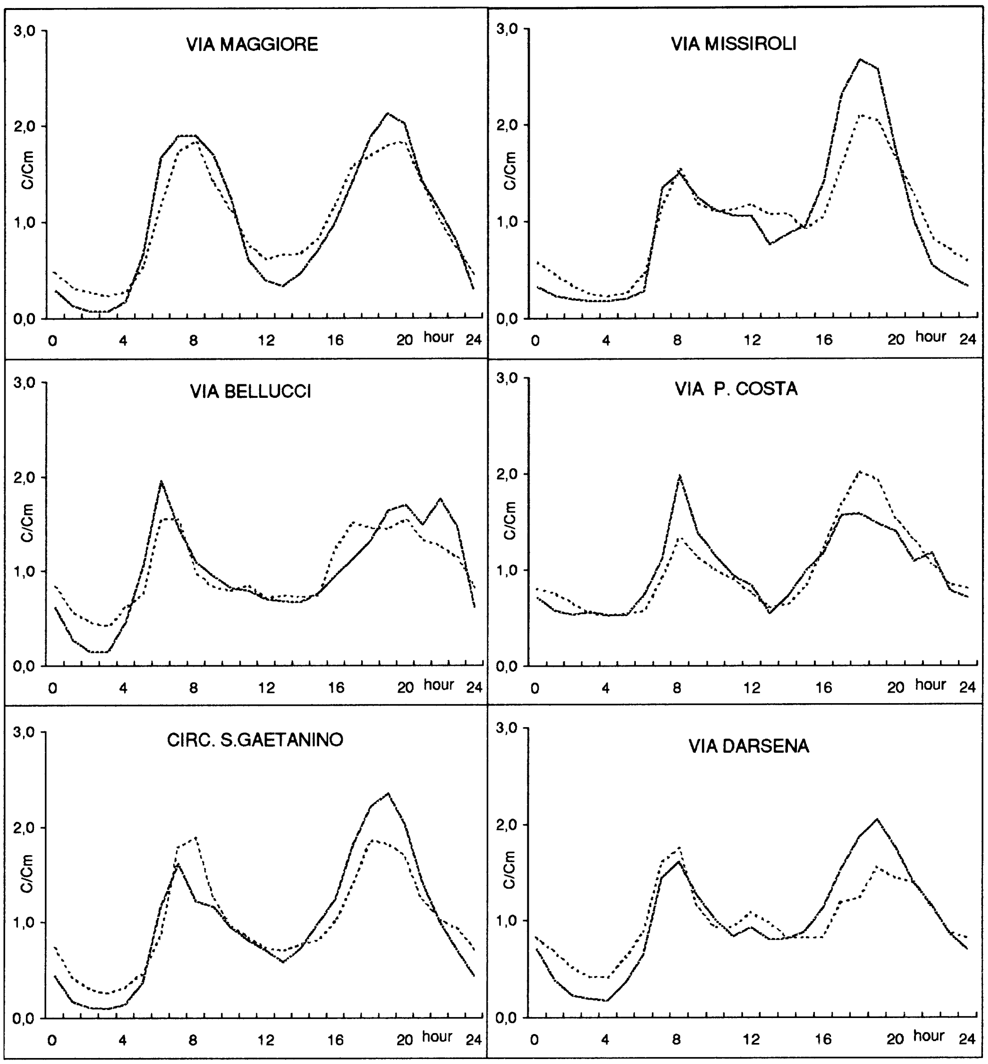

Fig. 1. – Average diurnal variation (hours in abscissa) of normalised concentrations of measured (bold line) and estimated (dotted line) CO in 6 streets of Ravenna during the period of table I.

3. – The evaluation of carbon monoxide concentrations in two cities

In order to check the reliability of the above considerations we applied the proposed methodology in two diverse Italian cities: Ravenna and Milan.

Ravenna is an artistic and industrial town of 140 000 inhabitants located on a completely flat terrain 10 km from the Adriatic Sea. The climate is basically continental but rendered more temperate by the proximity to the coast. The entire area is subject to a series of weak local circulations, frequent inversion phenomena and ensuing high relative humidity, particularly during extended period of anticyclonic conditions.

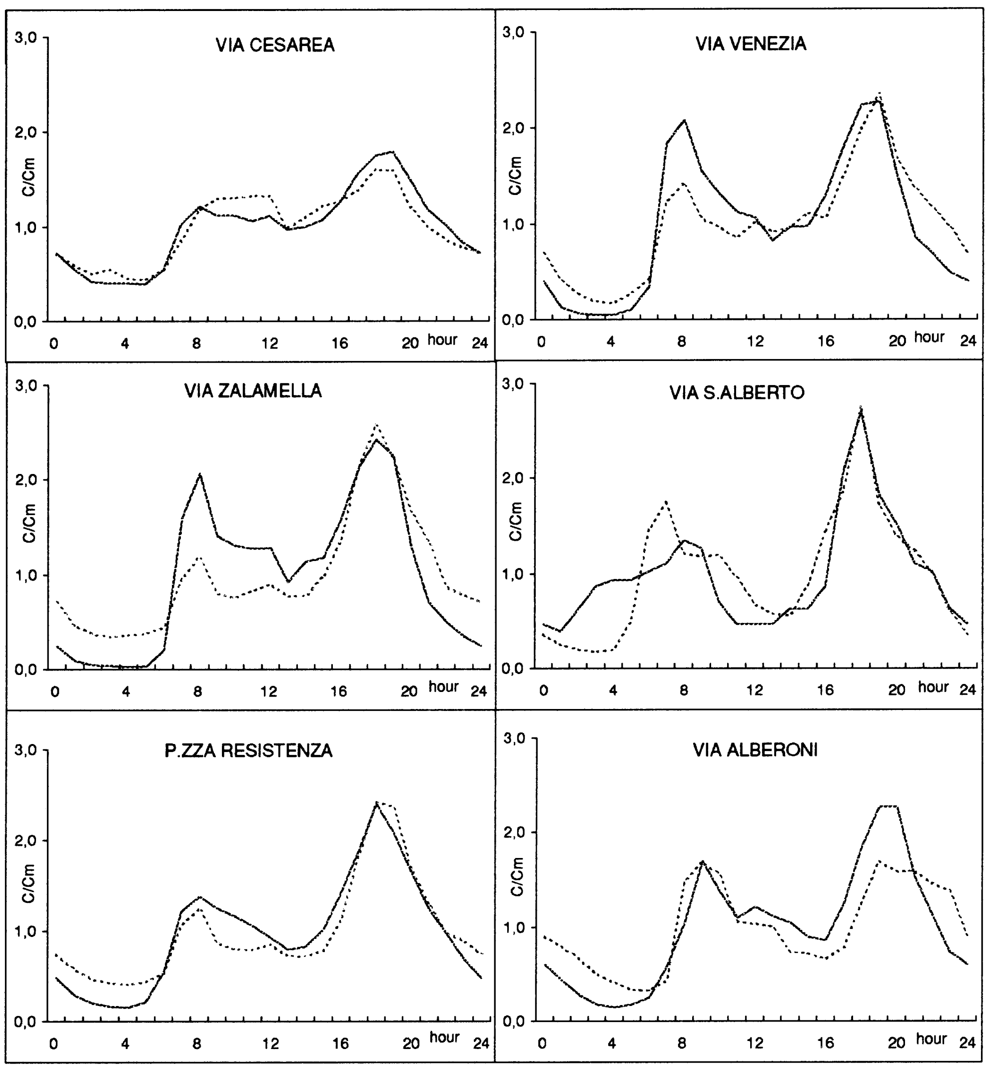

Fig. 2. – Average diurnal variation (hours in abscissa) of normalised concentrations of measured (bold line) and estimated (dotted line) CO in 6 streets of Ravenna during the period of table I.

Milan is the second largest Italian city with 1.5 millions inhabitants. It is situated on the flat Po Valley and has a continental climate (like Ravenna) with frequent inversion phenomena and high humidity. Usually, perturbations are of north-westerly origin.

As part of the second Health Plan of the Emilia Romagna Region, a measurement

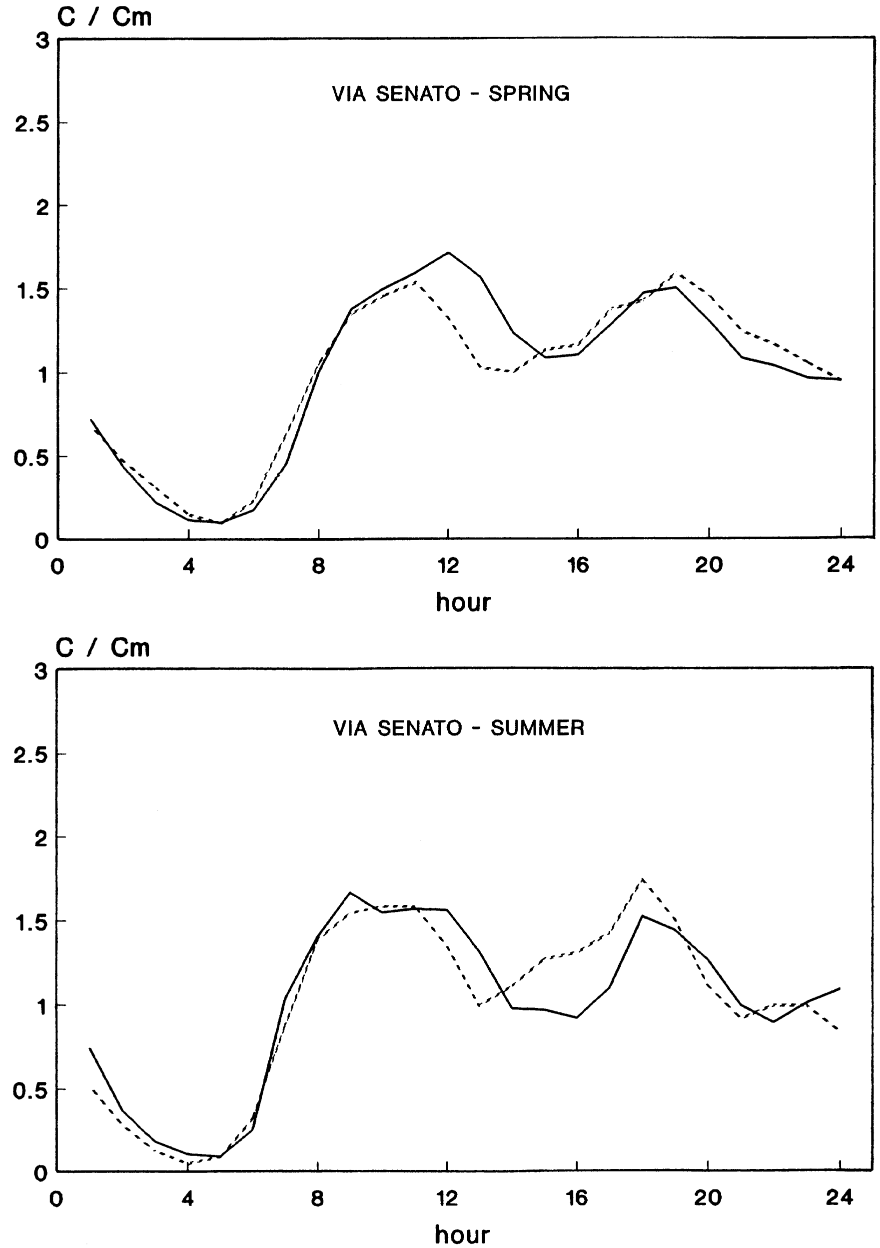

Fig. 3. – Average diurnal variation (hours in abscissa) of normalised concentrations of measured (continuous line) and estimated (dashed line) CO in via Senato (Milan) during spring and summer.

campaign relative to air and noise pollution was carried out in 12 streets of Ravenna characterised by heavy traffic conditions. The investigation took place between October 1990 and March 1992 using a mobile laboratory specially equipped with instrumentation belonging to a local air quality monitoring network. At all sites, among

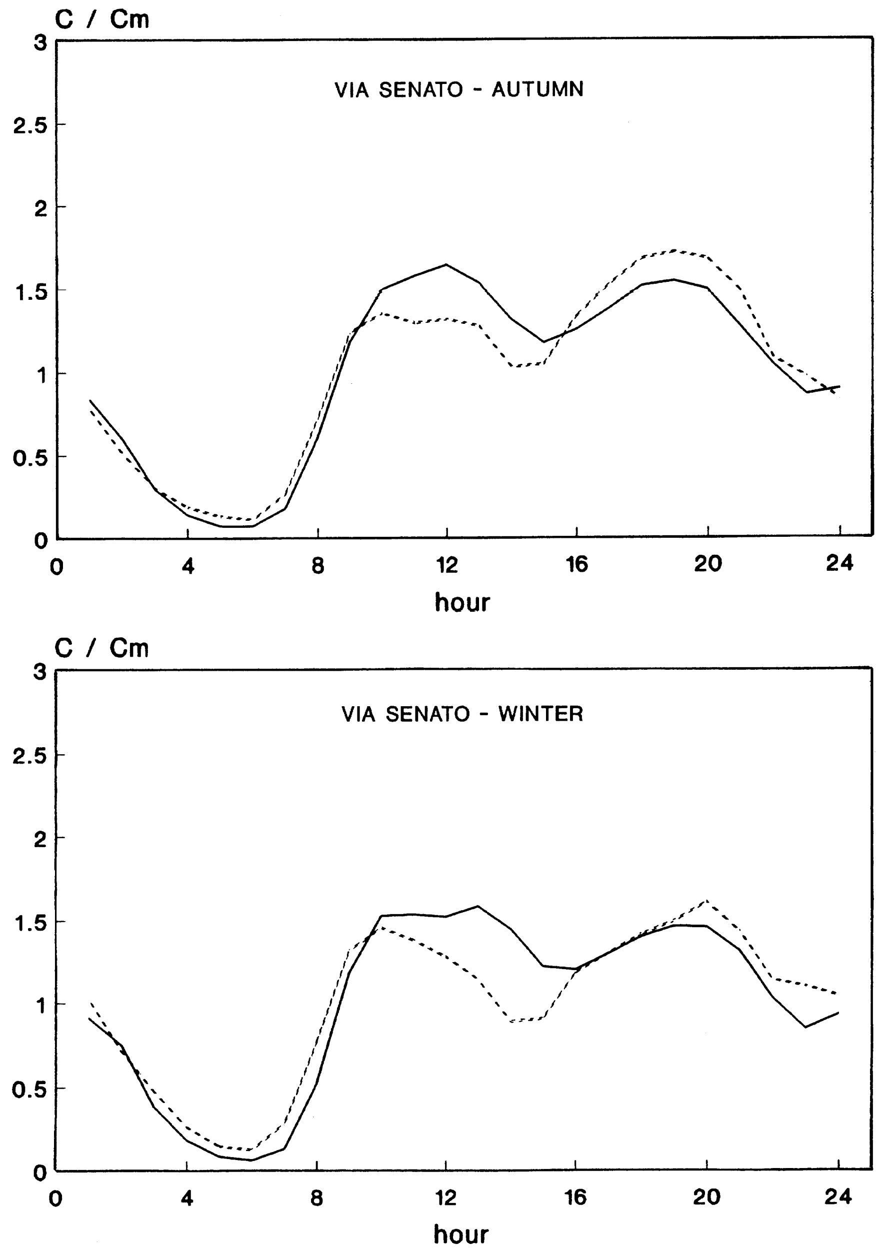

Fig. 4. – Average diurnal variation (hours in abscissa) of normalised concentrations of measured (continuous line) and estimated (dashed line) CO in via Senato (Milan) during autumn and winter.

other pollutants, carbon monoxide (CO) was monitored together with the main parameters of traffic noise (equivalent level, statistical noise levels $L1$, $L50$, $L95$, $L99$). At one site, as well as noise levels, the number and type of vehicles in transit were also

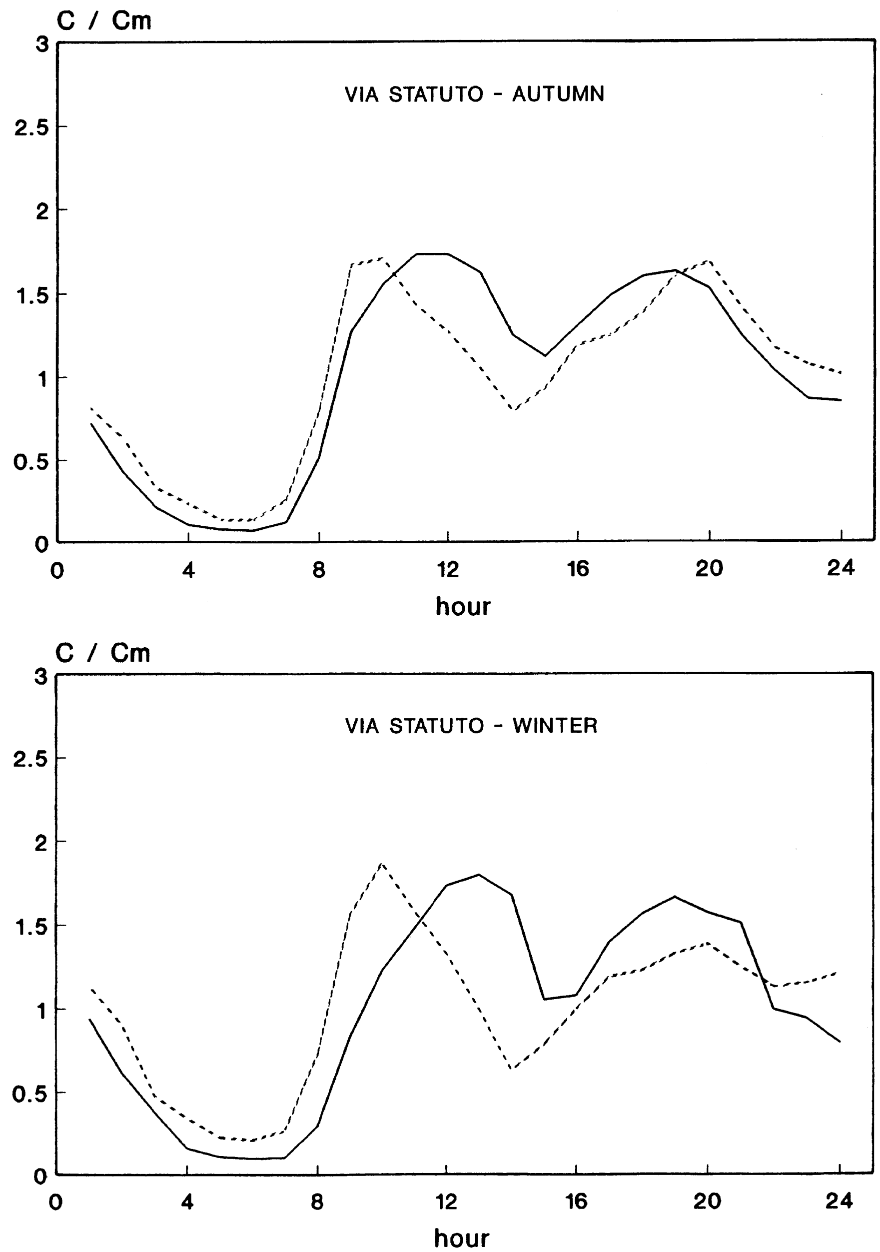

Fig. 5. – Average diurnal variation (hours in abscissa) of normalised concentrations of measured (continuous line) and estimated (dashed line) CO in via Statuto (Milan) during autumn and winter.

TABLE III. – *Sampling periods, mean values for noise and* CO *in Milan.*

Site	Season	*L*50 (dB)	CO (mg/m^3)
Via Senato	Spring	65.9	4.5
Via Senato	Summer	64.4	3.2
Via Senato	Autumn	66.0	6.4
Via Senato	Winter	65.9	7.8
Via Statuto	Autumn	64.4	6.7
Via Statuto	Winter	64.0	7.1

recorded. Table I shows the sampling periods and the mean values for noise (such as the statistical noise level *L*50) and carbon monoxide concentrations.

The wind velocity and temperature gradient (measured between 12 and 34 meters) were registered in the suburbs of Ravenna. Atmospheric turbulence was evaluated on the basis of the temperature gradient. In table II the values of the empirical coefficients a and b of eq. (3) are reported. In Ravenna, one constant value was utilised as the traffic fluxes were known for only one street; however, the structural characteristics of the streets where the noise values were measured are similar, with the heavy traffic in circulation minimal as compared to the light traffic and the speed of vehicles is rather homogeneous.

Figures 1 and 2 show a comparison between the measured and computed CO values for Ravenna, normalised over the mean for the period. The results are presented in the form of typical day, that is, a day where every hour is the mean value at that time over the period.

One can see a good agreement between the two profiles in nearly all localities.

In the case of Milan, we used data collected at two sites by the local air pollution monitoring network [6]. In particular, the data were collected in two streets (via Senato and via Statuto) that are characterised by buildings on both sides and where the canyon effect theory can be reasonably applied. We used data for both streets collected in winter (December, January and February) and autumn (September, October and November) 1990, and those relative only to via Senato in summer (June, July and August) and spring (March, April and May) of the same year. Atmospheric turbulence was evaluated on the basis of the temperature gradient from 1 to 26 meters. Table III shows the sampling periods and mean values of statistical noise level *L*50 and carbon monoxide concentrations.

TABLE IV. – *Statistical evaluation of the performances.*

Town	nmse	r	fa2 (%)
Milan	0.06	0.89	93
Ravenna	0.08	0.89	87

The results are shown in figs. 3 and 4 for via Senato and in fig. 5 for via Statuto. The figures also contain a comparison between typical days of the measured and computed CO values. The values are normalised over the mean for the period and there is a good agreement between measured and evaluated data.

Moreover, table IV presents some statistical indices, defined as normalised mean-square error (nmse), correlation coefficient (r) and factor of two (fa2):

$$\text{nmse} = \frac{\overline{(C_\text{o} - C_\text{p})^2}}{\overline{C}_\text{o}\,\overline{C}_\text{p}}\ ,$$

$$r = \frac{\overline{(C_\text{o} - \overline{C}_\text{o})(C_\text{p} - \overline{C}_\text{p})}}{\sigma_\text{o}\,\sigma_\text{p}}\ ,$$

$$\text{fa2} = \text{fraction of data (\%) for which } 0.5 \leqslant C_\text{p}/C_\text{o} \leqslant 2\ ,$$

where the subscript "o" and "p" are for the observed and predicted concentrations, respectively.

Statistical indices confirm the good performances of the presented methodology and the feasibility of obtaining information on CO concentrations in urban streets from traffic noise measurements.

4. – Conclusions

Town planning, traffic and street management with the creation of pedestrian precincts, transit limitations and the development of public transport require an evaluation of the environmental impact in terms of air quality. The control and management of urban pollution is performed by two means: air quality monitoring networks and mathematical models of pollution diffusion. In order to determine the pollution due to urban road traffic, a rather detailed knowledge is required on the traffic flows in the street plan, classified according to vehicle typology, information which, in Italy at least, is not always available. It therefore seems opportune to have recourse to methodologies based on all the air quality information that is available.

The present work makes a contribution in this direction by verifying the feasibility of obtaining information on CO concentrations in urban streets from traffic noise measurements.

The approach proposed was tested in two Italian cities of different size and meteoclimatic characteristics. In particular, it has been shown how the mean variations in the mean CO concentrations over a long period can be predicted with sufficient reliability, when the traffic noise is known along with the turbulent intensity, in the form of stability classes and wind speed.

Although preliminary, the results have been encouraging and indicate that this line of research should be carried forward with tests in other towns with different characteristics.

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